

Article

Spatial and Temporal Patterns of Carbon and Water Use Efficiency on the Loess Plateau and Their Influencing Factors

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Abstract: Quantitative assessment of the dynamics of carbon and water use efficiency on the Loess Plateau in the context of complex climate change and its driving mechanisms is important for the improvement of the regional ecological environment and the enhancement of ecological service functions. In order to assess the impact of climate change and human activities on the carbon and water use efficiency of the Loess Plateau, this study investigates the spatial and temporal rates of change in *CUE*, *WUE*, and meteorological factors at the image metric scale using one-dimensional linear fit regression, investigates the spatial correlation between *CUE* and meteorological factors using partial correlation analysis, and quantifies the relative contributions of human activities to *CUE* and *WUE* using residual analysis. The following are the study's conclusions: (1) The *CUE* and *WUE* of the Loess Plateau decreased geographically from 2000 to 2020, and both the *CUE* and *WUE* of the Loess Plateau exhibited a non-significant declining trend ($p > 0.05$), with the *CUE* falling at a rate of 0.001/10a (a: year) and the *WUE* decreasing at a rate of 0.047/10a (a: year). (2) From 2000 to 2020, the mean values of the *CUE* and *WUE* of the Loess Plateau were 0.60 and 1.75, respectively, with a clear spatial difference. (3) *CUE* was favorably linked with precipitation in 56.51% of the Loess Plateau, dispersed throughout the south-central portion of the Loess Plateau and Inner Mongolia, whereas the biased association with temperature was not statistically significant and often negative. (4) An examination of residuals revealed that human activities affected the trend of *CUE* and *WUE* to some degree. Only the *WUE* residuals of evergreen broadleaf forests exhibited a strong upward trend that was considerably influenced by people. In conclusion, this study used remote sensing image data and meteorological data to systematically analyze the spatial and temporal dynamic patterns of carbon use efficiency and water use efficiency on the Loess Plateau over the past 21 years, as well as the characteristics of their responses to climate change and human activities, thereby providing theoretical guidance for the study of carbon and water cycles in terrestrial ecosystems on the Loess Plateau.



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1. Introduction

According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the impacts of climate change on terrestrial, freshwater, coastal, and pelagic marine ecosystems are already large and growing irreversibly [1]. It is essential to investigate the driving processes between terrestrial ecosystems and climate change in light of global warming and the growing frequency of extreme weather events. As a key indicator of the response of terrestrial ecosystems to climate change, vegetation carbon and water use efficiency have been popular areas of study in climate change research [2–5]. Vegetation carbon use efficiency (*CUE*) is frequently described as the ratio of the net primary productivity (NPP) of vegetation to gross primary production (GPP) and represents the



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potential of ecosystems to assimilate and store carbon [6]. Vegetation water use efficiency (*WUE*) refers to the proportion of water lost by vegetation in fixing carbon per unit area, expressed as the ratio of vegetation productivity (NPP or GPP) to evapotranspiration (ET), and is a measure of the amount of carbon sequestered per ecosystem of water lost, characterizing ecosystems' response to changes in water resources [7]. As global warming continues to intensify, the potential of vegetation to sequester carbon and the evaporation of ecosystems' available water supplies will accelerate. Under the influence of global climate change, the carbon and water cycles of terrestrial ecosystems are systematically altered, posing a substantial threat to the stability and sustainability of ecosystems. Studying the drivers of carbon and water cycles and their interactions with the environment is crucial for resolving pressing ecological and environmental issues, maintaining ecosystem balance, and minimizing the greenhouse impact [8].

In recent years, many researchers have performed multiple studies on the variation patterns and driving mechanisms of vegetation carbon and water use efficiency at diverse spatial and temporal scales [2,9–12]. Observations and studies of vegetation carbon and water usage efficiency at small scales in the past have primarily employed vorticity correlation and thermal dispersion approaches. With the rapid advancement of remote sensing technology and related data outputs, numerous researchers have combined model simulations and remote sensing data to examine the carbon and water use efficiency of plants at broad scales. When Gong et al. investigated the characteristics of the carbon and water use efficiency of terrestrial ecosystems in Ningxia [13], they discovered that while ecological restoration increased vegetation productivity, it also increased regional water consumption, resulting in a decline in the overall water use efficiency of terrestrial ecosystems. Liu et al. discovered that precipitation was a significant factor influencing the change in land cover carbon and water use efficiency in the basin of Poyang Lake [14]. However, current research focuses primarily on the spatial and temporal variation in single indicators of *CUE* or *WUE* at a regional scale and the influence of climatic factors; few studies synthesize and compare the spatial and temporal variation of *CUE* and *WUE* in the different vegetation ecosystems within the same region.

The Loess Plateau is located in the coastal–inland, plains–plateau transition zone, from south to north through both the mild temperate zone and two heat zones, and from east to west over semi-humid, semi-arid to dry and wet regions. The eastern and southern portions of the plateau belong to the warm temperate semi-humid zone, while the central and western portions belong to the warm temperate semi-arid zone and the middle temperate semi-arid zone, respectively [15]. The climate of the Loess Plateau is influenced by both longitude and latitude and is confined by topography; it is a typical continental monsoon environment. Current research on the Loess Plateau's climatic factors, hydrological processes, vegetation cover, and productivity variations is relatively thorough [16,17]. On the Loess Plateau, however, there is less research on the carbon and water usage efficiency of various land use regimes. Since the 1990s, the ecological environment of the Loess Plateau has been significantly improved due to ecological restoration projects, such as the Grain for Green Project. Nevertheless, large-scale ecological projects have significantly altered the regional ecohydrological processes, and the enhanced carbon sequestration capacity of terrestrial ecosystems on the Loess Plateau has led to a dramatic increase in evapotranspiration, which has had a significant impact on the carbon and water cycle processes in the region. Therefore, studying the characteristics and driving factors of *CUE* and *WUE* changes in various vegetation ecosystems can help to comprehend the carbon and water cycle mechanisms of terrestrial ecosystems on the Loess Plateau in the context of global climate change, so that effective measures can be taken to improve the carbon and water use efficiency of ecosystems and achieve the sustainable development of ecological restoration vegetation. Considering the anomalous nature of climate change and the increasing negative human activities in the Loess Plateau region in recent years, the vegetation response to climate and human activities is more sensitive. This study takes the Loess Plateau as the research object, obtains the vegetation types and distribution area

of the Loess Plateau based on ESA CCI-LC land use types, and uses CRU meteorological data, MODIS vegetation remote sensing data, elevation data, etc., supplemented by trend analysis. The spatial and temporal dynamics of the *CUE* and *WUE* of vegetation on the Loess Plateau from 2000 to 2020 were systematically analyzed on an annual scale. Based on the meteorological and land use type data, we analyzed the spatial and temporal trends of the *CUE* and *WUE* of different vegetation types and their relationships with temperature and precipitation and investigated the mechanisms of the responses of vegetation *CUE* and *WUE* to climatic factors on the Loess Plateau. Based on the residual analysis, we qualitatively assessed the relative impacts and contributions of human activities on *CUE* and *WUE* on the Loess Plateau. By studying the response mechanisms of vegetation *CUE* and *WUE* to climate change and human activities on the Loess Plateau in the past 21 years, this study provides scientific guidance for the formulation of ecological restoration policies and the sustainable use of restored vegetation resources on the Loess Plateau.

2. Materials and Methods

2.1. Study Area

The Loess Plateau ($100^{\circ}52'–114^{\circ}33'$ E, $33^{\circ}41'–41^{\circ}16'$ N) is located in the Yellow River basin's middle reaches, covering more than 1000 km from east to west and 750 km from north to south, with a total area of 640,000 km² (Figure 1). The Loess Plateau region is in a zone of gradual change from arid to humid areas, influenced by the Asian monsoon, with hot summers with low precipitation, dry and cold winters, annual average temperatures between 3.6 and 14.3 °C, large spatial variability in precipitation, annual average precipitation of 100–800 mm, and a semi-arid continental monsoon climate, with the predominant vegetation being sand dunes [18]. The principal vegetation types include crop, shrub, grassland, forest, and mosaic-type vegetation (mosaic grass, mosaic forest).

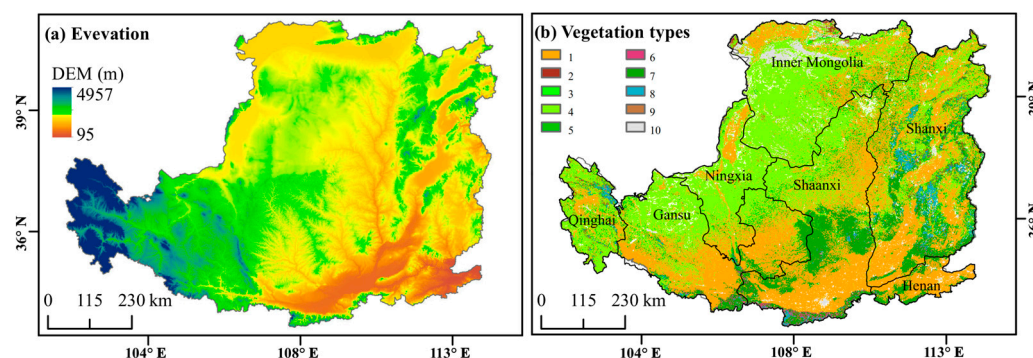


Figure 1. Vegetation types and elevation maps of the Loess Plateau. 1. Crop, 2. mosaic grass, 3. shrub, 4. grassland, 5. mosaic tree, 6. evergreen broadleaf forest, 7. deciduous broadleaf forest, 8. evergreen needleleaf forest, 9. evergreen broadleaf forest, 10. others.

2.2. Data

The gross primary production (GPP) data, net primary production (NPP) data, and evapotranspiration (ET) data required for the study were obtained from the National Aeronautics and Space Administration (NASA) website (<http://modis.gsfc.nasa.gov/data>, accessed on 17 November 2022). NASA launched the TERRA polar-orbiting environmental satellite equipped with the Moderate Resolution Imaging Spectroradiometer (MODIS) in 1999, and its remote sensing data have been widely utilized in the fields of land cover change, biological productivity, and ecological monitoring [19,20]. MODIS offers annual GPP and NPP products with a 500m resolution from 2000 to 2020 (MOD17). These data are derived from a light energy utilization model in order to estimate daily GPP and NPP values, as well as annual GPP and NPP values. This information has been validated and is widely used in Loess Plateau studies of vegetation biomass estimation, the carbon cycle, and ecohydrological processes [21]. The NASA MODIS global evapotranspiration product MOD16 provides a high spatial and temporal resolution land surface evapotranspiration

dataset. Numerous researchers have used the MOD16 product to assess the evolution of spatial and temporal patterns of evapotranspiration in the Loess Plateau region [22,23], validating the accuracy and reliability of the data in the Loess Plateau region. The MODIS Reprojection Tool (MRT) was used for batch stitching, projection conversion, and format conversion for vegetation *CUE* and *WUE* calculations for a total of 21 years of data from 2000 to 2020 in the study area. The specific information about remote sensing data is shown in Table 1.

Table 1. MODIS data details.

Data	Acronym	Data ID	Resolution	Data Format
Gross Primary Production	GPP	MOD17A2Hv006	500 m·8 d ^{−1}	HDF
Net Primary Production	NPP	MOD17A3HGFv-006	500 m·a ^{−1}	HDF
Evapotranspiration	ET	MOD16A2v006	500 m·8 d ^{−1}	HDF

With a geographical resolution of 300 meters, land cover classes were extracted from ESA CCI-LC photos in the context of climate change. Crop, mosaic grass (herbaceous > 50%), shrub, grassland, mosaic tree (tree > 50%), evergreen broadleaf forest, deciduous broadleaf forest, evergreen needleleaf forest, deciduous needleleaf forest, and others are the types of vegetation cover in the Loess Plateau region. The original classification data for the years 2000 and 2015 were used to identify a total of 10 categories of vegetation cover.

Precipitation and temperature data were obtained from the Loess Plateau Sub Center, National Earth System Science Data Center, National Science and Technology Infrastructure of China (<http://loess.geodata.cn>, accessed on 17 November 2022). Based on the global 0.5° climate data published by CRU and the global high-resolution climate data supplied by World Climate, the Delta spatial downscaling scheme was used to generate the data in the Chinese region. The data were also evaluated using 496 independent meteorological observation stations, and the credibility of the results was confirmed. Temperature and precipitation data with a 1 km resolution were used for the examination of factors impacting the carbon and water use efficiency of vegetation.

2.3. Methods

Calculation of *CUE* and *WUE*

In this paper, *CUE* is expressed as the ratio of net primary productivity (*NPP*) to total primary productivity (*GPP*); *WUE* is expressed as the ratio of net primary productivity (*NPP*) to evapotranspiration (*ET*). The formulae are as follows:

$$CUE = \frac{NPP}{GPP} \quad (1)$$

$$WUE = \frac{NPP}{ET} \quad (2)$$

where *CUE* and *WUE* are the carbon use efficiency and water use efficiency of plants, respectively. *CUE* is dimensionless and *WUE* is measured in g C·mm^{−1}·m^{−2}. *ET* is the ecosystem's evapotranspiration in millimeters. *NPP* (g C/m²), *GPP* (g C/m²), and *ET* (mm) were obtained from MODIS data products.

Trends analysis

To evaluate the trends of the carbon and water use efficiency of vegetation and climatic parameters, such as precipitation and temperature on the Loess Plateau, a one-dimensional linear regression was selected for this study, and its significance was determined using an F-test. The slope of the regression equation (*k*) represents the trend of the various variables over the time of the investigation. Specifically, the formula is as follows:

$$k = \frac{n \times \sum_{i=1}^n i \times X_i - \sum_{i=1}^n i \sum_{i=1}^n X_i}{n \times \sum_{i=1}^n i^2 - \left(\sum_{i=1}^n i \right)^2} \quad (3)$$

where K denotes the slope of the trend line; n denotes the cumulative number of years in the study time series; X_i denotes the value in year i . The p -value of significance was calculated using the slope and F-test, and the trends of different elements were classified into four categories: $k > 0$, $p < 0.05$ indicates a significant increase (sig increase), $k > 0$, $p > 0.05$ indicates no significant increase (no-sig increase), $k < 0$, $p < 0.05$ indicates a significant decrease (sig decrease) and $k < 0$, $p > 0.05$ indicates no significant decrease (no-sig decrease).

Biased correlation analysis

Biased correlation analysis was used to calculate the response of CUE and WUE to the dynamics of climate elements, such as precipitation and temperature. When a variable is correlated with two variables at the same time, partial correlation analysis can remove the influence of the other variable on it. The correlation coefficients between the two variables are first calculated, on the basis of which the partial correlation coefficients are further calculated. The correlation coefficients of CUE and WUE with precipitation and temperature were calculated as follows:

$$R_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (4)$$

$$R_{ab,c} = \frac{r_{ab} - r_{ac}r_{bc}}{\sqrt{(1 - r_{ac}^2)(1 - r_{bc}^2)}} \quad (5)$$

where R_{xy} represents the correlation coefficient between variables x and y ; x_i and y_i represent the values for the corresponding year; \bar{x} represents the mean and \bar{y} the cumulative across the corresponding time period; and n represents the length of the study period.

Residual analysis

Analysis of residuals is used to calculate the anthropogenic impact on CUE and WUE . This method has been used by a large number of scholars to distinguish between climate change and anthropogenic effects. The correlations between CUE and WUE and precipitation and temperature are calculated separately, and regressions are established. The difference between the time series CUE and WUE values and the predicted CUE and WUE values based on the regression relationship is called the CUE or WUE residual. This is calculated using the following formulae:

$$CUE' = a_1 \times p + b_1 \times t + c_1 \quad (6)$$

$$WUE' = a_2 \times p + b_2 \times t + c_2 \quad (7)$$

$$\delta_{CUE} = CUE_r - CUE' \quad (8)$$

$$\delta_{WUE} = WUE_r - WUE' \quad (9)$$

where CUE' and WUE' are predicted values based on regression models, CUE_r and WUE_r are calculated values based on remote sensing data; a , b and c are model parameters; p and t are the annual cumulative precipitation and annual mean temperature in mm and $^{\circ}\text{C}$, respectively; and δ is the residual. If the change in residuals is significant, the change in CUE and WUE is considered to be non-climatic; if the change is not significant, the change in CUE and WUE is considered to be dominated by climatic factors.

3. Results

3.1. Spatial and Temporal Characteristics of Vegetation Carbon Use Efficiency and Water Use Efficiency

From 2000 to 2020, the *CUE* and *WUE* of the Loess Plateau showed a non-significant decline ($p > 0.05$), with a rate of decline of 0.001/10a for *CUE* and 0.047/10a for *WUE*, indicating that the interannual trends of *CUE* and *WUE* were relatively stable over the study period, which was determined by a combination of significant increases in *GPP*, *NPP*, and *ET* during the study period (Figure 2). The lowest value of *CUE* occurred in 2016, and the highest occurred in 2014; the highest and lowest values of *WUE* occurred in 2004 and 2010, respectively. The spatial change rate of *CUE* in the studied area ranged between -0.45 and 0.21 , indicating a greater degree of spatial heterogeneity (Figure 3a). Although only 4.79% of the area passed the significance test ($p < 0.05$), 43.69% of the vegetation cover in the studied area showed a rising tendency, primarily in the lower elevation regions of the southern Loess Plateau and southern Shaanxi Province (Figure 3b). The geographic variation rate of *WUE* on the Loess Plateau ranged from -0.24 to 1.01 between 2000 and 2020, with the increase and reduction in *WUE* accounting for 35.6% and 64.4% of the vegetation cover on the Loess Plateau, respectively (Figure 3c). However, only 20.75% of the area passed the significance test ($p < 0.05$), with 16.62% showing a significant decline, primarily in the western and southeastern portions of the Loess Plateau, and 4.13% showing a significant rise, primarily at the southern edge of the Loess Plateau (Figure 3d).

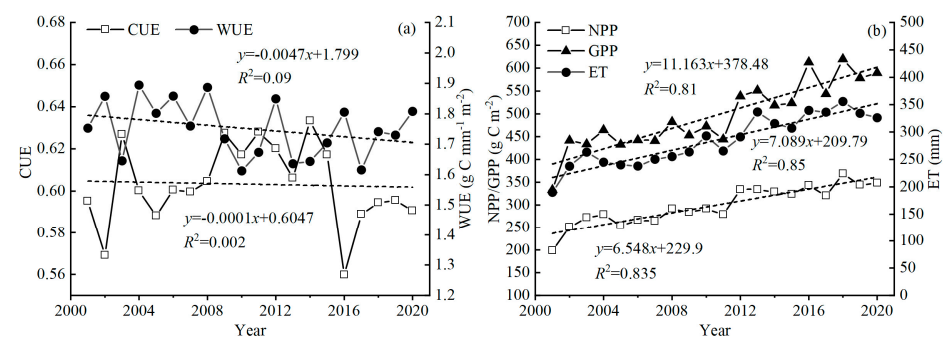


Figure 2. Variation in (a) *CUE* and *WUE* from 2000 to 2020 in the Loess Plateau. (b) *NPP*, *GPP* and *ET* from 2000 to 2020 in the Loess Plateau.

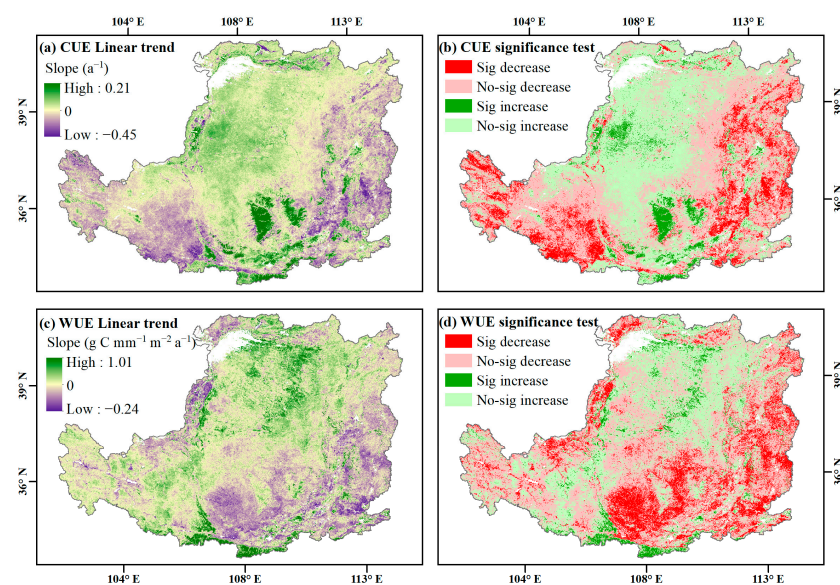


Figure 3. Spatial variation rate and its significance test of *CUE* (a,b) and *WUE* (c,d) from 2000 to 2020 in the Loess Plateau.

3.2. Spatial Distribution Characteristics of the Carbon and Water Use Efficiency of Vegetation on the Loess Plateau

The CUE of the Loess Plateau varied from 0.01 to 0.98, with a mean value of 0.60 (Figure 4a). Low values were patchily scattered around the southeast and northwest edges of the Loess Plateau. High values were primarily dispersed in Gansu and Qinghai. Grassland CUE had the highest value of 0.62, and deciduous broadleaf forest had the lowest value of 0.51; the other values were 0.63 for shrub, 0.62 for crop, 0.61 for mosaic forest, 0.60 for mosaic grassland, 0.54 for evergreen needleleaf forest, 0.53 for deciduous needleleaf forest, and 0.52 for evergreen broadleaf forest, in that order. Figure 4b depicts a progressive increase in WUE from northwest to southeast on the Loess Plateau, with a banded distribution of values ranging from 0.2 to 4.9 and a multi-year average of 1.75. The order was as follows: evergreen broadleaf forest > evergreen needleleaf forest > deciduous broadleaf forest > deciduous needleleaf forest > crop > mosaic forest > mosaic grassland > grassland > shrub.

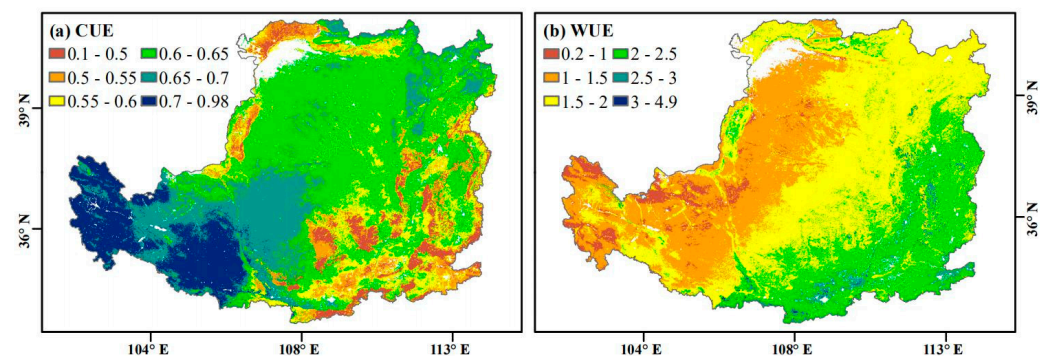


Figure 4. Characteristics of the spatial distribution of CUE (a) and WUE (b) in the Loess Plateau.

The CUE of various vegetation types failed the significance test ($p < 0.05$), with increasing trends in evergreen broadleaf forest, deciduous needleleaf forest, deciduous broadleaf forest, shrub, and evergreen needleleaf forest, and decreasing trends in grassland, crop, mosaic forest, and mosaic grassland (Figure 5a). For the WUE of the different vegetation types, only mosaic grassland (declining trend) and evergreen broadleaf forest (increasing trend) passed the significance test ($p < 0.05$). Shrub and evergreen needleleaf forest exhibited a rising trend, whereas all other land use groups exhibited a decreasing trend (Figure 5b).

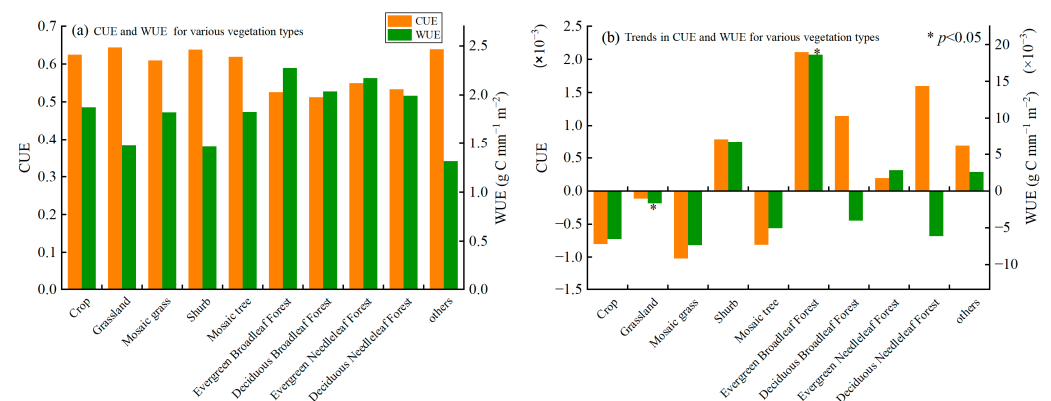


Figure 5. CUE and WUE for various types of vegetation and trend on the Loess Plateau between 2000 and 2020.

3.3. Spatial Patterns of Precipitation and Temperature Variation on the Loess Plateau

Figure 6 depicts the regional distribution and significance of precipitation and temperature trends on the Loess Plateau from 2000 to 2020. The rate of precipitation change on the Loess Plateau ranged from -1.77 to 7.49 over the course of the 21 years, with 95.62% of the area exhibiting minor precipitation trends and 4.38% of the overall study area exhibiting

significant precipitation changes. Further, 4.38% of the entire area of the Loess Plateau was affected by a rise in precipitation, primarily in Qinghai, Gansu, and Shanxi. Only 0.44% of the entire area of the Loess Plateau was impacted by a non-significant decline in precipitation.

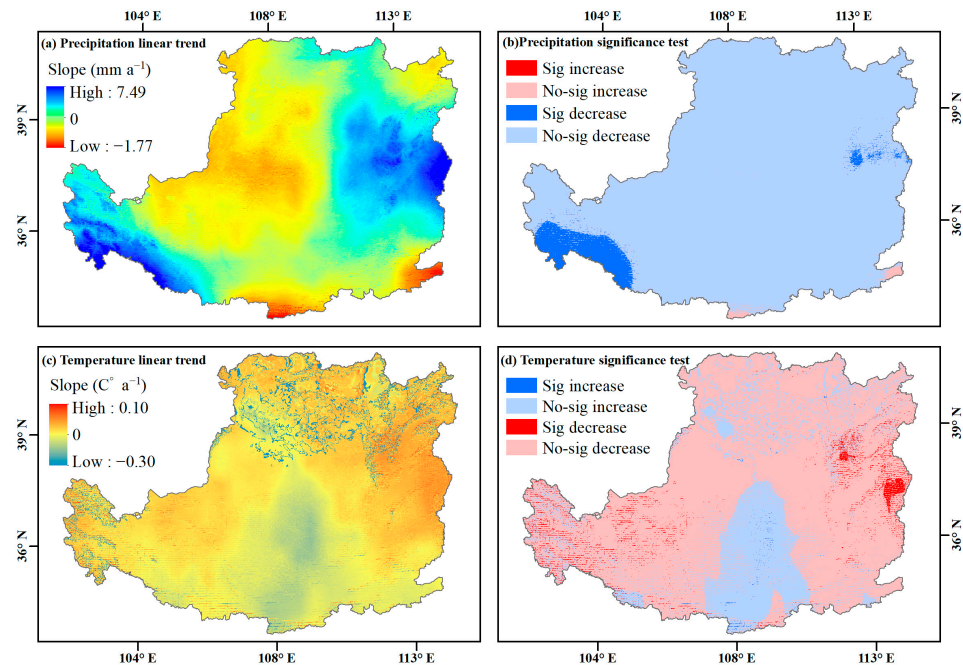


Figure 6. Trends in precipitation (a) and temperature (b) on the Loess Plateau and their spatial distribution of significance (c,d).

As depicted in Figure 6c, the distribution of the rate of change in temperature on the Loess Plateau spanned from -0.30 to 0.10 , with the majority of locations exhibiting a temperature increase. The significance test results indicate (Figure 6d) that 78.77% of the total grassland area showed an increase in temperature, with the proportion of significant and non-significant increases being 2.64 and 76.13%, respectively, with the significant increase being the larger of the two proportions. The eastern portion of the Loess Plateau was home to the majority of the regions with significant population growth. In addition, 21.23% of the overall area of the Loess Plateau had a fall in temperature, with significant and non-significant decreases of 0.18% and 21.05%, respectively, occurring predominantly in the southern portion of the central Loess Plateau.

3.4. Carbon and Water Use Efficiency of Vegetation in Response to Changes in Precipitation and Temperature

In 56.51% of the regions (with a significant positive correlation of 6.95%), *CUE* was significantly correlated with precipitation, primarily in the southern portion of the Loess Plateau and sections of Inner Mongolia (Figure 7a). Further, 43.49% of the areas had a negative correlation between *CUE* and precipitation (with a significant negative correlation of 5.19%), primarily in areas of Gansu. In contrast to precipitation, the correlation between *CUE* and temperature was predominantly negative, accounting for 69.71% of the study area, showing that the overall increase in temperature in the study area was detrimental to the growth in *CUE* (Figure 7b). A significant positive relationship between *CUE* and temperature was identified in 30.29% of the study area, primarily along the northwestern border of the study area and in the southern Shaanxi Province, indicating that the increase in temperature in this portion of the study region was conducive to the growth in *CUE*.

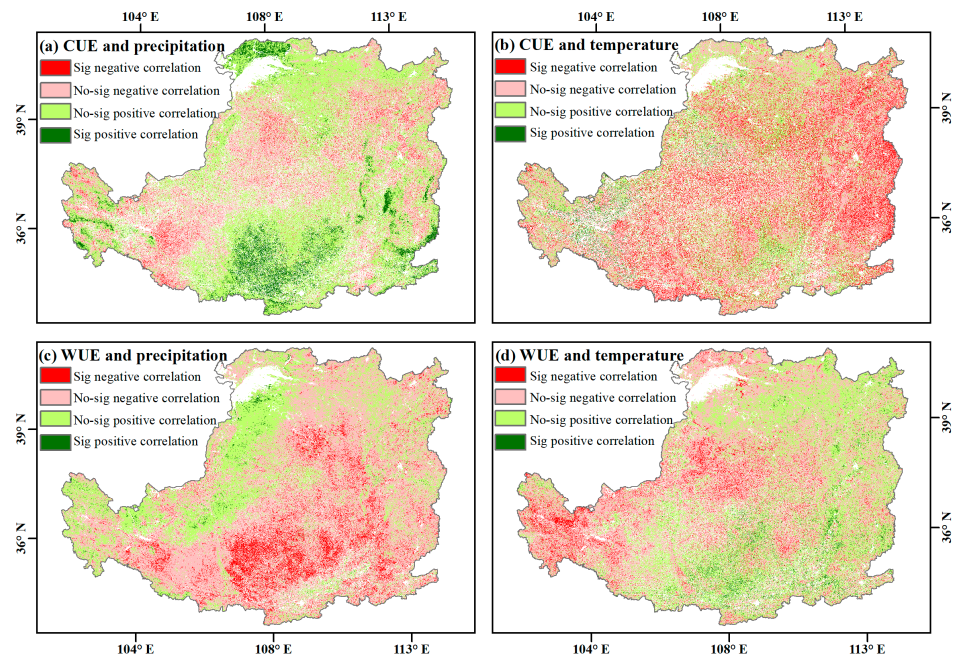


Figure 7. Significant correlations of *CUE* and *WUE* with precipitation (a,b) and temperature (c,d) in the Loess Plateau from 2000 to 2020.

In the majority of regions (70.86%), *WUE* was inversely linked with precipitation, with 10.5% of regions passing the significance test, primarily in the south-central region of the research area (Figure 7c). In the southwestern portion of Inner Mongolia, southern Ningxia, and northern Qinghai, 29.14% of the regions with a positive correlation between *WUE* and precipitation were patchily dispersed. The increase in precipitation in the aforementioned regions resulted in an increase in vegetation water use efficiency (*WUE*), and *WUE* was positively correlated with temperature in the majority of regions (59.34%) and negatively correlated in 40.66% of the regions (2.8% passing the significance test), primarily in regions such as the western portion of the Loess Plateau (Figure 7d).

The correlation between *CUE* and temperature was comparable to the correlation between *CUE* and precipitation, with the exception of two types of needleleaf forests, which also showed a negative correlation with other land types, but mosaic grassland *CUE* showed a significant negative correlation with temperature, with a correlation coefficient of -0.11 ($p < 0.05$) (Figure 8). In contrast to *CUE*, *WUE* and precipitation were positively correlated with all vegetation types other than mosaic grass and grassland, with crop, mosaic forest, and deciduous broadleaf forest exhibiting significant positive correlations, with correlation coefficients of 0.1 ($p < 0.05$), 0.03 ($p < 0.05$), and 0.4 ($p < 0.05$), respectively. While the link between *WUE* and temperature was identical to that between *CUE* and precipitation, it was inversely connected with all other vegetation types, with the exception of shrub and others. This demonstrates that precipitation has a substantially stronger correlation with *WUE* variance in different vegetation types on the Loess Plateau than air temperature.

3.5. Impact of Human Activities on Vegetation Carbon and Water Use Efficiency

The carbon and water use efficiency of vegetation on the Loess Plateau are altered not just by climate change, but also by human disturbances, such as grazing, mining, afforestation, and the construction of nature reserves. According to the results of the residual analysis (Figure 9), 44.49% of the Loess Plateau *CUE* residuals exhibited an increasing trend from 2000 to 2020, with only 4.77% of the areas exhibiting a significant increase, primarily in southern Inner Mongolia, south-central Shaanxi, and eastern Ningxia. The residual trend of *WUE* was comparable to that of *CUE*, with 39.32% of the region exhibiting an increasing tendency and only 4.21% exhibiting a considerable increase, primarily in Inner Mongolia

and the southern edge of the Loess Plateau. On the southeastern and western edges of the Loess Plateau, 60.68% of the land was in decline. During the research period, only the evergreen broadleaf forest *WUE* residuals displayed a substantial upward trend that was considerably influenced by humans (Figure 10).

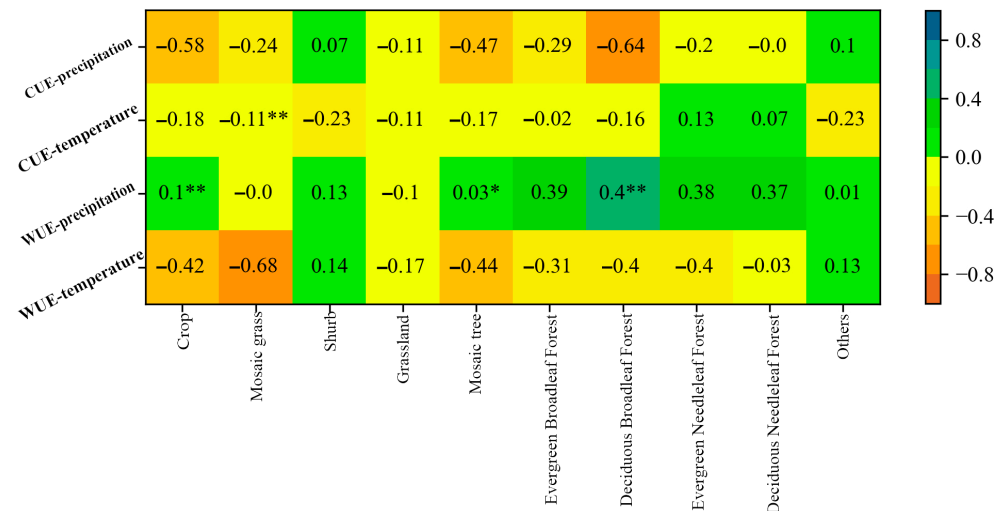


Figure 8. Correlation coefficients of *CUE* (a) and *WUE* (b) with temperature and precipitation for various Loess Plateau vegetation types (*: $p < 0.05$; **: $p < 0.01$).

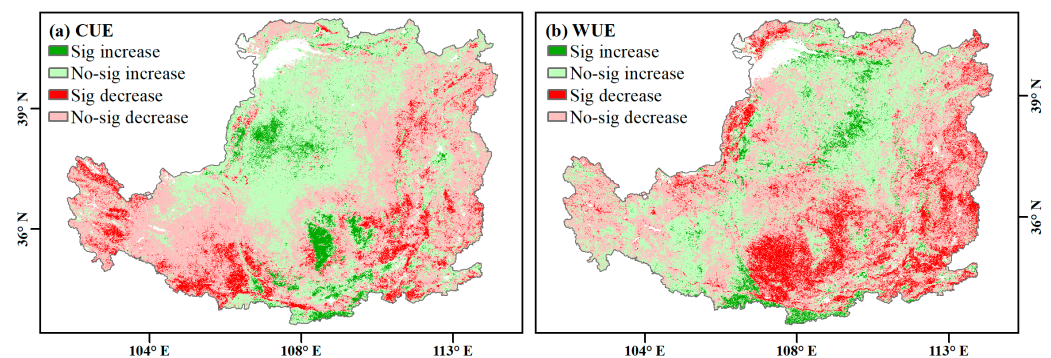


Figure 9. Residual rate of change in carbon and water use efficiency of vegetation on the Loess Plateau (a) and its significance (b).

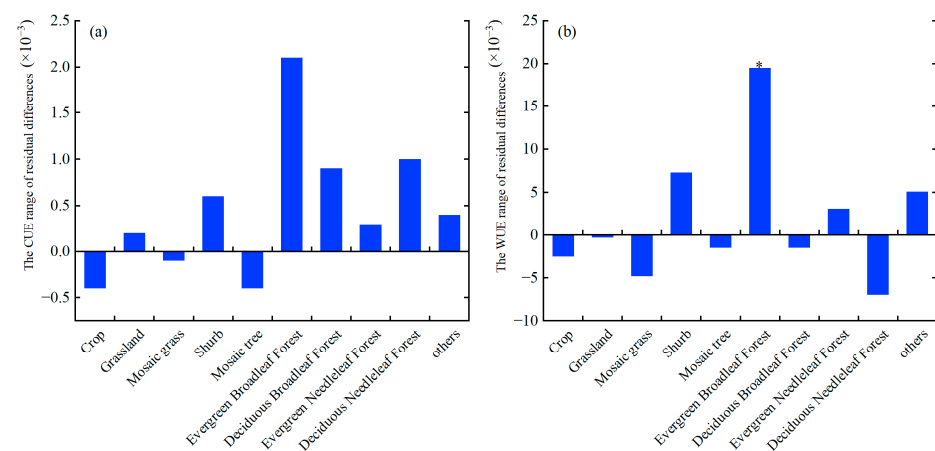


Figure 10. Trends of residuals of *CUE* (a) and *WUE* (b) for different land use types on the Loess Plateau.

4. Discussion

Based on meteorological and remote sensing data, this study analyzed the carbon and water use efficiency of the Loess Plateau from 2000 to 2020 and found that the mean

value of *CUE* on the Loess Plateau was 0.60 for the 21-year period. Chen et al. discovered that the overall vegetation *CUE* in Chinese terrestrial ecosystems ranged between 0.44 and 0.53, but the mean value remained relatively constant at 0.5 [24]; findings by Liu et al. on vegetation *CUE* in China revealed that the mean value of vegetation *CUE* in grassland ecosystems was much greater than in other types of vegetation [25]. The above studies are in general agreement with the results obtained in this paper. In this study, both *CUE* and *WUE* showed a general downward trend, while the growth rates of *GPP* and *ET* were much larger than those of *NPP*, resulting in a decline in the multi-year mean values of *CUE* and *WUE* in the Loess Plateau from 2000 to 2020. Zhang et al. demonstrated a modest reduction in the worldwide terrestrial ecosystem *CUE* between 2000 and 2009 [26], while Xia et al. demonstrated a non-significant decline in the global terrestrial ecosystem *WUE* between 2000 and 2012 [27]. Nonetheless, some researchers have concluded that *CUE* and *WUE* in the studied regions exhibited an increasing trend during the study period, such as Chen et al., who concluded that forest *CUE* in northeast China exhibited a significant increasing trend during 2000–2015 [28], and Liu et al., who demonstrated that vegetation *WUE* in the Loess Plateau exhibited an increasing trend during 2000–2014 [29]. This demonstrates that the patterns of *CUE* and *WUE* in terrestrial ecosystems vary geographically according to the study region and time period.

The highest multi-year mean *CUE* values are predominantly distributed in regions with complex and diverse landscapes (grasslands and shrubs), such as Qinghai and Gansu, where, due to the relatively high altitude and more humid and cold areas, the ecosystems consume less energy through autotrophic respiration and the vegetation is more efficient in carbon sequestration and transfer [30,31]. Low *CUE* values are most prevalent in the southern portion of the Loess Plateau and the northwestern boundary of the region, among other locations. According to the elevation map, the landscape consists primarily of basins and plains at lower elevations, where precipitation is quite abundant, and heat is the primary factor restricting the growth of plants. With an increase in precipitation and warmth, the respiration rate of plants grows exponentially, whilst the photosynthesis rate remains essentially constant, resulting in a drop in *CUE* [24,32–34]. The increase in *GPP* exceeds the increase in *NPP*, which indirectly results in a decline in vegetation *CUE*. An increase in *CUE* was observed in 43.69% of the Loess Plateau (only 4.79% passed the significance test), primarily in Shaanxi, Ningxia, and Inner Mongolia, which is significantly related to the ecological restoration policies, such as the return of farmland to forests and grassland, and the enhancement of ecological restoration effects in these areas.

By altering photosynthesis and respiration, both temperature and precipitation can impact the carbon usage efficiency of plants [35–38]. When temperature and precipitation conditions are optimal, vegetation flourishes and utilizes more autotrophic respiration, resulting in a lower vegetation *CUE*. When both temperature and precipitation increase by the same amount, the increase in *GPP* exceeds the increase in *NPP*, which leads indirectly to a decrease in vegetation *CUE*. Partial correlation analysis revealed that the spatial distribution of *CUE* and precipitation on the Loess Plateau was substantially diverse, with 56.51% of the *CUE* in the research area exhibiting a positive association with precipitation. This was primarily found in the middle and southern portions of the Loess Plateau as well as portions of Inner Mongolia. This suggests that increased precipitation is the primary meteorological factor that increases the *CUE* of vegetation ecosystems on the Loess Plateau, and that increased precipitation can reduce the average ratio of the dark respiration rate to the photosynthetic rate in vegetation while simultaneously increasing photosynthesis, resulting in an increase in vegetation *CUE* [39–43]. In contrast to precipitation, the correlation between *CUE* and temperature was predominantly negative, accounting for 69.71% of the study area, showing that the overall increase in temperature in the study area was detrimental to the growth in *CUE*.

The *CUE* values of different vegetation types are highly variable, with grassland *CUE* values being higher than those of other vegetation types. This is likely because forest ecosystems are more complex than grassland ecosystems, where photosynthesis

fixes more solar energy and respiration consumes more energy for plant growth and reproduction [44–46]. *CUE* values for various land use types failed the significance test ($p < 0.05$), with increasing trends for evergreen broadleaf forest, deciduous needleleaf forest, deciduous broadleaf forest, shrub, and evergreen needleleaf forest, and decreasing trends for grassland, crop, mosaic forest, and mosaic grass. In addition to temperature and precipitation, vegetation *CUE* is also affected by plant cover and vegetation autotrophic respiration. Irrigation and fertilization of agricultural soil can reduce root respiration, while a small vegetation cover leads to less above-ground respiration and a larger *CUE* [47–50].

In addition, Zou et al. discovered that the water use efficiency of ecosystems in central Asia and Xinjiang exhibited a slow increase over the past 15 years [51], whereas this study concluded that the interannual-scale *WUE* in the Loess Plateau region slowly decreased due to the rapid increase in *ET* of the region's vegetation. Consistent with the findings of others, the spatial distribution of *WUE* on the Loess Plateau has a distinct zonal pattern, i.e., a steady decrease from southeast to northwest (Figure 4a). In the southeast of the Loess Plateau, which is next to the Taihang Mountains and has more complicated geomorphological characteristics and less evapotranspiration, *WUE* values are the highest. In addition, the shadowing impact of more vegetation cover on the soil might reduce *ET*, resulting in a higher *WUE*. In arid regions, precipitation is low, vegetation is sparse, and soil evapotranspiration is high, making it difficult for water to permeate the soil and promote plant development [52]; therefore, the northwestern Loess Plateau has a lower *WUE*. In contrast to *CUE*, the *WUE* values of evergreen broadleaf forest were generally greater than those of other vegetation types, in descending order: evergreen broadleaf forest > evergreen needleleaf forest > deciduous broadleaf forest > deciduous needleleaf forest > crop > mosaic forest > mosaic grass > grassland > shrub > other. The *WUE* of forest ecosystems is much greater than that of grassland ecosystems, primarily because forests are dominated by tall tree vegetation with a high leaf area index, canopy cover, and strong leaf photosynthesis. The grassland ecosystem has less vegetation cover, less production, and increased evaporation at the surface [53].

The study by T.C. indicated that water conditions were the primary predictor of plant water use efficiency [54], but the study by Jr R [55] stated that light and water were the primary factors influencing plant water use efficiency. In this study, *WUE* and precipitation were negatively associated (in an encompassing pattern) in the majority of locations (70.86%). In the study area, 29.14% of the regions with a positive association between *WUE* and precipitation were scattered in a patchy fashion, including southwest Inner Mongolia, southern Ningxia, and northern Qinghai. Due to the climatic conditions of the Loess Plateau, precipitation is not the primary limiting factor for *WUE* on the Loess Plateau. The Loess Plateau is situated in the coastal–inland, plain–plateau transition zone. From south to north, it straddles two heat zones: the warm temperate zone and the medium temperate zone. The eastern and southern portions of the plateau belong to the warm temperate semi-humid zone, the central portion belongs to the warm temperate semi-arid zone, and the western and northern portions belong to the mid-temperate semi-arid zone. Wu et al. also demonstrated that the regional wet and dry conditions govern the variation in vegetation *WUE* [56]. As temperature can affect plant photosynthesis and transpiration by changing leaf stomatal conductance, the association between *WUE* and temperature was positive in most regions (59.34%) but not significant. It has been demonstrated that precipitation and temperature have a threshold influence on the responsiveness of *WUE* [57–60], with excessive precipitation and temperature having a negative effect on vegetation *WUE*. *WUE* and precipitation were positively connected with all land use types, with the exception of mosaic grassland and grassland, with farmland, mosaic woodland, and deciduous broadleaf forest exhibiting substantial positive correlations with coefficients of 0.10, 0.03, and 0.40, respectively. Under identical conditions of water supply, woods and agriculture can generate and store more biomass and organic matter than grassland. In prior studies, Santiago et al. demonstrated that the water use efficiency of trees, shrubs, herbs, and vines

varied, with vines having the highest water use efficiency, followed by trees and shrubs, which were all greater than herbs [61].

Additionally, some Loess Plateau vegetation restoration initiatives have been effective and have had a good impact on the growth of vegetation [62,63]. After the year 2000, the implementation of different ecological restoration programs, such as returning farms to grassland, fencing, and limiting overgrazing, contributed greatly to the increase in vegetation productivity on the Loess Plateau. The residual values of *CUE* rose in 44.49% of the Loess Plateau and rose significantly in 4.77% of the areas, primarily in southern Inner Mongolia, south-central Shaanxi, and eastern Ningxia. Although *CUE* was favorably connected with precipitation and negatively correlated with temperature in these places, its correlation with climatic parameters was not statistically significant, suggesting that human activities, such as grazing, are the primary factors controlling *CUE* in these regions.

By systematically analyzing the spatial and temporal evolution of carbon and water use efficiency on the Loess Plateau from 2000 to 2020, and by discussing the potential influencing factors on carbon and water use efficiency, this study provides important guidance values for the formulation and implementation of vegetation conservation policies by supervisory and management agencies on the Loess Plateau. However, precipitation and temperature are not the only climatic factors influencing vegetation water use efficiency; the influence of several climatic parameters on the carbon water use efficiency of the Loess Plateau will be thoroughly examined in a forthcoming study.

5. Conclusions

This paper analyzed the evolution of the geographical and temporal patterns of vegetation carbon and water use efficiency and their probable drivers by analyzing the Loess Plateau's carbon and water use efficiency based on remote sensing data. The *CUE* and *WUE* of the Loess Plateau decreased at a rate of 0.001/10a and 0.047/10a, respectively, from 2000 to 2020. However, this trend was not statistically significant ($p > 0.05$). From 2000 to 2020, the mean values of *CUE* and *WUE* on the Loess Plateau were 0.60 and 1.75, with noticeable geographic divergence characteristics ("U" form). The geographical correlation between *CUE* and precipitation on the Loess Plateau was predominantly positive and dispersed throughout the middle and southern portions of the Loess Plateau and Inner Mongolia; the biased association with temperature was not statistically significant and often negative. In most places, *WUE* was negatively connected with precipitation (in an enclosed form), but positively correlated with temperature. On the Loess Plateau, the correlation between *CUE* and precipitation and temperature for different vegetation types was predominantly negative, whereas the correlation between *WUE* and precipitation was positive for all vegetation types except for mosaic grassland and grassland, while the correlation between *WUE* and temperature was comparable to that of *CUE*. The examination of residuals indicated that human activities influenced the *CUE* and *WUE* to some degree, the *CUE* residuals increased significantly in 4.77% of the Loess Plateau, primarily in southern Inner Mongolia, south-central Shaanxi, and eastern Ningxia, etc. The *WUE* residuals increased significantly in 4.21% of the Loess Plateau, primarily in Inner Mongolia and the southern edge of the Loess Plateau, etc. Only the *WUE* residuals of evergreen broadleaf forest exhibited a strong upward trend that was considerably influenced by people.

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