



Article Vegetation in Arid Areas of the Loess Plateau Showed More Sensitivity of Water-Use Efficiency to Seasonal Drought

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Abstract: Studying the impact of regional or seasonal drought on vegetation water-use efficiency (WUE) can identify an effective theoretical basis by which vegetation can cope with future climate change. Based on remote sensing data and climate grid data, in this study, we calculated the ecosystem WUE and standardized precipitation evapotranspiration index (SPEI), analyzed the temporal and spatial divergence of seasonal drought and WUE, and explored the relationship between WUE and seasonal drought in the Loess Plateau. The results indicate that from 2001 to 2019, the humidity in spring and summer on the Loess Plateau shows an increasing trend, and the aridity in fall also shows an increasing trend. Averaged over four seasons, WUE presents distribution characteristics of "high in the southeast and low in the northwest", with the highest WUE in summer. However, the geological distribution of the sensitivity of WUE to seasonal drought was significantly different. Spring drought increased WUE, whereas summer drought led to a decrease in WUE. When fall drought was less severe, the WUE increased; WUE response to winter SPEI was negative, but the sensitivity did not change with variation of drought degree. The sensitivity of WUE to the magnitude of seasonal drought was affected by regional dry and wet conditions. A clear seasonal divergence was found in four climate regions, along with increased drought intensity, and the sensitivity of WUE to drought magnitude in arid areas was generally higher than that in semi-arid, semi-humid areas, or humid areas. With this study, we deeply explored how ecosystems deal with the water supply strategy of seasonal drought, which is of great significance in the understanding of the coupling relationship between the carbon-water cycle and climate change.

Keywords: ridge regression; standardized precipitation evapotranspiration index (SPEI); sensitivity; drought response

1. Introduction

Drought is the main environmental factor limiting terrestrial ecosystems and has seriously affected ecological security and human society [1]. Moreover, the relationship between vegetation growth and water use of terrestrial ecosystems is significantly affected by drought [2]. For example, drought can constrain vegetation growth, lead to decreased primary productivity and carbon absorption, affect the water supply conditions, and impact ecosystem structure and function [3–5]. With global warming, the intensity and frequency of drought worldwide are significantly increasing [6,7]; consequently, there is an urgent need to quantify the grades and spatial extent of drought to deal with this increasingly serious natural hazard [5]. Many drought indices have been developed to



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). quantitatively and accurately measure droughts [8,9]. For example, the standardized precipitation evapotranspiration index (SPEI) is obtained through three steps: first, by calculating evapotranspiration using meteorological data, then normalizing the cumulative probability of the difference sequence between precipitation and evapotranspiration, and finally revealing drought characteristics within the region using the deviation degree between the difference between precipitation and evapotranspiration and its average state [10,11]. This index combines the multi-scale utility of the standardized precipitation index and the sensitivity of the Palmer drought severity index with temperature and precipitation and is an effective index for studying drought under global climate change [12]. SPEI is an effective measure to study the influence of drought on artificial and natural ecosystems [13]. Water use efficiency (WUE) is related to the amount of fixed CO_2 or dry matter produced by plants consuming a unit mass of water [5,14], which links the coupling of carbon and water cycles and can be used as a feedback index of the terrestrial ecosystem to climate change terrestrial ecosystems [2,15–17]. In addition, ecosystem WUEconnected biological processes and physical processes [5], i.e., the disturbance of gross primary productivity (GPP) and evapotranspiration (ET), simultaneously affect ecosystem WUE [18]. Moreover, the increased frequency and magnitude of global drought events have a profound impact on the water–carbon coupling cycles [8,18]. Therefore, an in-depth understanding of WUE sensitivity to drought will help us better understand the ecological adaptation of vegetation and feedback in response to climate change [19].

As global droughts continue to increase, more scholars are researching the impact of drought on ecosystem WUE on both a regional and a global scale [20]. Studies have shown that biological communities can adapt to water stress by enhancing their WUE [21]. However, this conclusion is challenged by regional studies [8,18,22]. For example, Yang et al. [18] found that the WUE of different terrestrial ecosystems responded differently to drought across global. WUE sensitivity to drought varies with the magnitude of the drought, the duration of the drought, and the type of biological community [18,22–24]. Some researchers investigated the impact of drought events on the WUE of distinct vegetation types and found that the WUE of diverse vegetation types responded differently to drought [23]. A study of the responses of ecosystem WUE to meteorological drought (when dry weather patterns dominate a region) in northern China found that forests had the greatest tolerance to drought, followed by cropland, grassland, and desert, in that order [24]. There is still a lack of scientific consensus on the response mechanism of WUE to drought. Some studies have found that drought reduces WUE [25,26], whereas others found that the response to drought includes increased WUE [27–29]. In addition, it has been found that WUE is also affected by the magnitude and seasonal nature of the drought. For example, Tong et al. [30] found that drought increased ecosystem WUE in spring. Ma et al. [19] found that drought decreased WUE in the summer but increased it in the fall, whereas there was no significant impact in the spring. Xie et al. [31] found that extreme drought decreased ecosystem WUE in the spring and summer but increased WUE in the fall. This shows that WUE's response to drought requires more in-depth research.

Although many scholars have studied the influence of drought on WUE and have drawn many valuable conclusions, most studies on the WUE sensitivity of different ecosystems to drought have been based on long-term drought; few research groups have paid attention to the impact of seasonal drought on the WUE of different climate regions, a relationship that is essential to understanding ecosystem processes under drought stress [8]. Moreover, there have been few studies on the impact of seasonal drought magnitude on WUE. The Loess Plateau in China is characterized by ecological fragility and climatic sensitivity. This region suffers from serious soil erosion, low vegetation coverage, and a continuous drought trend in recent years [32]. Furthermore, the WUE of the Loess Plateau is gradually decreasing, and the drought is becoming more and more serious, which has seriously threatened regional ecological security. However, studies on the response of WUE to seasonal drought is still lacking in the Loess Plateau in northwestern China. Therefore, the focus of this study is on (1) exploring the temporal and spatial differentiation character-

istics of seasonal drought and WUE in the Loess Plateau from 2001 to 2019; (2) analyzing WUE sensitivity to seasonal characteristic drought in the Loess Plateau; and (3) evaluating the impact of seasonal drought on WUE in different climate regions. The goal of this study is to provide as much understanding as possible of the response of terrestrial ecosystems to drought stress, with reference for the Loess Plateau, in order to carry out appropriate ecosystem management [5,32]. Therefore, understanding the relationship between ecosystem WUE and droughts is necessary for evaluation of the ecological security of the Loess Plateau and has great practical significance and scientific value.

2. Materials and Methods

2.1. Site Descriptions

The Loess Plateau is located in the northern part of China (34°–40° N, 103°–114° E). It is the plateau with the largest loess coverage in the world and includes Henan, Ningxia, Qinghai, Gansu, Shaanxi, and Shanxi Provinces, as well as the Inner Mongolia Autonomous Region [32], with an area of about 640,000 km² (Figure 1a). Moreover, the area spans semi-arid, arid, semi-humid, and humid regions, with an average annual temperature of 3.6–14.3 °C and annual precipitation of 150–750 mm. The precipitation mostly occurs in summer and fall, and there is little rain in the winter and spring, which is characteristic of a continental monsoon climate [33,34]. The vegetation coverage is low, and the vegetation from south to north is distributed in the forest belt, forest–steppe transition zone, and grassland zone in an obvious zoning pattern. The main tree species are *Pinus tabulaeformis* Carr., *Robinia pseudoacacia* L., *Armeniaca sibirica, Ailanthus altissima*, and others (Figure 1b). The area suffers from serious soil erosion, and the ecological environment is very fragile. The Loess Plateau is the environment with the most severe soil erosion and the most fragile ecology in China and possibly in the entire world [32,35].



Figure 1. Map outlining the geographic location (a) and vegetation types (b) of the Loess Plateau.

2.2. Data Sources and Preprocessing

A dataset of monthly precipitation and temperature data was extracted from climate sites of the National Meteorological Science Data Center (https://data.cma.cn/data/index. html, accessed on 11 June 2020) for the period from 1986 to 2019, meeting the minimum requirements for SPEI calculation of at least 30 years [36], and the horizontal resolution was $0.5^{\circ} \times 0.5^{\circ}$. In this study, we used 448 climate grid points of the Loess Plateau and its surrounding areas to calculate the grid point SPEI index with R software (SPEI package), and the results were interpolated into SPEI raster data with a resolution of 500 m \times 500 m by the ANUSPLIN package; the average SPEI index for each season from 2001 to 2019 was obtained, which could be used to characterize the drought of each season. Gross primary productivity (GPP) and evapotranspiration (ET) were derived from

remote sensing data. MODIS GPP (MOD17A2H) and MODIS ET (MOD16A2) product data were from the United States Land Processes Distributed Active Archive Center (https://lpdaacsvc.cr.usgs.gov/appeears/task/area, accessed on 13 March 2020), the spatial resolution was 500 m, the time resolution was 8 days, and the study period was from 2001 to 2019. Preprocessing, including image mosaic, reprojection, and format conversion, was completed with the MODIS reprojection tool (MRT).

2.3. Methodology

2.3.1. Calculation of Water Use Efficiency (WUE)

In this research, the ratio of GPP (g $C \cdot m^{-2}$) to ET (mm) was used to calculate the ecosystem WUE (g $C \cdot mm^{-1} \cdot m^{-2}$):

$$WUE = \frac{GPP}{ET}$$
(1)

2.3.2. Calculation of the Standardized Precipitation Evapotranspiration Index (SPEI)

The standardized precipitation evapotranspiration index (SPEI) was used to characterize drought degree [5]. The different time scales of SPEI (running from 1 to 48 months) represent the precipitation deficit or precipitation surplus over the preceding period. In this study, we calculated the three-month SPEI (denoted as SPEI₃) to determine the droughts of the Loess Plateau. The SPEI time scale has been shown to reflect seasonal variations in drought conditions [37]. The SPEI index is calculated as follows:

Step 1: Calculation of potential evapotranspiration (PET):

$$PET = 16 \left(\frac{N}{12}\right) \left(\frac{M}{30}\right) \left(\frac{10T}{H}\right)^{A}$$
(2)

where T represents the monthly average temperature (°C), N represents the maximum sunshine hours, M represents the number of days in the current month, and H represents the heat index. A is a constant determined by the heat index, H: A = $(0.492 + 0.179H - 7.71) \times (10^{-5}H^2 + 6.75 \times 10^{-7}H^3)$.

Step 2: Calculation of the differences between monthly precipitation (*P*) and potential evapotranspiration (PET) at different time scales:

$$D_i = P_i - PET_i \tag{3}$$

where D_i is the difference between precipitation and evapotranspiration, P_i is the monthly precipitation, and PET_i is the monthly potential evapotranspiration.

Step 3: Calculation of SPEI using the log-logistic probability distribution of three parameters to normalize the D_i (the results of step 2) and then obtain the SPEI series [38].

To analyze the drought characteristics of the Loess Plateau, we divided five drought grades using China's meteorological drought grade standard, geographical characteristics of the Loess Plateau, and a related research [39,40] (Table 1). The smaller the SPEI value, the more severe the drought.

Table 1. Drought classification is based on the standardized precipitation evapotranspiration index (SPEI).

Standardized Precipitation Evapotranspiration Index (SPEI)	Drought Magnitude
0 < SPEI	No drought
$-1 < \text{SPEI} \le 0$	Mild drought
$-1.5 < \text{SPEI} \le -1$	Moderate drought
$-2 < \text{SPEI} \le -1.5$	Severe drought
$SPEI \leq -2$	Extreme drought

2.3.3. Ridge Regression

Ridge regression analysis is a refined least squares estimation method [41] and biased estimation regression method that can eliminate the collinearity of independent variables. Therefore, in this paper, we used ridge regression to explore the sensitivity of WUE to seasonal drought.

The multiple linear regression models can be expressed as follows:

$$Y = X \cdot \beta + \varepsilon$$

where *Y* is the dependent variable; *X* is the independent variable (in the form of a multivariate matrix); β is the regression coefficient; and ε is the error, which obeys the normal distribution.

If the regression coefficient, β , is estimated according to the least square method, then:

$$\beta_1 = \left(X^{\mathrm{T}} \cdot X\right)^{-1} \cdot X^{\mathrm{T}} \cdot Y$$

However, if there are multiple collinearities between the data of the independent variable, *X*, it may cause instability in the obtained coefficients and a lack of explanatory and physical meaning. Therefore, an improved least square estimation method, ridge regression, is proposed [33]. Its general form is:

$$\beta_2 = \left(X^{\mathrm{T}} \cdot X + k \cdot I \right)^{-1} \cdot X^{\mathrm{T}} \cdot Y$$

where *k* is the ridge parameter (usually, $k \ge 0$; when k = 0, it becomes the least squares estimator), and *I* is the unit matrix. The greater the *k* value, the better the effect of eliminating the effect of collinearity, whereas the smaller the *k* value, the smaller the fitting variance and the greater the fitting accuracy but the poorer the effect of eliminating the effect of collinearity [33].

In this paper, WUE is the dependent variable; and spring drought (March to May), summer drought (June to August), fall drought (September to November), and winter drought (December to February of the following year) are independent variables. All variables are detrended linearly before ridge regression, and the calculated regression coefficient is the sensitivity coefficient of each variable to the dependent variable, represented by γ [33]. Ridge regression was performed in the R language (Ridge package), with significance level of 0.05.

3. Results

3.1. Dynamic Characteristics of Seasonal Drought

The averages of SPEI₃ from March to May, June to August, September to November, and December to February of the following year were used to characterize the seasonal variation of drought in spring, summer, fall, and winter, respectively, on the Loess Plateau. From a seasonal perspective (Figure 2), the interannual SPEI values of the Loess Plateau increased in the spring and summer from 2001 to 2019, showing a trend of increasing humidity ($R^2 = 0.0041$ and $R^2 = 0.1112$, respectively), whereas the SPEI value for the fall decreased overall, showing a trend of increasing aridity ($R^2 = 0.0481$). In the spring, SPEI increased slowly at a rate of 0.02/10a, with the lowest value of SPEI appearing in 2013. The cumulative anomaly curve shows that the SPEI value fluctuates considerably in the spring, and a decreasing trend was found in 2003–2009 and 2012–2013. In the summer, there was a pervasive drought from 2001 to 2019, and SPEI increased at a rate of 0.16/10a over the entire study period, with SPEI showing a trend of "rising-falling-rising" during the periods of 2001–2004, 2004–2011, and 2011–2019, with average SPEI values of -0.91, -1.08, and -0.82, respectively. The lowest SPEI values were in 2001, when the drought was at its most serious, reaching a moderate grade of drought. In the fall season of the 2001–2019 period, the SPEI value decreased at a rate of 0.2/10a, showing a decreased trend as a whole. The SPEI value was lowest in 2019, and the magnitude of the drought was moderate. The trend of SPEI values in winter is not clear, but they were more than zero from 2001 to 2019, indicating that there was no drought in winter during the study period. It can be seen from the cumulative anomaly curve that the winter SPEI showed a "rising–falling–rising" trend during the periods of 2001–2005, 2005–2014, and 2014–2019, with average SPEI values of 0.66, 0.61, and 0.68, respectively.



Figure 2. Long-term dynamic characteristics of seasonal standardized precipitation evapotranspiration index (SPEI) in the Loess Plateau.

A clear seasonal divergence was identified in the spatial patterns of drought index and magnitude of drought (Figure 3). The seasonal ordering of magnitude of drought was: summer > spring > fall > winter. In spring, SPEI increased from southeast to northwest with the decrease in precipitation gradient, indicating that the spring drought in the southeast with more precipitation is more severe (Figure 3(a1)). The drought intensities were mainly mild (40.9%) and no drought (59.1%) in spring (Table 2). The mild droughts in the spring were mainly located in the southeast of the Loess Plateau and Qinghai, with the drought being most severe in central Shaanxi, most of Shanxi, eastern Gansu, and Qinghai, where the vegetation types were mainly forest and grassland (Figure 3(b1), Table A1). In the summer, the drought grade is no drought (2.5%), mainly distributed in Qinghai and southern Shaanxi, and most regions experienced mild drought (39.8%) or moderate drought (57.2%) (Table 2). The drought index (SPEI) increased gradually with the increase in precipitation from the northwest (moderate drought) to the southeast (mild drought), that is, the summer drought in the northwest of the Loess Plateau, with less precipitation, is more serious (Figure 3(a2, b2)). Severe drought (0.5%) was found in some areas of Inner Mongolia, Ningxia, and Gansu, where the main vegetation types are shrubs and grasslands

(Table 2, Table A1). The magnitude of the drought in the forest was mild (Table A1), and the drought magnitude in the summer was the most severe of all four seasons (Figure 3(b2)). The spatial distribution of drought index in the fall was similar to that in the summer, reflecting that drought was more serious in areas with less precipitation, the climate being drier in the northwest, where grassland is the main vegetation type, but more humid in the southeast and southwest, where forest is the main vegetation type (Table A1). It is worth mentioning that the SPEI value was the highest and the drought magnitude was the least in Qinghai and the central Loess Plateau (Figure 3(a3)). The magnitude of drought in fall was mainly mild (25.9%) or no drought (74.1%); the former was mainly distributed in Inner Mongolia, Ningxia, and some areas of Gansu, whereas other areas experienced no drought (Figure 3(b3), Table 2). The spatial distribution of SPEI values in the winter was similar to that in the spring, with SPEI values in the northwest being higher than those in the southeast and southwest, that is, the more precipitation there was, the more serious the winter drought was (Figure 3(a4)). Except for the most regions of Qinghai and the southern Loess Plateau, which are dominated by grassland and experienced mild drought (5.5%), most of the regions generally experienced no drought (94%) in winter (Figure 3(b4), Table 2).



Figure 3. Spatial distribution of seasonal SPEI average (a1–a4) and drought magnitudes (b1–b4) in the Loess Plateau from 2001 to 2019.

Table 2. Percentage of the area under different drought magnitudes in each season.

	Proportion of No Drought	Proportion of Mild Drought	Proportion of Moderate Drought	Proportion of Severe Drought
Spring	59.1%	40.9%	-	-
Summer	2.5%	39.8%	57.2%	0.5%
Autumn	74.1%	25.9%	-	-
Winter	94.0%	5.5%	0.5%	-

Note: "-" means that there was no such drought magnitude in the season.

3.2. Dynamic Characteristics of Seasonal WUE

As illustrated in Figure 4, there is an evident discrepancy in the spatial distribution of seasonal WUE in the Loess Plateau (Figure 4). In the spring (March–May), the vegetation

WUE changed from 0.1 to 24 mg C·mm⁻¹·m⁻²; the average value was 3.1 mg C·mm⁻¹·m⁻², the low value occurred in the southwest study region with higher elevation, and the grassland had the highest WUE (2.17 mg $C \cdot mm^{-1} \cdot m^{-2}$) (Table 3). The spring WUE decreased generally with the decrease in precipitation from the southeast to the northwest, with a decreasing trend from 2001 to 2019. In the summer (June-August), the spatial distribution of vegetation WUE was relatively uniform, in the range of 0.2–5.5 mg C·mm⁻¹·m⁻², with an average value of 3.6 mg C·mm⁻¹·m⁻². Of all seasons, the average WUE in summer was the highest, presenting the spatial distribution features of "high in the southeast and low in the northwest". The border zone between Gansu and Ningxia had the lowest WUE, whereas the highest WUE values were in the southeast forest area and the Qinghai grassland area. In fall (September–November), the spatial distribution characteristics of WUE were quite similar to those in the spring; the WUE range was $0.1-16 \text{ mg C} \cdot \text{mm}^{-1} \cdot \text{m}^{-2}$, with an average value of 3.4 mg C·mm⁻¹·m⁻², and the forests had the highest WUE (1.74 mg C·mm⁻¹·m⁻²) (Table 3). The average WUE in the fall was slightly higher than that in the spring. Compared to spring, summer, and fall, winter (December-February) WUE exhibited a lower value and an increasing trend. The WUE value ranged from 0 to 11 mg C·mm⁻¹·m⁻², with an average value of 1.4 mg C·mm⁻¹·m⁻².

Table 3. Seasonal WUE of different vegetation types (mg $C \cdot mm^{-1} \cdot m^{-2}$).

	Forests	Shrublands	Grasslands
Spring	2.06	1.88	2.17
Summer	1.81	1.54	1.98
Fall	1.74	0.83	0.49
Winter	0.78	0.35	0.21



Figure 4. Cont.



Figure 4. Spatial (left) and temporal (right) distribution of seasonal vegetation water-use efficiency (WUE) on the Loess Plateau.

3.3. Sensitivity Analysis of WUE to Drought Index

Ridge regression was used to explore the sensitivity of WUE to drought index (γ), and a clear seasonal divergence was observed in the spatial patterns of γ during the period of 2001–2019 (Figure 5).



Figure 5. Cont.

-0.4



Figure 5. Spatial distribution of the sensitivity coefficient(γ) of water-use efficiency (WUE) to seasonal drought (SPEI) (**a1–a4**) and scatter plot of the change in WUE sensitivity of each season in relation to the magnitude of drought (**b1–b4**).

Generally, negative γ_{spring} values (81%), meaning spring drought led to increased WUE, were observed in the spring in the study region, with a mean (γ_{spring}) of -0.06

(Figure 5(a1)). The significant test area (8.2%) was mainly dominated by shrublands and grasslands (Figure S1(a)). The relationship between interannual sensitivity of WUE to SPEI and drought index in spring (Figure 5(b1)) showed a consistently increasing γ_{spring} , along with an increasing magnitude of drought in the Loess Plateau. When the drought continued to increase, the magnitude of the increase, γ_{spring} , was smaller, which means that the higher magnitude of drought, the lower the sensitivity of WUE to drought (Figure 5(b1)).

In comparison, a pervasively positive sensitivity of WUE to SPEI, which means summer drought led to a decrease in WUE, was found (accounting for 70.8% of the whole region). In summer, γ_{summer} was significantly positive (11%) in the northwest of the Loess Plateau (including the Gansu and Ningxia Provinces and southwestern Inner Mongolia), which is dominated by shrublands and grasslands (Figure 5(a2), Figure S1b). There were three magnitudes of drought in summer; the higher the magnitude of drought (moderate drought), the larger the response of WUE to SPEI (Figure 5(b2)).

Similar to spring, a generally negative sensitivity of WUE to drought (accounting for 80.2% of the whole region), which means fall drought increased WUE, was shown in fall, with eastern Gansu, western Shaanxi, and northern Shanxi being the most significant regions (p < 0.05) (Figure 5(a3), Figure S1c). The relationship between SPEI and γ_{fall} (Figure 5(b3)) showed that with decreased SPEI, a negative γ_{fall} gradually changed to a positive γ_{fall} , which indicates that when the SPEI value > 0 and there is no drought, the higher the SPEI, the lower the negative sensitivity of WUE to SPEI, whereas when the SPEI value < 0 during mild drought, fall drought decreased WUE.

A generally clear negative sensitivity of WUE to SPEI (accounting for 74.2% of the whole region) was found in winter (Figure 5(a4)). Significantly negative γ_{winter} (with 7.8% of the areas passing the significance test) was distributed in the southeast of the Loess Plateau (including the south of Shaanxi and Shanxi), where the vegetation type is dominated by forests (Figure 5(a4), Figure S1d). In winter, relatively uniform sensitivity coefficients were shown, and γ_{winter} did not change with the varying SPEI, which suggests a minimal effect of SPEI on WUE in winter when SPEI > 0 and there is no drought (Figure 5(b4)).

To further explore the seasonal difference of γ in climate regions of the Loess Plateau, the seasonal γ in humid, semi-humid, semi-arid, and arid areas was extracted. The results showed a clear seasonal divergence in four climate regions, along with the increased magnitude of drought (Figure 6, Table A2).



Figure 6. Water-use efficiency (WUE) sensitivity coefficients in response to seasonal drought in climates regions. Note: SP: spring; SU: summer; FA: fall; WI: winter.

Mild drought in spring increased WUE in arid, semi-arid, and semi-humid regions and decreased WUE in humid regions. There was no moderate or severe drought in spring. The sensitivity of WUE to no drought and mild drought was quite different in the four climate regions. The sensitivity coefficients of WUE to no drought in arid, semi-arid, and humid areas were -0.129, -0.051, and -0.008, respectively, whereas the coefficient was positive ($\gamma = 0.015$) in the semi-humid area. The sensitivity coefficients of WUE to mild drought in arid, semi-arid, and semi-humid areas were -0.011, -0.039, and -0.023, respectively, whereas the coefficient was positive ($\gamma = 0.017$) in the humid area.

In the summer, the magnitude of drought significantly influences the sensitivity of WUE to SPEI. Mild drought in the summer reduced WUE in four climate regions, whereas moderate drought decreased WUE in arid and semi-arid areas and increased WUE in semi-humid areas, and severe drought decreased WUE in arid and semi-arid areas. The sensitivity coefficient of WUE to mild drought was positive in arid, semi-arid, semi-humid, and humid areas, and the sensitivity coefficients were 0.102, 0.007, 0.005, and 0.018, respectively, with the highest sensitivity coefficient occurring in arid areas. The sensitivity coefficients of WUE to moderate drought in arid and semi-arid areas. The sensitivity coefficients of WUE to moderate drought in arid and semi-arid areas were 0.096 and 0.039, respectively, whereas the coefficient was negative in semi-humid areas ($\gamma = -0.005$). The sensitivity of WUE to severe drought was positive in both arid and semi-arid areas.

In the fall, mild drought reduced WUE in arid and semi-arid areas and increased WUE in semi-humid areas; there were no moderate or severe droughts in the fall. The sensitivity coefficients of WUE to no drought or mild drought were low in different climate regions. The sensitivity of WUE to no drought was negative in arid, semi-humid, and humid areas, with values of -0.003, -0.017, and -0.017, respectively. The sensitivity coefficient of WUE to mild drought in arid areas was 0.005 and 0.002, respectively, whereas that in semi-humid areas was negative ($\gamma = -0.004$).

In the winter, in most regions with SPEI > 0 and no drought, the sensitivity coefficient of WUE to SPEI was negative. When SPEI < 0 and mild drought occurred, the sensitivity of WUE to SPEI was negative in arid and semi-arid areas, with the sensitivity coefficient being highest in arid areas ($\gamma = -0.172$), whereas the sensitivity coefficient was positive in semi-humid and humid areas, with coefficients of 0.029 and 0.035, respectively. The sensitivity coefficients of WUE to moderate drought in semi-arid, semi-humid, and humid areas were -0.032, -0.009, and -0.013, respectively. The sensitivity coefficients of WUE to severe drought in semi-arid and sub-humid regions were negative. On the whole, mild drought in winter increased WUE in arid and semi-arid regions but decreased WUE in semihumid and humid regions. Moderate and severe drought increased water-use efficiency in semi-arid and semi-humid regions. On the whole, in arid and semi-arid areas, mild drought in the spring and winter increased WUE, whereas mild, moderate, and severe droughts in the summer decreased WUE. In semi-humid areas, mild droughts in the spring and fall, moderate droughts in the summer, and moderate and severe droughts in the winter increased WUE, although mild drought in the summer and winter decreased WUE. Mild drought in the spring, summer, and winter all decreased WUE in humid areas, whereas the sensitivity coefficient of WUE to SPEI in the arid region of the Loess Plateau was generally higher than that in the semi-arid, semi-humid, and humid regions. That means that vegetation is more sensitive to water change in arid regions than in other climate regions in the study region.

4. Discussion

4.1. Characteristics of Seasonal Drought Changes

In this paper, we analyzed the seasonal characteristics of drought changes in the Loess Plateau from 2001 to 2019. The results showed that the spatial distribution of drought varied significantly in four seasons, predominated by mild drought, with the following order of the drought magnitudes: summer > spring > fall > winter. Spatially, Severe drought was in southeast–southwest and mild drought was in the northwest in spring and winter, whereas summer and autumn droughts had the opposite spatial distribution. These

findings were identical to the results of previous studies, such as those of Sun et al. [32] and Zhang et al. [38], who found that the areas with significant drought in the spring were located in southern Shanxi, northern Shaanxi, and southeastern Gansu, with the driest regions being in Inner Mongolia and Ningxia in the summer. Zhang et al. [42] analyzed the drought characteristics of the Loess Plateau in Gansu Province and found that the northwest of the Loess Plateau in spring, summer, and fall is a drought-prone area, whereas the drought-prone area in Gansu Province in winter is mainly concentrated in the south of the Loess Plateau. It should be noted that the different results from the various studies was are partially due to different calculation methods and study periods for the selected drought index; furthermore, when analyzing the spatial distribution characteristics of seasonal drought in the Loess Plateau, whereas previous studies mainly analyzed the spatial change trend of drought. Therefore, the overall trend is similar, but the spatial distribution pattern of drought is different.

4.2. Characteristics of WUE Changes

Seasonal water-use efficiency (WUE) in the Loess Plateau has obvious spatial distribution characteristics, which may be different from the previous research results [42]. There are several reasons for these differences: (1) different research periods; (2) the spatial resolution of GPP and ET used to calculate WUE was different, which depends on the choice of remote sensing products. The difference in the spatial distribution of seasonal WUE is mainly related to different seasonal water-use strategies adopted by different vegetation types [22,43–48]. In this study, we found that WUE was generally higher in forests with more precipitation located in the southeast of the study region, which is in agreement with previous research on the differences in WUE of different ecosystems [22,43]. Some studies have confirmed the positive trend of WUE along a precipitation gradient [44–46]. In humid areas, forest roots are deeper and the canopy is denser, which can block solar irradiance and use more soil water, which is conducive to plant growth and WUE of the ecosystem [47,48].

4.3. Response of WUE to Seasonal Drought

Interestingly, spring drought increased WUE and summer drought decreased WUE, although all significant sensitivity of WUE to SPEI in two seasons was found in the northwest study region dominated by grassland. When drought occurs, the sensitivity of WUE to the drought index is low in spring and high in summer. The divergence of sensitivity of WUE to SPEI in spring and summer may be related to the drought tolerance of vegetation and the magnitude of drought [9,18,19,22,49,50]. First, there is generally less precipitation in spring than in summer, and vegetation has adapted to the drier climate of spring so that when the drought is prolonged, the drought tolerance of grass in the spring is greater than that in the summer when drought continues [13,18,22,51,52]; therefore, spring drought led to increased WUE. Secondly, higher sensitivity of WUE to SPEI was found in grasslands because the grass is more sensitive to environmental and climate change than deep-rooted vegetation [18,21]. In other words, shallow-rooted herbs rely on precipitation to supplement soil water, whereas deep-rooted trees or shrubs primarily use deep soil water or groundwater [53-56]. Lastly, we found that mild drought caused lower sensitivity of WUE to SPEI, and moderate drought caused higher sensitivity of WUE to SPEI, implying that drought tolerance of vegetation may have a threshold effect, which is consistent with previous studies [32,33]. The divergent influence of seasonal drought on WUE may be explained by the divergent change rate of GPP and ET [13,24,57]. Some studies investigated whether the ecosystem WUE response to drought was positive or negative depending on the divergent ecosystem GPP and ET sensitivity to drought [22]. Drought can reduce soil water content, as well as GPP and ET [24,57], which can explain why summer drought causes a decrease in WUE, whereas spring drought can cause an increase in WUE to some extent.

The response of ecosystem WUE to drought is an extremely complex process that is affected by a variety of biotic and environmental factors. WUE has strong inherent variability and plasticity [44,58]. The results of our study show that the response of WUE to drought is varies in different climatic regions of the Loess Plateau, and the sensitivity of WUE to drought magnitude in the arid area was generally higher than that in the semi-arid, semi-humid, and humid regions. In most cases, the impact of drought on WUE is that it affects ecosystem productivity and ET to varying degrees. However, under different hydrothermal conditions, different biological types of productivity and ET exhibit different sensitivities to drought [18]. Persistent drought has little effect on vegetation growth in arid areas because vegetation in such regions have stronger tolerance to drought and adapt well to drought [18,51,52]. On the other hand, low vegetation coverage leads to more soil evaporation in arid regions and higher sensitivity of ET to changed hydroclimatic conditions [59]. In contrast, in semi-arid and semi-humid regions, ecosystem functions and activities depend largely on water availability [21]. Consequently, the change in WUE in arid areas is generally controlled by evaporation (ET) (which is a physical process), whereas that in semi-arid and semi-humid areas is primarily regulated by assimilation (GPP) (which is a biological process). Divergent changes in GPP and ET lead to different WUE sensitivities to drought in different climate regions [18].

Vicente-Serrano et al. [13] pointed out that persistent water deficit (i.e., the drought time-scale) in arid and humid areas affects the sensitivity of vegetation WUE to drought. Vegetation in arid areas has a mechanism that allows it quickly adapt to the changing water resources, with vegetation quickly adapting when water resources are less than a threshold value in a short time [13]. In humid areas, vegetation is usually less adaptable to water stress, and the response to drought is different from those of physiological mechanisms operating in arid biomes on short time scales. On the contrary, the response of biomes to drought in semi-arid and semi-humid regions occurs on long time-scales because plants can resist water shortages [13]. Some studies have also found a complicated relationship between vegetation activity and drought in humid regions with surplus water. The response of plants in humid regions to drought is affected by phenology aspects, such as vapor pressure and the period of active leaf flushing [60]. Moreover, the tissue structure of plants in humid regions is very likely damaged by drought [61]. However, once the dry spell is over, vegetation in humid regions can rapidly recover to its previous state [13]. Therefore, vegetation in arid regions is more sensitive to drought than vegetation in humid regions.

In the current study, it was found that seasonal WUE responses to drought of different magnitudes varied among different ecosystems. Spring and winter mild drought increased WUE in arid and semi-arid regions, whereas WUE decreased in humid regions. Similarly, moderate drought in the summer decreased WUE in arid and semi-arid areas but increased WUE in semi-humid areas. Similar results were found in previous studies [13,22,24], such as a study by Xu et al. [24], who found that the response of WUE to drought stress differed in arid, semi-arid, semi-humid, and humid regions. Furthermore, some researchers found that a drought in autumn and spring in Southwest China continued from 2009 to 2010, resulting in a decrease in primary productivity and carbon absorption, whereas a drought in early summer promoted the growth of Amazon vegetation and increased carbon storage [62]. Therefore, seasonal drought significantly influenced vegetation, especially in terms of ecosystem WUE.

4.4. Uncertainties and Limitations

Compared with previous studies, the present study explored the impact of drought on WUE from a seasonal perspective and further authenticated the function of ecosystem WUE in dealing with external environmental interference. Our results confirmed findings of previous studies, such as that WUE responds differently to drought in different seasons and that different vegetation types and ecosystems exhibit different responses to drought. However, there were also some differences between the findings of previous studies and those of the research described in this paper. This may be due to discrepancies in data collection, analysis methods, research cycle, and research area [8]. It should be noted that although previous studies pointed out that the response of ecosystem WUE to drought is affected by many factors, such as vegetation characteristics [24], drought magnitude, and regional characteristics [9,49,50], few studies have been conducted on the impact of seasonal drought magnitude on different ecosystem WUE values; therefore, more theoretical and model simulations are needed to verify this conclusion. Furthermore, the SPEI value used to characterize drought in the current study was calculated based on grid data of relatively low-level resolution, so the accuracy was not high, and the time scale of GPP and ET collection data (2001–2019) was relatively short. In addition, the sensitivity of GPP and ET to drought was not taken into account in the current study of the effect of seasonal drought on WUE, which may have an impact on the results of the study. On the other hand, our study did not consider the persistence of the water deficit (i.e., the drought time-scale) and lag effects of drought. It is very important to understand the relationship between WUE and drought, and experimental observational data and high-precision remote sensing data should be used to improve analysis accuracy.

5. Conclusions

In the current study, the impact of seasonal drought on WUE was analyzed using ridge regression, which appeared in the temporal and spatial distribution characteristics of seasonal drought and WUE in the Loess Plateau from 2001 to 2019. The results show that from 2001 to 2019, there was significant spatial heterogeneity in seasonal drought and WUE, with generally mild drought levels and the highest WUE values in the summer. Seasonal drought had different effects on WUE, and the sensitivity coefficient also differed significantly as the SPEI changed. On the other hand, the sensitivity of seasonal WUE to drought magnitude was affected by regional dry and wet conditions. The impact of drought intensity on WUE in the four climate regions showed a clear seasonal divergence, and the sensitivity of WUE to drought magnitude in arid areas was generally higher than that in semi-arid, semi-humid, or humid areas. However, there are still many deficiencies in this study. Future research should pay more attention to the response processes of GPP and ET to drought and consider the impact of drought accumulation and lag effect on WUE. Our findings are crucial for understanding the impact of climate change on the Loess Plateau's ecosystem carbon and water cycles.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13050634/s1, Figure S1. The area proportion of the sensitivity coefficient (WUE to seasonal SPEI) passing the significance test.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon request.

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Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that might affect the work reported in this article.

Appendix A

Table A1. Percentage of the area of	different vegetation	vpes with drought	magnitude in eac	h season (%)
0	- 0	1	0	(-)

Vegetation Types Seasons		Proportion of No Drought	Proportion of Mild Drought	Proportion of Moderate Drought	Proportion of Severe Drought
Forest	Spring	4.2	95.8	-	-
	Summer	5.6	93.5	0.9	-
	Autumn	99.9	0.1	-	-
	Winter	81.3	18.5	0.2	-
	Spring	63.8	36.2	-	-
	Summer	3.2	33.2	63.2	0.4
Grassland	Autumn	69.0	31.0	-	-
	Winter	93.6	5.9	0.5	-
Shrub	Spring	64.7	35.3	-	-
	Summer	-	32.6	66.5	0.9
	Autumn	35.8	64.2	-	-
	Winter	99.9	0.1	-	-

Note: "-" represented that there was no such drought magnitude in the season.

Table A2. Water-use efficiency (WUE) sensitivity coefficients in response to seasonal drought in climates regions.

	No Drought					Slight Drought]	Moderate Drought				Severe Drought		
-	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Arid Region	-0.129	0.000	-0.003	-0.164	-0.011	0.102	0.005	-0.172	0.000	0.096	0.000	0.000	0.000	0.032	0.000	0.000
Semi-arid Region	-0.051	-0.006	0.000	-0.054	-0.039	0.007	0.002	-0.002	0.000	0.039	0.000	-0.032	0.000	0.039	0.000	-0.016
Semi-humid Region	0.015	0.000	-0.017	-0.078	-0.023	0.005	-0.004	0.029	0.000	-0.005	0.000	-0.009	0.000	0.000	0.000	-0.049
Humid Region	-0.008	0.007	-0.017	-0.042	0.017	0.018	0.000	0.035	0.000	0.000	0.000	-0.013	0.000	0.000	0.000	0.000

References

- 1. Tornros, T.; Menzel, L. Addressing drought conditions under current and future climates in the Jordan River region. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 305–318. [CrossRef]
- 2. Huang, M.; Piao, S.; Sun, Y.; Ciais, P.; Cheng, L.; Mao, J.; Poulter, B.; Shi, X.; Zeng, Z.; Wang, Y. Change in terrestrial ecosystem water-use efficiency over the last three decades. *Glob. Chang. Biol.* **2015**, *21*, 2366–2378. [CrossRef] [PubMed]
- Song, L.; Zhu, J.; Zhang, J.; Zhang, T.; Wang, K.; Wang, G.; Liu, J. Effect of Drought and Topographic Position on Depth of Soil Water Extraction of Pinus sylvestris L. var. mongolica Litv. Trees in a Semiarid Sandy Region, Northeast China. *Forests* 2019, 10, 370. [CrossRef]
- 4. Teuling, A.J.; Van Loon, A.F.; Seneviratne, S.I.; Lehner, I.; Aubinet, M.; Heinesch, B.; Bernhofer, C.; Grünwald, T.; Prasse, H.; Spank, U. Evapotranspiration amplifies European summer drought. *Geophys. Res. Lett.* **2013**, *40*, 2071–2075. [CrossRef]
- 5. Wang, M.; Ding, Z.; Wu, C.; Song, L.; Ma, M.; Yu, P.; Lu, B.; Tang, X. Divergent responses of ecosystem water-use efficiency to extreme seasonal droughts in Southwest China. *Sci. Total Environ.* **2020**, *760*, 143427. [CrossRef]
- Liu, W.; Sun, F. Increased adversely-affected population from water shortage below normal conditions in China with anthropogenic warming. *Sci. Bull.* 2019, 64, 567–569. [CrossRef]
- Liu, W.; Sun, F.; Lim, W.H.; Zhang, J.; Wang, H.; Shiogama, H.; Zhang, Y. Global drought and severe drought-affected populations in 1.5 and 2 °C warmer worlds. *Earth Syst. Dyn.* 2018, *9*, 267–283. [CrossRef]
- 8. Huang, L.; He, B.; Han, L.; Liu, J.; Wang, H.; Chen, Z. A global examination of the response of ecosystem water-use efficiency to drought based on MODIS data. *Sci. Total Environ.* **2017**, *601–602*, 1097–1107. [CrossRef]
- 9. Zhao, J.; Xu, T.; Xiao, J.; Liu, S.; Mao, K.; Song, L.; Yao, Y.; He, X.; Feng, H. Responses of Water Use Efficiency to Drought in Southwest China. *Remote Sens.* 2020, 12, 199. [CrossRef]
- 10. Guo, Y.; Hu, Q.; Fu, W.; Wang, S.; Liu, Y. Drought Trend over the Grasslands in the Tianshan Mountains, Xinjiang in Recent 55 Years Based on SPEI. *J. Arid. Zone Res.* **2019**, *36*, 670–676. [CrossRef]
- 11. Li, W.; Yi, X.; Hou, M.; Chen, H.L.; Chen, Z.L. Standardized precipitation evapotranspiration index shows drought trends in China. J. Chin. J. Eco-Agric. 2012, 20, 643–649. [CrossRef]
- 12. Li, Y.; Ding, J.; Zhang, J.; Wu, P. Response of vegetation cover to drought in the northern slope of the Tianshan Mountains during 2001—2015 based on the land-use and land-cover change. *J. Acta Ecol. Sin.* **2019**, *39*, 6206–6217.

- Vicente-Serrano, S.M.; Gouveia, C.; Camarero, J.J.; Beguería, S.; Trigo, R.; Lopez-Moreno, J.I.; Azorin-Molina, C.; Pasho, E.; Lorenzo-Lacruz, J.; Revuelto, J.; et al. Response of vegetation to drought time-scales across global land biomes. *Proc. Natl. Acad. Sci. USA* 2013, 110, 52–57. [CrossRef] [PubMed]
- 14. Hu, Z.; Yu, G.; Wang, Q.; Zhao, F.H. Ecosystem level water use efficiency: A review. J. Acta Ecol. Sin. 2009, 29, 1498–1507.
- 15. Gang, C.; Wang, Z.; Chen, Y.; Yang, Y.; Li, J.; Cheng, J.; Qi, J.; Odeh, I. Drought-induced dynamics of carbon and water use efficiency of global grasslands from 2000 to 2011. *Ecol. Indic.* **2016**, *67*, 788–797. [CrossRef]
- 16. Qing-Wei, W.; Da-Pao, Y.; Li-Min, D.; Li, Z.; Wang-Ming, Z.; Guang, Q.; Lin, Q.; Yu-Jing, Y. Research progress in water use efficiency of plants under global climate. *Change J. Chin. J. Appl. Ecol.* **2010**, *21*, 259–269. [CrossRef]
- 17. Du, X.; Zhao, X.; Wang, H.; He, B. Responses of terrestrial ecosystem water-use efficiency to climate change: A review. J. Acta Ecol. Sin. 2018, 38, 33–42.
- Yuting, Y.; Huade, G.; Okke, B.; Tim R, M.; Di, L.; Shilong, P.; Wei, L.; Bing, L.; Zhao, J.; Craig T, S. Contrasting responses of water use efficiency to drought across global terrestrial ecosystems. J. Sci. Rep. 2016, 6, 23284. [CrossRef]
- 19. Ma, J.; Jia, X.; Zha, T.; Charles, P.-A.; Bourque, Y.T.; Bai, Y.; Liu, P.; Yang, R.; Li, C.; Li, C.; et al. Ecosystem water use efficiency in a young plantation in Northern China and its relationship to drought. J. *Agric. For. Meteorol.* **2019**, 275, 1–10. [CrossRef]
- Zou, J.; Ding, J.L.; Qin, Y.; Wang, F. Response of water use efficiency of Central Asia ecosystem to drought based on remote sensing data. J. Trans. Chin. Soc. Agric. Eng. 2018, 34, 145–152.
- Ponce Campos, G.E.; Moran, M.S.; Huete, A.; Zhang, Y.; Bresloff, C.; Huxman, T.E.; Eamus, D.; Bosch, D.D.; Buda, A.R.; Gunter, S.A.; et al. Ecosystem resilience despite large-scale altered hydroclimatic conditions. *J. Nature* 2013, 494, 349–352. [CrossRef]
- 22. Liu, Y.; Xiao, J.; Ju, W.; Zhou, Y.; Wang, S.; Wu, X. Water use efficiency of China's terrestrial ecosystems and responses to drought. *J. Sci. Rep.* **2015**, *5*, 13799. [CrossRef]
- 23. Dan, L.; Chenglong, Y.; Fang, Z. Response of the water use efficiency of natural vegetation to drought in Northeast China. *J. Geogr. Sci.* **2018**, *28*, 611–628.
- Hao-Jie, X.; Xin-ping, W.; Chuan-yan, Z.; Xiao-xiao, Z. Responses of ecosystem water-use efficiency to meteorological drought under different biomes and drought magnitudes in northern China. *Agric. For. Meteorol.* 2019, 278, 107660. [CrossRef]
- Tang, J.; Bolstad, P.V.; Ewers, B.E.; Desai, A.R.; Davis, K.J.; Carey, E.V. Sap flux-upscaled canopy transpiration, stomatal conductance, and water use efficiency in an old-growth forest in the Great Lakes region of the United States. *J. Geophys. Res. Biogeosci.* 2015, *111*, G02009. [CrossRef]
- Zhang, F.; Ju, W.; Shen, S.; Wang, S.; Yu, G.; Han, S. How recent climate change influences water use efficiency in East Asia. *Theor. Appl. Climatol.* 2014, 116, 359–370. [CrossRef]
- 27. Sheng-Gong, L.; Werner, E.; Jun, A.; Ayumi, K.; Gombo, D.; Dambaravjaa, O.; Michiaki, S. Response of gross ecosystem productivity, light use efficiency, and water use efficiency of Mongolian steppe to seasonal variations in soil moisture. *J. Geophys. Res. Biogeosci.* 2008, *113*, G1. [CrossRef]
- 28. Yu, G.; Song, X.; Wang, Q.; Liu, Y.; Guan, D.; Yan, J.; Sun, X.; Zhang, L.; Wen, X. Water-use efficiency of forest ecosystems in eastern China and its relations to climatic variables. *New Phytol.* **2008**, *177*, 927–937. [CrossRef]
- Linderson, M.-L.; Mikkelsen, T.N.; Ibrom, A.; Lindroth, A.; Ro-Poulsen, H.; Pilegaard, K. Up-scaling of water use efficiency from leaf to canopy as based on leaf gas exchange relationships and the modeled in-canopy light distribution. *Agric. For. Meteorol.* 2011, 152, 201–211. [CrossRef]
- 30. Tong, X.; Zhang, J.; Meng, P.; Li, J.; Zheng, N. Ecosystem water use efficiency in a warm-temperate mixed plantation in the North China. *J. Hydrol.* **2014**, *512*, 221–228. [CrossRef]
- Xie, J.; Zha, T.; Zhou, C.; Jia, X.; Yu, H.; Yang, B.; Chen, J.; Zhang, F.; Wang, B.; Charles, P.-A.; et al. Seasonal variation in ecosystem water use efficiency in an urban-forest reserve affected by periodic drought. *Agric. For. Meteorol.* 2016, 221, 142–151. [CrossRef]
- 32. Sun, Y.; Liu, X.; Ren, Z.; Li, S. Spatiotemporal variations of multi-scale drought and its influencing factors across the Loess Plateau from 1960 to 2016. *Geogr. Res.* **2019**, *38*, 1820–1832.
- Pei, T.; Li, X.; Wu, H.; Wu, X.; Chen, Y.; Xie, B. Sensitivity of vegetation water use efficiency to climate and vegetation index in Loess Plateau, China. *Trans. Chin. Soc. Agric. Eng.* 2019, 35, 119–125.
- 34. He, Y.; Li, W.; Lang, H. Study on the Characteristics of Precipitation Resources and Afforestation suitability in the Loess Plateau. *Arid. Zone Res.* **2009**, *26*, 406–412. [CrossRef]
- 35. Liu, Z.; Guo, W.; Yang, Q.; Guo, Y.; Zhu, X.; Li, R. Vegetation cover changes and their relationship with rainfall in different physiognomy type areas of Loess Plateau. *Sci. Soil Water Conserv.* **2011**, *9*, 16–23. [CrossRef]
- 36. Zhang, L.; Wang, Y.; Chen, Y. Spatial and temporal distribution characteristics of drought in Central Asia based on SPEI index. *Arid. Zone Res.* **2020**, *37*, 331–340. [CrossRef]
- Xu, K.; Yang, D.; Yang, H.; Li, Z.; Qin, Y.; Shen, Y. Spatio-temporal variation of drought in China during 1961–2012: A climatic perspective. J. Hydrol. 2015, 526, 253–264. [CrossRef]
- Zhang, Y.; Zhang, Y.; Jin, Z.; Kang, X. The Temporal and Spatial Characteristics of Summer Drought in the Loess Plateau Based on SPEI. Ecol. Environ. Sci. 2019, 28, 1322–1331. [CrossRef]
- Liu, Z.P.; Wang, Y.Q.; Shao, M.G.; Jia, X.X.; Li, X. L Spatiotemporal analysis of multiscalar drought characteristics across the Loess Plateau of China. J. Hydrol. 2016, 534, 281–299. [CrossRef]
- 40. Zhao, A.; Zhang, A.; Liu, J.; Feng, L.; Zhao, Y. Assessing the effects of drought and "Grain for Green" Program on vegetation dynamics in China's Loess Plateau from 2000 to 2014. *Catena* **2019**, *175*, 446–455. [CrossRef]

- 41. Walker, E.; Birch, J.B. *Influence Measures in Ridge Regression*; Taylor & Francis Group: Oxfordshire, UK, 2012; Volume 30, pp. 221–227.
- 42. Zhang, D.; Zhang, B.; Zhang, M.; Liu, X.; Sun, L.; An, M. Spatiotemporal pattern of drought in Loess Plateau of Gansu Province, Northwest China in 1961–2010. *Chin. J. Ecol.* **2012**, *31*, 2066–2074. [CrossRef]
- 43. Guangchao, L.; Wei, C.; Ruren, L.; Xuepeng, Z.; Jialiang, L. Assessing the spatiotemporal dynamics of ecosystem water-use efficiency across China and the response to natural and human activities. *Ecol. Indic.* **2021**, *126*, 107680. [CrossRef]
- 44. Xiao, J.; Sun, G.; Chen, J.; Chen, H.; Chen, S.; Dong, G.; Gao, S.; Guo, H.; Guo, J.; Han, S. Carbon fluxes, evapotranspiration, and water use efficiency of terrestrial ecosystems in China. *Agric. For. Meteorol.* **2013**, *182*, 76–90. [CrossRef]
- Zheng, H.; Lin, H.; Zhou, W.; Bao, H.; Zhu, X.; Jin, Z.; Song, Y.; Wang, Y.; Liu, W.; Tang, Y. Revegetation has increased ecosystem water-use efficiency during 2000–2014 in the Chinese Loess Plateau: Evidence from satellite data. *Ecol. Indic.* 2019, 102, 507–518. [CrossRef]
- 46. Zhu, X.J.; Yu, G.R.; Wang, Q.F.; Hu, Z.M.; Zhang, H.; Li, S.G.; Sun, X.M.; Zhang, Y.P.; Yan, J.H.; Wang, H.M.; et al. Spatial variability of water use efficiency in China's terrestrial ecosystems. *Glob. Planet. Change* **2015**, *129*, 37–44. [CrossRef]
- Hu, Z.; Yu, G.; Fu, Y.; Sun, X.; Li, Y.; Shi, P.; Wang, Y.; Zheng, Z. Effects of vegetation control on ecosystem water use efficiency within and among four grassland ecosystems in China. *Glob. Change Biol.* 2008, 14, 1609–1619. [CrossRef]
- Niu, S.L.; Xing, X.R.; Zhang, Z.; Xia, J.Y.; Zhou, X.H.; Song, B.; Li, L.H.; Wan, S.Q. Water-use efficiency in response to climate change: From leaf to ecosystem in a temperate steppe. *Glob. Change Biol.* 2011, 17, 1073–1082. [CrossRef]
- 49. Gao, Y.; Markkanen, T.; Aurela, M.; Mammarella, I.; Thum, T.; Tsuruta, A.; Yang, H.; Aalto, T. Response of water use efficiency to summer drought in a boreal Scots pine forest in Finland. *Biogeosciences*. **2017**, *14*, 4409–4422. [CrossRef]
- 50. Tian, Z.; Jian, P.; Wei, L.; Yuting, Y.; Yanxu, L. Spatial-temporal patterns of water use efficiency and climate controls in China's Loess Plateau during 2000–2010. *Sci. Total Environ.* **2016**, *565*, 105–122. [CrossRef]
- 51. Fischer, R.A.; Turner, N.C. Plant productivity in the arid and semiarid zones. Ann. Rev. Plant Physiol. 1978, 29, 277–307. [CrossRef]
- 52. Chaves, M.M.; Maroco, J.P.; Pereira, J.S. Understanding plant responses to drought– from genes to the whole plant. *Funct. Plant Biol.* 2003, *30*, 239–264. [CrossRef]
- 53. Dodd, M.; Lauenroth, W.; Welker, J. Differential water resource use by herbaceous and woody plant life-forms in a shortgrass steppe community. *Oecologia* **1998**, *117*, 504–512. [CrossRef]
- 54. Ward, D.; Wiegand, K.; Getzin, S. Walter's two-layer hypothesis revisited: Back to the roots! *Oecologia* 2013, 172, 617–630. [CrossRef]
- 55. Liu, W.J.; Wang, P.Y.; Li, J.T.; Liu, W.Y.; Li, H.M. Plasticity of source-water acquisition in epiphytic, transitional, and terrestrial growth phases of Ficus tinctoria. *Ecohydrology* **2014**, *7*, 1524–1533. [CrossRef]
- 56. Jackson, P.C.; Meinzer, F.C.; Bustamante, M.; Goldstein, G.; Franco, A.; Rundel, P.W.; Caldas, L.; Lgler, E.; Causin, F. Partitioning of soil water among tree species in a Brazilian Cerrado ecosystem. *Tree Physiol.* **1999**, *19*, 717–724. [CrossRef]
- 57. Yu, Z.; Wang, J.; Liu, S.; Rentch, J.; Sun, P.; Lu, C. Global gross primary productivity and water use efficiency changes under drought stress. *Environ. Res. Lett.* 2017, 12, 014016. [CrossRef]
- Jelle, G.; Van Minnen, K.; Goldewijk, K.; Leemans, R. The importance of feedback processes and vegetation transition in the terrestrial carbon cycle. J. Biogeogr. 1995, 22, 805.
- 59. Zhang, Y.Q.; Peña-Arancibia, J.L.; McVicar, T.R.; Chiew, F.H.S.; Vaze, J.; Liu, C.M.; Lu, X.J.; Zheng, H.X.; Wang, Y.P.; Liu, Y.Y.; et al. Multi-decadal trends in global terrestrial evapotranspiration and its components. *Sci. Rep.* **2016**, *5*, 19124. [CrossRef]
- 60. Brando, P.M.; Goetz, S.J.; Baccini, A.; Nepstad, D.C.; Beck, P.S.A.; Christman, M.C. Seasonal and interannual variability of climate and vegetation indices across the Amazon. *Proc. Natl. Acad. Sci. USA* 2010, 107, 14685–14690. [CrossRef]
- 61. Anderegg, W.R.L.; Berry, J.A.; Smith, D.D.; Sperry, J.S.; Anderegg, L.D.L.; Field, C.B. The roles of hydraulic and carbon stress in a widespread climate-induced forest die-off. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 233–237. [CrossRef]
- 62. Li, X.; Li, Y.; Chen, A.; Gao, M.; Slette, I.J.; Piao, S. The impact of the 2009/2010 drought on vegetation growth and terrestrial carbon balance in Southwest China. *Agric. For. Meteorol.* **2019**, 269–270, 239–248. [CrossRef]