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Research Article

Spatiotemporal Variation Characteristics of Vegetative PUE in China from 2000 to 2015

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Vegetative precipitation-use efficiency (PUE) is a key indicator for evaluating the dynamic response of vegetation productivity to the spatiotemporal variation in precipitation. It is also an important indicator for reflecting the relationship between the water and carbon cycles in a vegetation ecosystem. This paper uses data from MODIS Net Primary Production (NPP) and China's spatial interpolation data for precipitation from 2000 to 2015 to calculate the annual value, multiyear mean value, interannual standard deviation, and interannual linear trend of Chinese terrestrial vegetative PUE over the past 16 years. Based on seven major administrative regions, eleven vegetation types, and four climate zones, we analyzed the spatiotemporal variation characteristics of China's vegetative PUE. The research results are shown as follows: (1) China's vegetative PUE shows obvious spatial variation characteristics, and it is relatively stable interannually, with an overall slight increasing trend, especially in Northwest and Southwest China. The vegetative PUE is higher, and its stability is declined in Xinjiang, western Gansu, and the southern Tibetan valley. The vegetative PUE is lower, and its stability is increased in northeastern Tibet and southwestern Qinghai. An increasing trend in vegetative PUE is obvious at the edge of the Tarim Basin, in western Gansu, the southern Tibetan valley, and northwestern Yunnan. (2) There is a significant difference in the PUEs among different vegetation types. The average PUE of Broadleaf Forest is the highest, and the average PUE of Alpine Vegetation is the lowest. The stability of the PUE of Mixed Coniferous and Broadleaf Forest is declined, and the stability of the PUE of Alpine Vegetation is increased. The increasing speed of the PUE of Grass-forb Community is the fastest, and the decreasing speed of the PUE of Swamp is the fastest. (3) There is a significant difference in the PUEs among different vegetation types in the same climate zone, the difference in vegetative PUE in arid and semiarid regions is mainly affected by precipitation, and the difference in vegetative PUE in humid and semihumid regions is mainly affected by soil factors. The PUEs of the same vegetation type are significantly different among climate zones. The average PUE of Cultural Vegetation has the largest difference, the stability of the PUE of Steppe has the largest difference, and the increasing speed of the PUE of Swamp has the largest difference.

1. Introduction

The Earth's climate is strongly influenced by the characteristics of atmosphere and ground surface which is known as the ecological environment [1–3]. The human economic activities have been proved to have significant impact on the ecosystems. For example, Xu et al. [4, 5] make a comprehensive investigation on the spatial, temporal, and vertical distributions of dust over China, finding that airborne dust and its inducements like precipitation and vegetation are very important factors in the climate system and can be greatly influenced by the human economic activities.

Climate change has brought about profound effects on the patterns and functions of vegetation ecosystems. Vegetation has responded significantly to climate change through the exchange of energy, moisture, and material reaction [6, 7]. The interactions and mutual adaptations of ecosystems and the environment are embodied by the response relationship between global climate change and the vegetation ecosystem [8–10]. After its reform and opening up, China's ecological environment is worsening, leading to the degradation of vegetation, and vegetation degradation results from the interactions between climate change and human activities [11–13]. Climate change is the main reason for vegetative degradation, directly resulting in the decrease of vegetation, causing desertification. Land-surface vegetative change can also affect climate change. Human activities and climate change interact in complex ways [14, 15].

Climate change has obvious impacts on the spatiotemporal distribution of precipitation. Precipitation also greatly influences vegetative activity because fluctuations in interannual precipitation change vegetative biomass [16]. Vegetative biomass is usually measured by vegetative NPP, which refers to the total amount of organic dry matter produced from green plants in unit time and unit area. Vegetative NPP is an important characteristic of ecosystem function and structure and plays an important role in reducing atmospheric CO_2 content [17, 18]. Vegetative NPP is a major factor in determining carbon sources and sinks. It plays an important role in the global carbon cycle, reflecting the combined effects of climate change and human activities on terrestrial vegetation [19, 20]. Many scholars have performed many studies on the response relationship between vegetative NPP and climate change in China. This research has shown that precipitation is usually a key factor affecting the dynamic changes in ecosystem structure and function and is an important driving factor of the spatial distribution and interannual fluctuation of vegetative NPP [21–23]. PUE is a key indicator for exploring vegetative NPP response to precipitation change [17, 24]. PUE is the ratio of vegetative NPP to annual precipitation, which reflects the relationship between the photosynthetic production processes and the water consumption characteristics of vegetation. It is a key indicator for analyzing and evaluating vegetative productivity in response to the spatiotemporal variation characteristics of precipitation on a regional scale [25, 26]. It reflects the spatial variation characteristics of ecosystem water use along the climatic gradient [27].

Vegetative PUE is not only an important variable for linking the carbon and water cycles of vegetative ecosystems but also a way of regulating ecological populations and systems responding to climate change [28]. Changes in PUE are closely related to climatic zones, vegetation types, soil factors, and other elements. The difference in the PUEs among different vegetation types is affected by the biological community structure or biogeochemical factors [25, 27]. In past studies of China's vegetative PUE, the regions studied were almost entirely in the Qinghai-Tibet Plateau and the arid regions of Northwest China [21, 28], the vegetation types studied were usually selected from specific vegetation types such as Steppe and Desert, and the time series studied was short. As a result, there have been no reports on the study of vegetative PUE in the whole of China based on climatic zones and different vegetation types for more than 15 years [23–25]. Therefore, this paper begins at a national scale, using China's time-series remote-sensing NPP data and meteorological precipitation data from 2000 to 2015 to calculate the PUE of China's vegetation. Then, the paper analyzes changes and spatiotemporal patterns in Chinese terrestrial vegetative PUE from the most recent 16 years to assess the general characteristics of vegetative PUE in China, obtain the relationship between spatiotemporal patterns of vegetative PUE and vegetation types and climate zones, and discuss the main influencing factors of vegetative PUE. The results indicate that the spatiotemporal patterns of vegetative PUE can clearly show the response relationship between precipitation change and vegetative NPP, which will deepen our understanding of the formation process of vegetative productivity among different vegetation types and climatic zones. Therefore, the study of the relationship between ecosystem water and carbon cycles and climate change in China is of great theoretical and practical significance [17, 24].

2. Data and Methods

2.1. Method of Calculating Vegetative PUE. The concept of vegetative PUE is proposed based on vegetative water-use efficiency (WUE) [29, 30]. Usually, the ratio of vegetative NPP to precipitation is adopted for the simulated calculation of vegetative PUE [25]. Owing to the limitations of vegetative NPP data obtained by traditional ecological observation methods, some scholars have replaced vegetative NPP with the aboveground net primary productivity (ANPP) of vegetation when calculating the PUE based on measured data [25, 26]. Additionally, the normalized differential vegetation index (NDVI) has a significant linear correlation with vegetative NPP; thus, the NDVI can be used to replace vegetative NPP [21, 31]. In this paper, vegetative PUE is calculated based on the ratio of vegetative NPP to precipitation. Vegetative NPP data from 2000 to 2015 are obtained based on the terrestrial level-4 product of US Terra MODIS MOD17A3 (https://ladsweb.nascom.nasa.gov/search/) with a spatial resolution of 1 km.

2.2. Processing Method of Precipitation Data. Spatial processing methods of precipitation data in conventional ground meteorological stations mainly include inverse distance weight (IDW) tension, spline with tension, trend, ordinary kriging, and universal kriging. Many studies have analyzed and discussed the benefits and drawbacks of these methods [32–34]. Annual cumulative precipitation from 2000 to 2015 is calculated based on the daily precipitation of 833 standard meteorological stations in China, with data sourced from the China Meteorological Data Service Center (http://data.cma.cn/). First, the precipitation data are spatialized using IDW, spline, trend, ordinary kriging, universal kriging, and other methods based on measured data from 800 stations. Then, measured data from an additional 33 stations are processed using the normal population mean t-test method [34, 35]. The results show that the precipitation value obtained using the five interpolation methods is not

Table 1: Accuracy comparison of the five interpolation methods.

Interpolation method	Maximum (mm)	Minimum (mm)	Mean (mm)	Standard deviation (mm)	t-test	p
IDW	2686.0908	15.8132	567.8891	474.8156	0.2500	0.8043
Spline	8519.6455	−2830.9712	560.7704	487.1202	0.0273	0.9784
Trend	4136.6260	114.0831	577.2636	448.7920	0.3870	0.7014
Ordinary kriging	2613.2412	−28.6841	559.9145	476.0661	0.3520	0.7273
Universal kriging	2201.4834	−932.9639	560.7932	472.1631	0.2088	0.8360

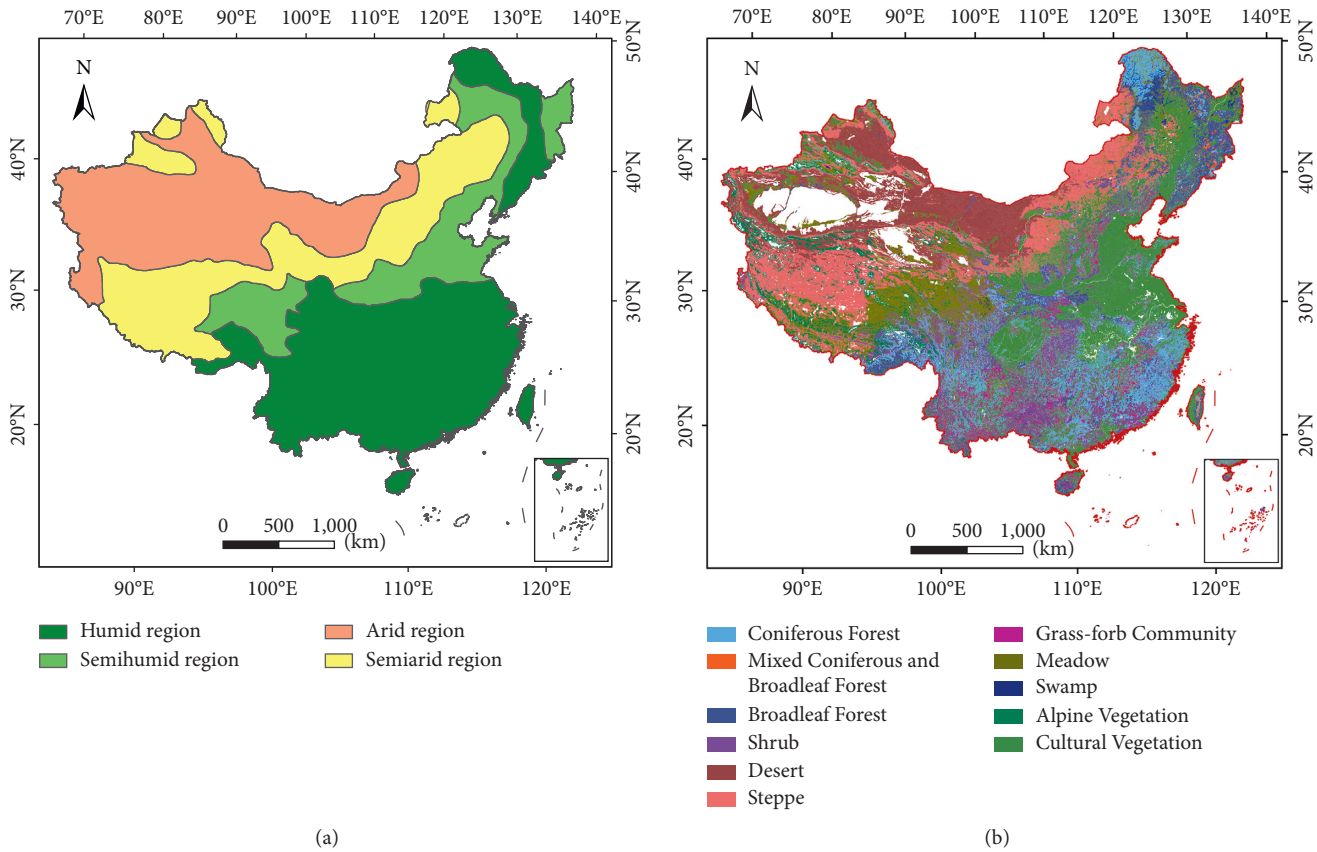


Figure 1: The maps of (a) arid and humid climate zones and (b) vegetation types in China.

significantly different from the measured value at each station, as shown in Table 1. Because the precipitation values obtained using spline, trend, ordinary kriging, universal kriging, and other methods have problematic situations such as negative values and values that are too large or too small, these methods do not meet the calculation requirements of PUE. Therefore, this study uses the precipitation value obtained with the IDW interpolation method.

2.3. Spatiotemporal Variation Analysis Method of Vegetative PUE. China's climatic regionalization in 1981–2010, as proposed by Zheng et al. [36], is adopted to represent the classification diagram of China's arid and humid climate zones, as shown in Figure 1. The classification of vegetation types by regions mainly depends on the Vegetation Map of The People's Republic of China (1 : 1,000,000) compiled by the Chinese Vegetation Map Editorial Board of Chinese Academy of Sciences [37], in which vegetation types are divided into 11 categories: Coniferous Forest, Mixed Coniferous and Broadleaf Forest, Broadleaf Forest, Shrub, Desert, Steppe, Grass-forb Community, Meadow, Swamp, Alpine Vegetation, and Cultural Vegetation. In order to recognize the spatiotemporal variation feature of vegetative PUE, statistical indicators, including multiyear mean value, standard deviation, and linear trend, are calculated, and the comparative analysis method is used to find PUE difference of different statistical indicators of climatic regionalization and vegetation types.

2.4. Significance Testing of Linear Trend of Vegetative PUE. In statistics, the t-test method of the regression coefficient is usually used to test the statistical significance of linear trends, which is judged by calculating the rejection region or p value. The significance level is generally 0.05. If the calculated p value is less than 0.05, the regression coefficient is significant, and the linear trend is effective; otherwise, the

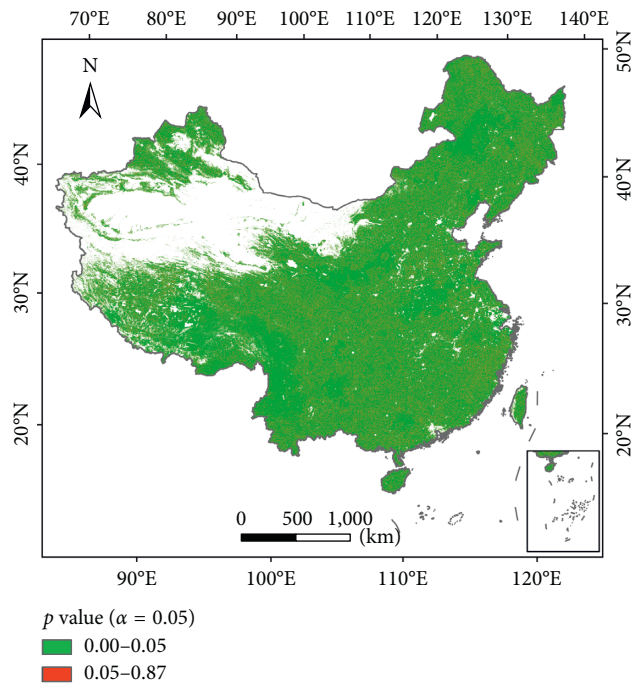


Figure 2: The p value of the linear trend of China's vegetative PUE.

regression coefficient is not significant and there is no linear relation [35]. This paper will also test the validity of the linear trend of vegetative PUE by a significance level of 0.05. The p value calculated is shown in Figure 2. It shows that the p value in green is less than 0.05, so the regression coefficient is significant, and there is a linear relation. However, the p value in red is greater than 0.05, which shows that there is no linear relation. In the following study, the analysis of linear trends of vegetative PUE will not include the pixels with linear trends that correspond with the red zone.

3. Results

In this section, the general characteristics of vegetative PUE are analyzed; then, there will be contrastive analysis on the difference in the PUEs among different vegetation types by studying Cultural Vegetation, Natural Vegetation, Woody Vegetation, and Herbaceous Vegetation; finally, there will be a comprehensive analysis on the difference in the PUEs among different vegetation types in climate zones and the difference of the same vegetation type's PUEs among climate zones.

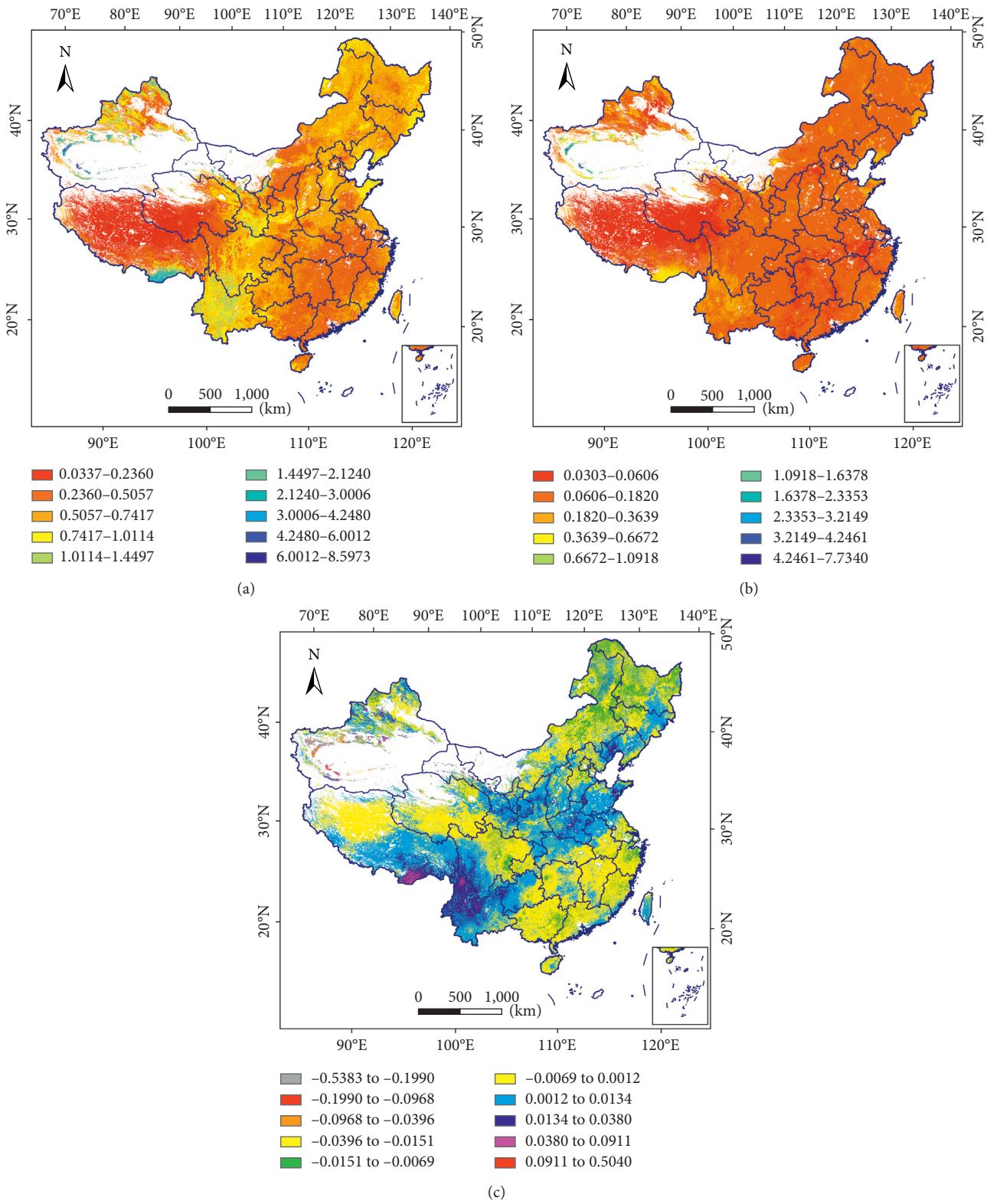
3.1. General Characteristics of Vegetative PUE. The multiyear mean value of vegetative PUE has obvious spatial variation characteristics in China, as shown in Figure 3. The multiyear mean value of vegetative PUE in China ranges from 4.0×10^{-3} gC·m^{-2}·mm^{-1} to 8.597 gC·m^{-2}·mm^{-1}, with an average of 5.54×10^{-1} gC·m^{-2}·mm^{-1}, and with maximum in Northwest and minimum values in Central China. The vegetative PUE is higher in Northeast China, Northwest China, and North China, where the averages of multiyear mean values are 6.4×10^{-1} gC·m^{-2}·mm^{-1}, 6.23×10^{-1} gC·m^{-2}·mm^{-1}, and 5.89×10^{-1} gC·m^{-2}·mm^{-1}, respectively. These averages are significantly higher than the national average, especially in northeastern Jilin, southeastern Liaoning, most of Xinjiang and Gansu, northwestern Qinghai, northern Ningxia, western Inner Mongolia and other regions, and the southern Tibetan valley in Southwest China. The vegetative PUE in South China is the lowest, where the average of the multiyear mean value is 4.37×10^{-1} gC·m^{-2}·mm^{-1}; it is significantly lower than the national average, especially in northeastern Guangxi, northwestern Guangdong, and other regions.

China's vegetative PUE is stable interannually, but the spatial difference is relatively significant, as shown in Figure 3. It can be seen from the interannual standard variation that the mean value of the standard deviation of China's vegetative PUE is 1.173×10^{-1}, showing an overall trend of no significant interannual fluctuations. However, the interannual spatial variation characteristics of the vegetative PUE are significant, with a minimum value of 2.8×10^{-3}. It is mainly distributed in northern Xinjiang, southwest Qinghai, northeastern Tibet, southern Anhui and other regions in Northwest China, Southwest China, and East China; the maximum value is 7.734, mainly distributed in the edge area of the Tarim Basin in Northwest China. The vegetative PUE stability is declined in Northeast and Northwest China, where the interannual standard variations are 1.387×10^{-1} and 1.474×10^{-1}, respectively, especially in northeastern Jilin, southern Liaoning, the edge of the Tarim Basin, and other regions. The stability of the vegetative PUE in central China is increased, where the interannual standard variation is 8.8×10^{-2}, especially in the majority of Hunan, southern Hubei, and other regions.

China's vegetative PUE shows an overall slightly increasing trend, and the rate of increase in the mean values of 2011–2015 is 2.1% compared to those of 2000–2010. From the interannual trend of linear variation, it can be seen that the mean value of the increasing speed of China's vegetative PUE is 1.1×10^{-3}. However, China's vegetative PUE shows relatively obvious spatial variation characteristics, even decreasing trends in a few regions, accounting for 67.5% of the total land area of the country. The regions with the most obvious decreasing trends are mainly distributed in the western edge of the Tarim Basin, northern Ningxia, eastern Inner Mongolia, southwest of Heilongjiang, northwest of Jilin and other regions in Northwest China, North China, and Northeast China; the regions with the most obvious increasing trends are mainly distributed in the majority of Xinjiang, western Gansu, the southern Tibetan valley, northwest Yunnan and other regions in Northwest China, and Southwest China.

3.2. Variation Characteristics of Different Vegetation Types' PUEs

3.2.1. Variation Characteristics of Cultural and Natural Vegetative PUEs. The multiyear mean values of Cultural Vegetative and Natural Vegetative PUEs have obvious spatial variation characteristics, as shown in Figure 4. The average of the multiyear mean value of Cultural Vegetative PUE is 6.07×10^{-1} gC·m^{-2}·mm^{-1}, which is higher than that of China's vegetative PUE. The maximum value is 8.597 gC·m^{-2}·mm^{-1},



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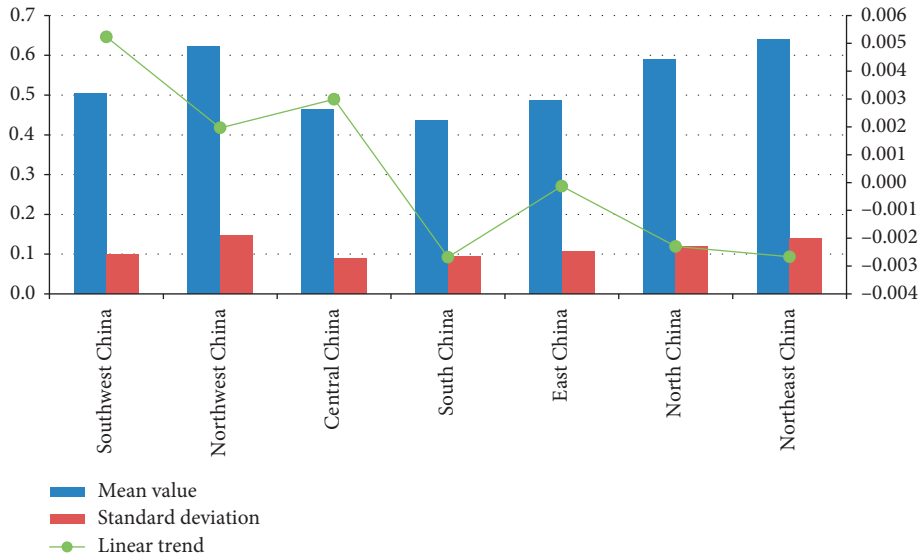


(d)

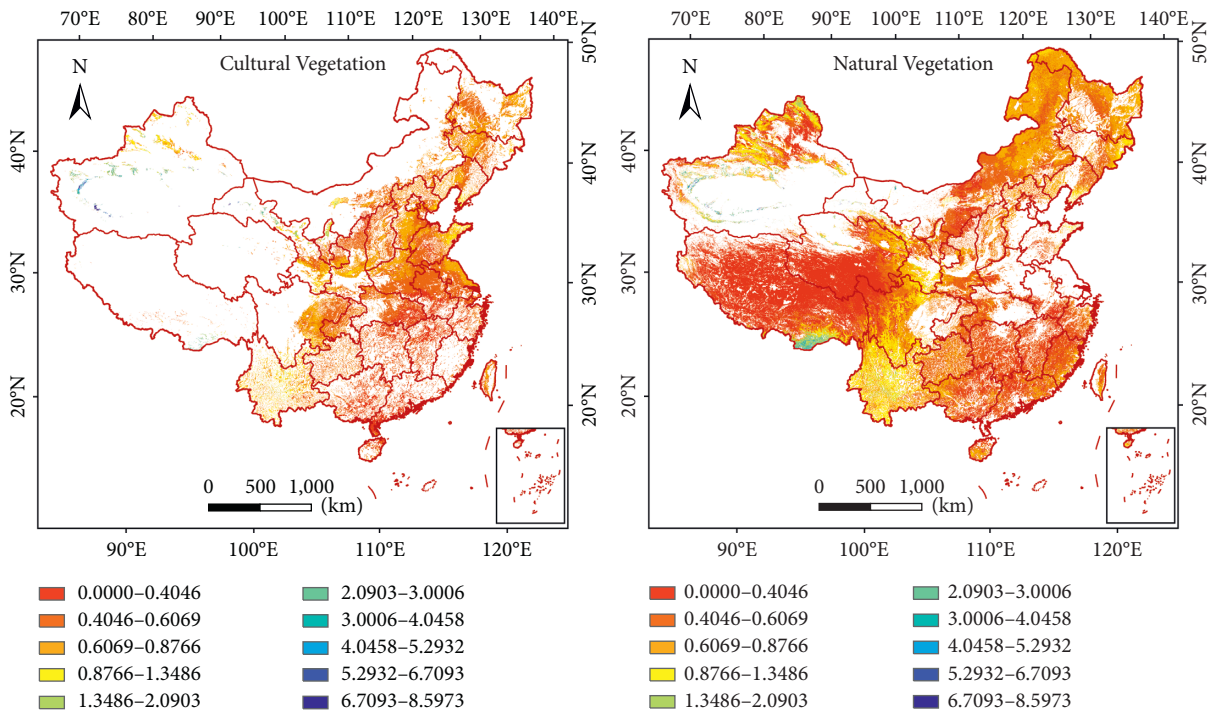
Figure 3: Temporal variation and spatial distribution of China's vegetative PUE from 2000 to 2015. (a) Spatial distribution of the multiyear mean value of China's vegetative PUE. (b) Standard deviation of China's vegetative PUE. (c) Linear trend of China's vegetative PUE. (d) Statistical central tendency of the mean value, standard deviation and linear trend of China's vegetative PUE.

and the minimum value is 3.4×10^{-2} gC·m^{-2}·mm^{-1}; this value is significantly higher than the national average, especially in the edge of the Tarim Basin, northwest of Gansu, the southern Tibetan valley, and other regions. The average of the multiyear mean value of Natural Vegetative PUE is 5.36×10^{-1} gC·m^{-2}·mm^{-1}, which is lower than that of China's vegetative PUE. The maximum value is 8.596 gC·m^{-2}·mm^{-1}, and the minimum value is 3.4×10^{-2} gC·m^{-2}·mm^{-1}; this value is significantly lower than the national average, especially in northeastern Tibet, southwestern Qinghai, and other regions.

The PUEs of Cultural Vegetation and Natural Vegetation are relatively stable interannually, but the spatial difference is relatively significant, as shown in Figure 4. It can be seen from the interannual standard deviation that the mean values of standard deviations of Cultural Vegetative and Natural Vegetative PUEs are 1.304×10^{-1} and 1.125×10^{-1}, respectively, showing an overall trend of no significant interannual fluctuations. However, the spatial variation characteristics of Cultural Vegetative and Natural Vegetative PUEs are significant. The maximum value of the standard deviation of Cultural Vegetative PUE is 6.274, which is mainly distributed in southwest Xinjiang, western Gansu, and other regions, and the minimum value is 2.46×10^{-2}, which is mainly distributed in the middle and lower reaches of the Yangtze River. The maximum value of the standard deviation of Natural Vegetative PUE is 7.734, which is mainly distributed in eastern and southern Xinjiang, northwest Qinghai and Inner Mongolia, and western Gansu, and other regions. The minimum value is 3.03×10^{-2}, which is mainly distributed in northeastern Tibet, southwestern Qinghai, and other regions.

Cultural and Natural Vegetative PUEs show an overall slightly increasing trend, as shown in Figure 4. From the interannual linear variation trend, it can be seen that the mean values of the increasing speeds of Cultural Vegetative and Natural Vegetative PUEs are all 1.1×10^{-3}, which is the same as that of China's vegetative PUE. However, the Cultural and Natural Vegetative PUEs show relatively obvious spatial variation characteristics and even decreasing trends in a few regions. The regions where Cultural Vegetative PUE shows a decreasing trend account for 21.9% of China's total land area; regions with the most obvious decreasing trends are mainly distributed in northwestern Xinjiang, western Gansu and Jilin, northern Ningxia, and other regions. The regions with the most obvious increasing trends of Cultural Vegetative PUE are mainly distributed in southeastern Xinjiang, the southern Tibetan valley, and other regions. The regions where Natural Vegetative PUE shows a decreasing trend account for 64.1% of China's total land area; the regions with the most obvious decreasing trend are mainly distributed in the edge of the Tarim Basin, northwestern Qinghai, eastern Inner Mongolia, western Heilongjiang, and other regions. The regions with the most obvious increasing trend of Natural Vegetative PUE are mainly distributed in the majority of Xinjiang, western Gansu, the southern Tibetan valley, northwestern Yunnan, and other regions.

3.2.2. Variation Characteristics of Different Natural Vegetation Types' PUEs. Natural Vegetation is divided into two main categories: Woody Vegetation (Coniferous Forest, Mixed Coniferous and Broadleaf Forest, Broadleaf Forest, and Shrub) and Herbaceous Vegetation (Desert, Steppe, Grass-forb Community, Meadow, Swamp, and Alpine Vegetation). The multiyear mean values of Woody Vegetative and Herbaceous Vegetative PUEs have obvious spatial variation characteristics, as shown in Figure 5. The average of the multiyear mean value of Woody Vegetative PUE is 6.22×10^{-1} gC·m^{-2}·mm^{-1}, which



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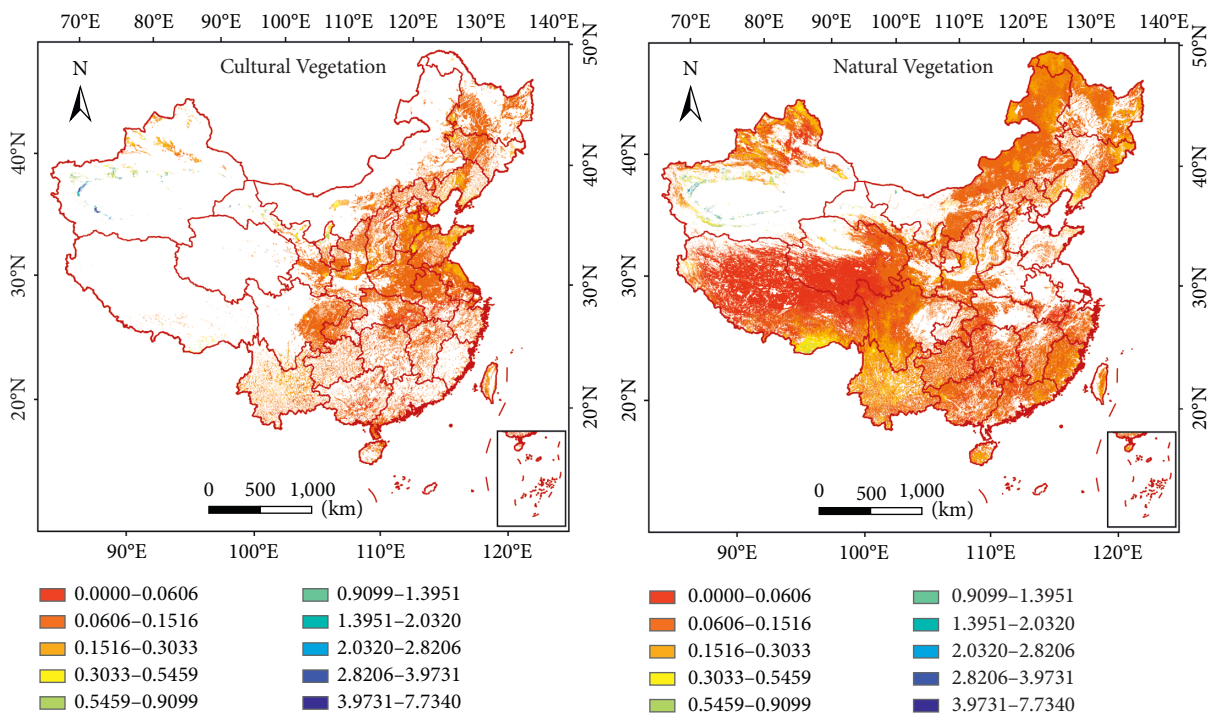

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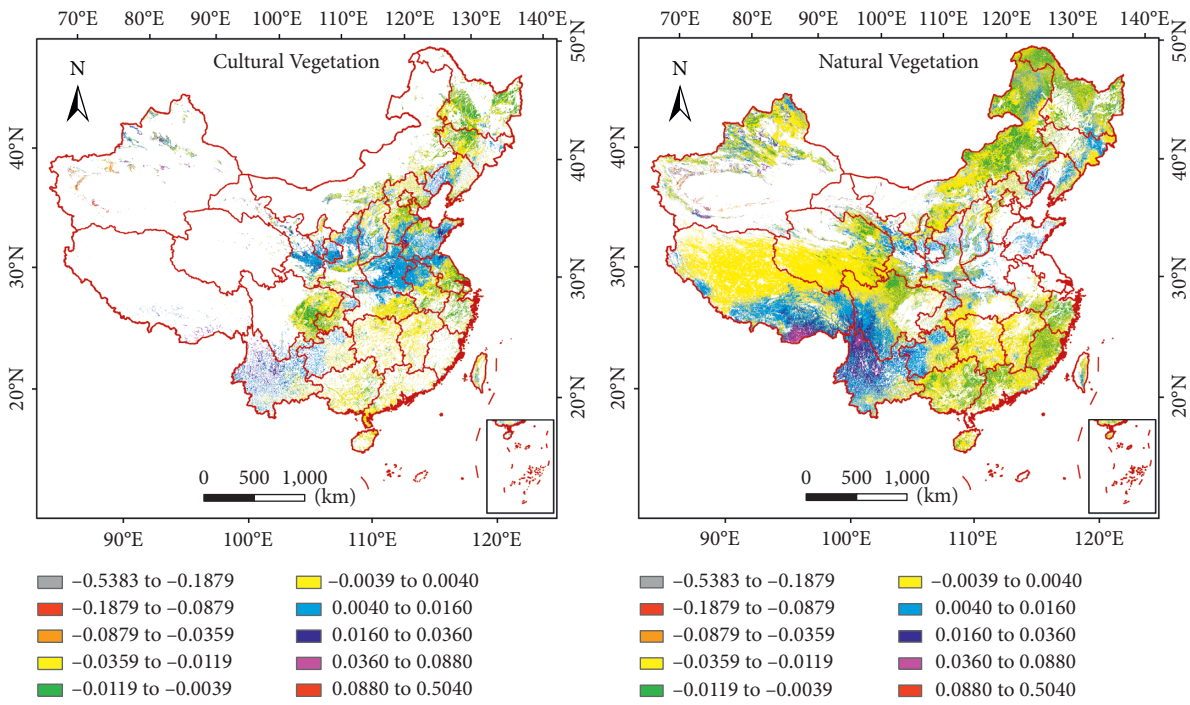


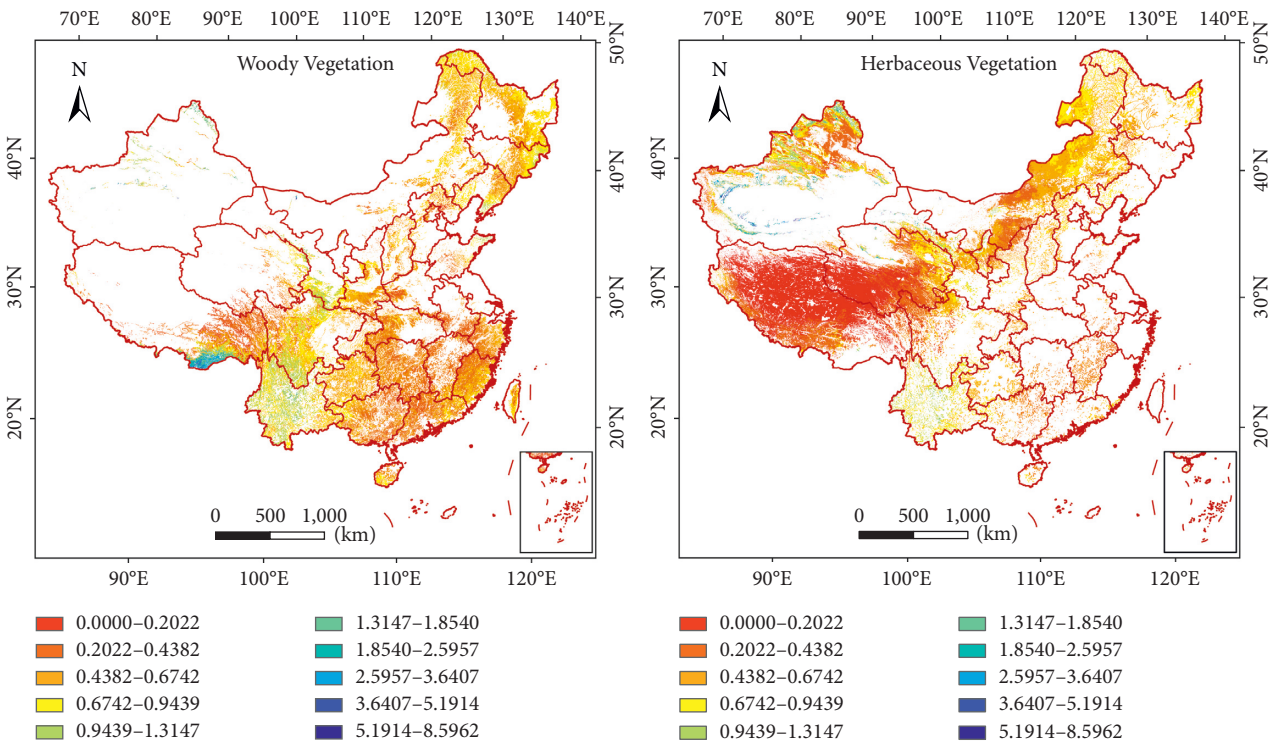
(c)

Figure 4: Temporal variation and spatial distribution of Cultural Vegetative and Natural Vegetative PUEs from 2000 to 2015. (a) Spatial distribution of the multiyear mean values of Cultural Vegetative and Natural Vegetative PUEs. (b) Standard deviations of Cultural Vegetative and Natural Vegetative PUEs. (c) Linear trends of Cultural Vegetative and Natural Vegetative PUEs.

is higher than that of China's vegetative PUE in China. The maximum value is 8.181 $gC{\cdot}m^{-2}{\cdot}mm^{-1}$ and the minimum value is 3.2×10^{-2} $gC{\cdot}m^{-2}{\cdot}mm^{-1}$; this is significantly higher than the national average, especially in northern Xinjiang, the southern Tibetan valley, northwestern Inner Mongolia, and other regions. The average of the multiyear mean value of Herbaceous Vegetative PUE is 4.66×10^{-1} $gC{\cdot}m^{-2}{\cdot}mm^{-1}$, which is lower than that of China's vegetative PUE; the maximum value is 8.596 $gC{\cdot}m^{-2}{\cdot}mm^{-1}$, and the minimum value is 3.4×10^{-2} $gC{\cdot}m^{-2}{\cdot}mm^{-1}$; this is significantly lower than the national average, especially in northeastern Tibet, southwest Qinghai, and other regions. The Broadleaf Forest's PUE is the highest, and the average of the multiyear mean values is 6.97×10^{-1} $gC{\cdot}m^{-2}{\cdot}mm^{-1}$; this is significantly higher than the national average, especially in the southern Tibetan valley, southwestern Yunnan, and other regions. Alpine Vegetative PUE is the lowest, and the average of the multiyear mean value is 1.87×10^{-1} $gC{\cdot}m^{-2}{\cdot}mm^{-1}$; this is significantly lower than the national average, especially in northeastern Tibet, southwest Qinghai, and other regions.

Woody Vegetative and Herbaceous Vegetative PUEs are relatively stable interannually, but the spatial difference is relatively significant, as shown in Figure 5. It can be seen from the interannual standard deviation that the mean values of the standard deviations of Woody Vegetative and Herbaceous Vegetative PUEs are 1.273×10^{-1} and 1.003×10^{-1}, respectively, showing an overall trend of no significant interannual fluctuations. However, the spatial variation characteristics of Woody Vegetative and Herbaceous Vegetative PUEs are significant. The maximum value of the standard deviation of Woody Vegetative PUE is 6.6877, which is mainly distributed in some regions in northwestern Inner Mongolia and the northern edge of the Tarim Basin; the minimum value is 2.62×10^{-2}, which is mainly distributed in most of Hunan, southern Anhui, and other regions. The maximum value of the standard deviation of Herbaceous Vegetative PUE is 7.734, which is mainly distributed in some regions in western Gansu and the edge of the Tarim Basin; the minimum value is 3.03×10^{-2}, which is mainly distributed in northeast Tibet, southwest Qinghai, locally in northern Xinjiang, and other regions. The stabilities of the Mixed Coniferous and Broadleaf Forest's and Broadleaf Forest's PUEs are declined, and the mean values of their standard deviations are 1.486×10^{-1} and 1.476×10^{-1}, respectively; this is especially significant in the southern Tibetan valley, locally at the northern edge of Tarim Basin, locally in southeastern Liaoning, and in northeast Jilin, and other regions. The stabilities of the Steppe's and Alpine Vegetative PUEs are increased, and the mean values of their standard deviations are 8.39×10^{-2} and 5.16×10^{-2}, respectively; this is especially significant in northeastern Tibet, western Qinghai, and other regions.

Woody Vegetative and Herbaceous Vegetative PUEs show an overall slightly increasing trend, as shown in Figure 5. From the interannual linear variation trend, it can be seen that the mean values of the increasing speeds of Woody Vegetative and Herbaceous Vegetative PUEs are 1.9×10^{-3} and 4×10^{-4}, respectively. However, Woody Vegetative and Herbaceous Vegetative PUEs show relatively obvious spatial variation characteristics and even decreasing trends in a few regions. Woody Vegetative PUE regions showing a decreasing trend



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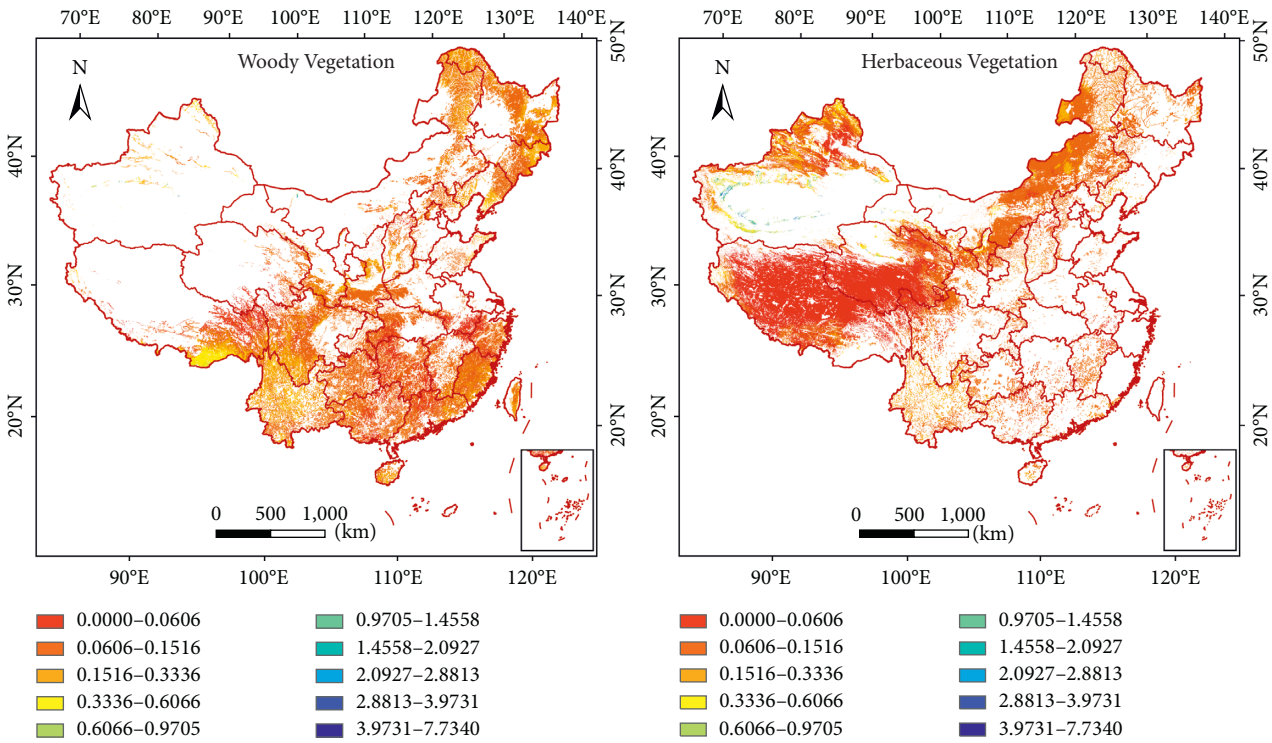

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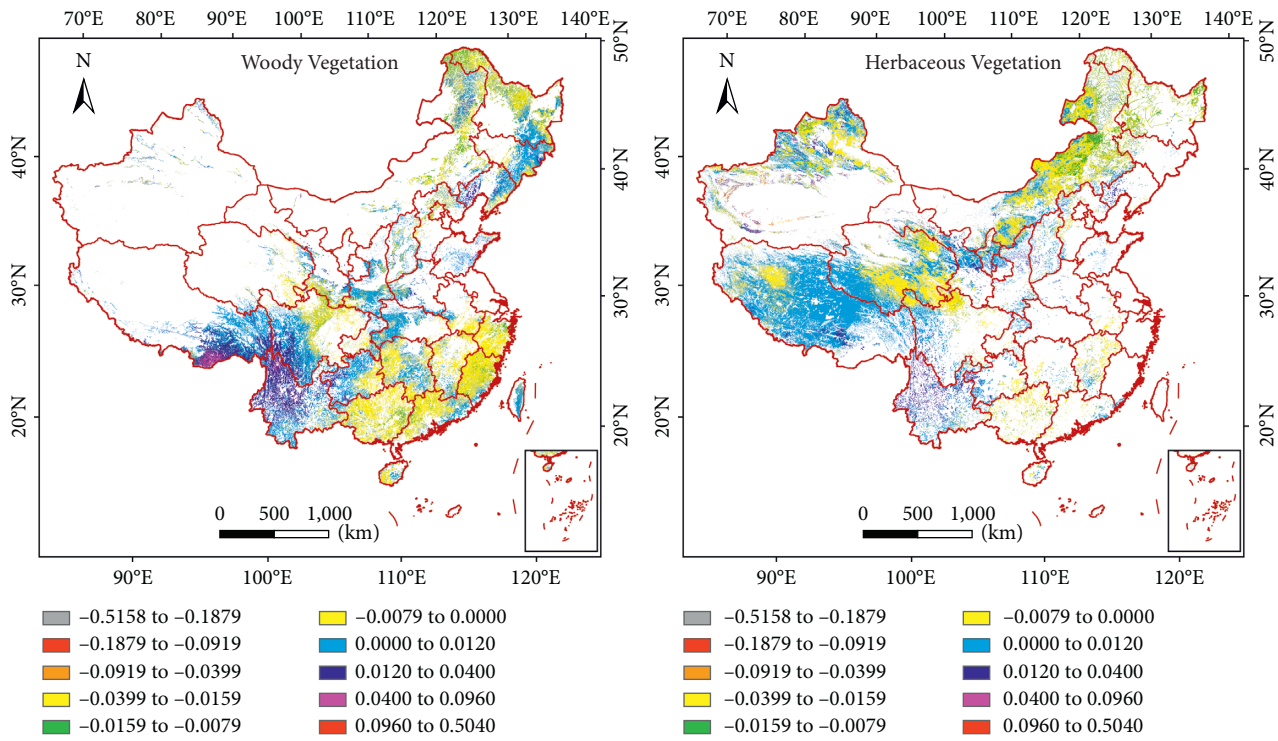

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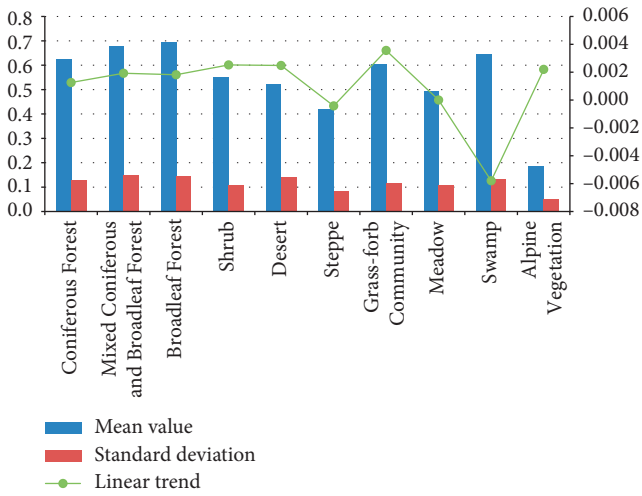
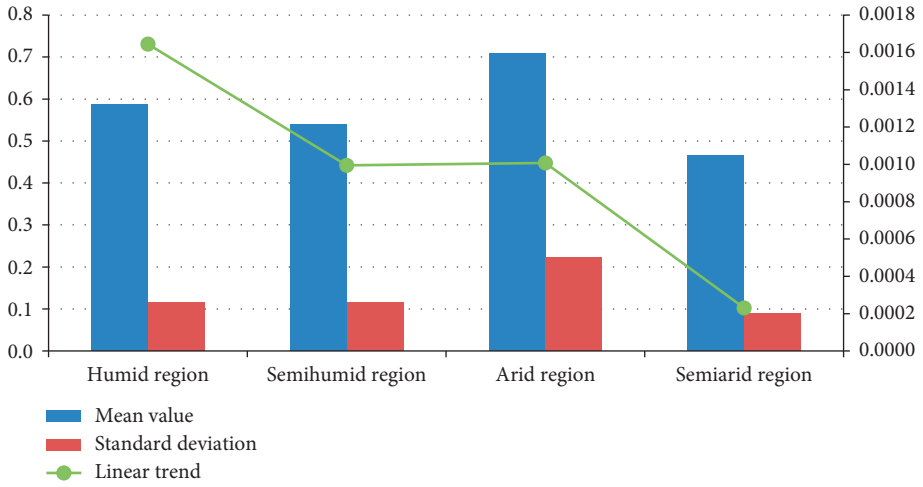


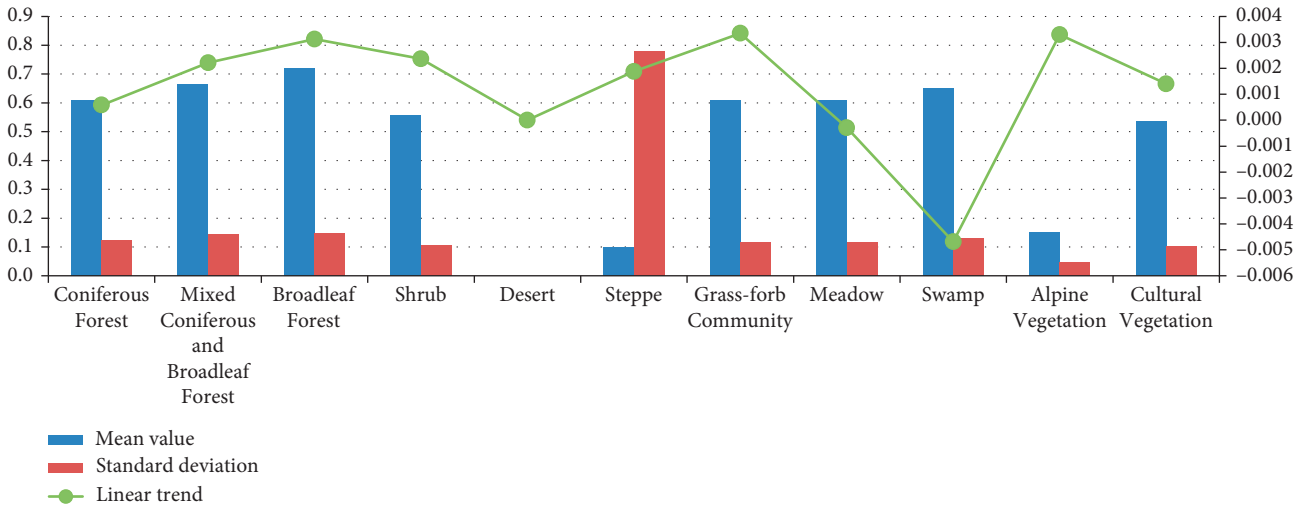
(d)

Figure 5: Temporal variation and spatial distribution of different Natural Vegetation types' PUEs. (a) Spatial distribution of the multiyear mean values of Woody Vegetative and Herbaceous Vegetative PUEs. (b) Standard deviations of Woody Vegetative and Herbaceous Vegetative PUEs. (c) Linear trends of Woody Vegetative and Herbaceous Vegetative PUEs. (d) Statistical central tendency of the mean values, standard deviations, and linear trends of different Natural Vegetation types' PUEs.

account for 24.5% of China's total land area; regions with the most obvious decreasing trends are mainly distributed in the northern edge of the Tarim Basin, northeast Inner Mongolia, northwest Heilongjiang, and other regions. Woody Vegetative PUE with the most obvious increasing trend is mainly distributed in the southern Tibetan valley, northwest of Yunnan, and other regions. Herbaceous Vegetative PUE regions showing a decreasing trend account for 42.2% of the total land area in China; regions with the most obvious decreasing trends are mainly distributed in the western edge of the Tarim Basin, northeastern Inner Mongolia, and most of Heilongjiang. A small number of Herbaceous Vegetative PUE regions with the most obvious increasing trend are mainly distributed in Xinjiang and western Gansu. The increasing speed of Grass-forb Community's PUE is the fastest, with a mean value of 3.6×10^{-3}; the increasing trend is most obvious in a small number of regions in northwestern Yunnan. The decreasing speed of Swamp's PUE is the fastest, with a mean value of -5.8×10^{-3}; the decreasing trend is most obvious in a small number of



(a)



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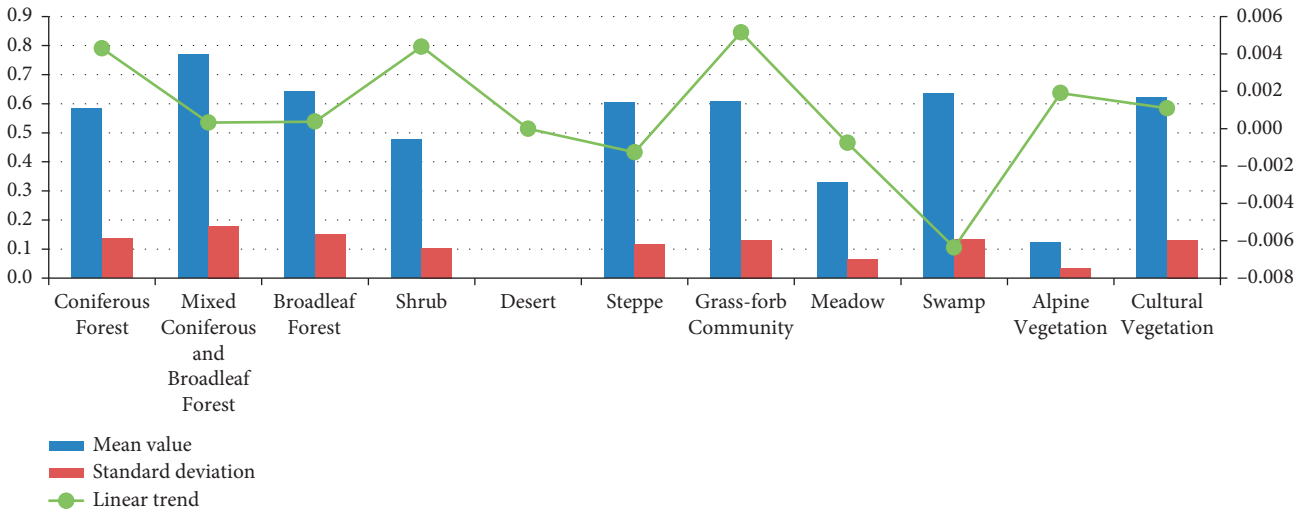

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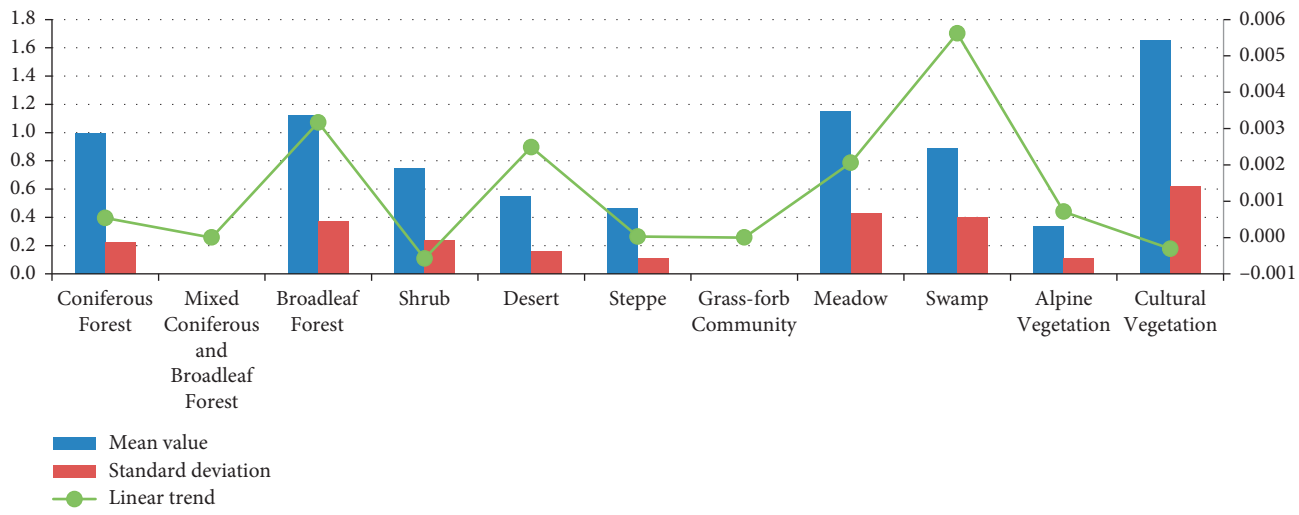
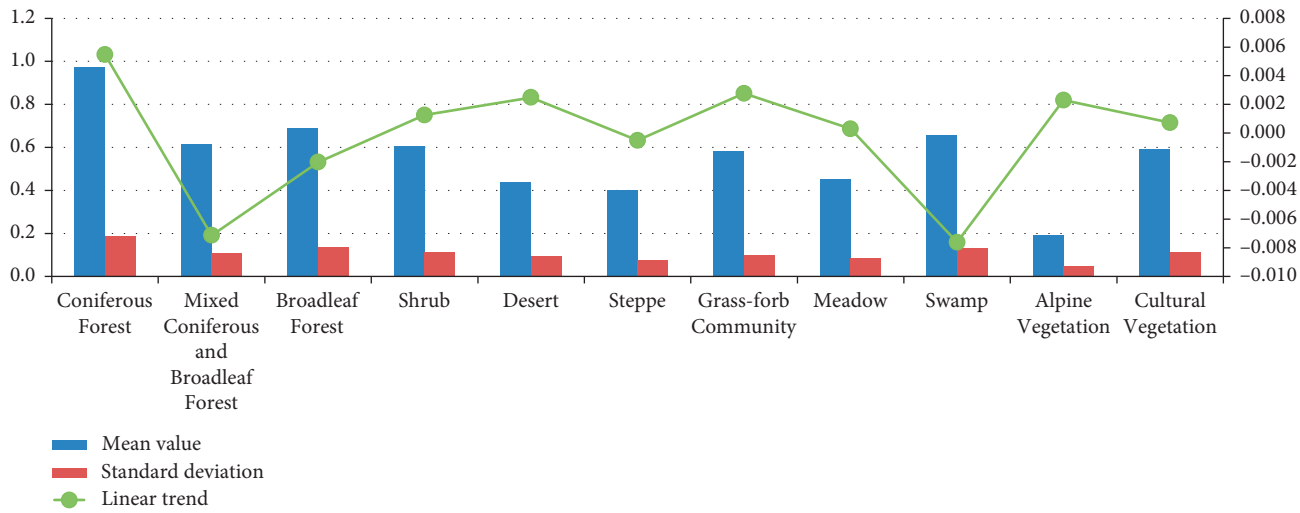


(d)



(e)

Figure 6: Statistical central tendency of the mean value, standard deviation, and linear trend of vegetative PUE in climate zones from 2000 to 2015: (a) climate zones; (b) humid regions; (c) semihumid regions; (d) arid regions; (e) semiarid regions.

regions in northeastern Inner Mongolia and Heilongjiang. The mean value of the increasing speed of Meadow's PUE is 0, tending to be stable.

3.3. Variation Characteristics of Climate Zones and Different Vegetation Types' PUEs

3.3.1. Variation Characteristics of Different Vegetation Types' PUEs in Climate Zones. The multiyear mean value of vegetative PUE in climate zones has obvious spatial variation characteristics, as shown in Figure 6. The averages of the multiyear mean values of vegetative PUE in humid, semihumid, arid, and semiarid regions are 5.86×10^{-1} gC·m^{-2}·mm^{-1}, 5.41×10^{-1} gC·m^{-2}·mm^{-1}, 7.09×10^{-1} gC·m^{-2}·mm^{-1}, and 4.67×10^{-1} gC·m^{-2}·mm^{-1}, respectively. The averages of the multiyear mean values of vegetative PUE in humid and arid regions are significantly higher than that of China's vegetative PUE, and they are significantly higher than the national average, especially along the edge of the Tarim Basin, south of Sichuan and Gansu, in central and western Yunnan, the southern Tibetan valley, and other regions. The averages of the multiyear mean values of vegetative PUE in semihumid and semiarid regions are significantly lower than that of China's vegetative PUE, and they are significantly lower than the national average, especially in northeastern Tibet, southwestern Qinghai, and other regions. The mean values of the standard deviations of vegetative PUE in humid, semihumid, arid, and semiarid regions are 1.155×10^{-1}, 1.162×10^{-1}, 2.237×10^{-1}, and 8.85×10^{-2}, respectively, showing an overall trend of no significant interannual fluctuations. However, interannual variation in vegetative PUE is significant in spatial. The stability of vegetative PUE in the arid region is declined, especially along the edge of the Tarim Basin. The stability of vegetative PUE in the semiarid region is increased, especially in northeastern Tibet, western Qinghai, and other regions. The vegetative PUE in climate zones shows an overall slightly increasing trend. From the interannual linear variation trend, it can be seen that the mean values of the increasing speed of

vegetative PUE in humid, semihumid, arid, and semiarid regions are 1.6×10^{-3}, 1.0×10^{-3}, 1.0×10^{-3}, and 2.0×10^{-4}, respectively. However, the vegetative PUE shows relatively obvious spatial variation characteristics and even decreasing trends in a few regions. The regions in which vegetative PUEs have the most obvious lowering trends are mainly distributed in humid and semihumid regions. The regions in which vegetative PUEs have the most obvious increasing trends are mainly distributed in arid and semiarid regions.

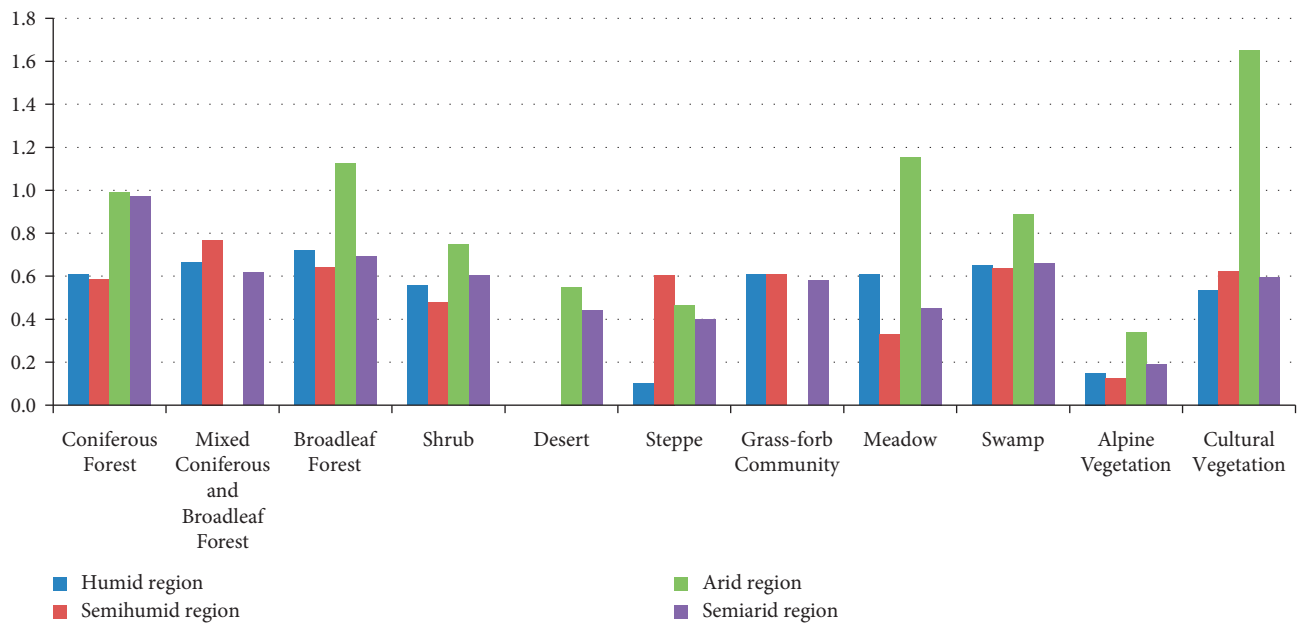
In humid regions, as shown in Figure 6, the PUEs of Mixed Coniferous and Broadleaf Forest, Broadleaf Forest, and Swamp are higher, and the averages of their multiyear mean values are 6.64×10^{-1} gC·m^{-2}·mm^{-1}, 7.2×10^{-1} gC·m^{-2}·mm^{-1}, and 6.5×10^{-1} gC·m^{-2}·mm^{-1}, respectively; they are significantly higher than the national average, especially in the southern Tibetan valley, locally in northeastern Inner Mongolia, and other regions. Steppe's PUE is the lowest, and the average of the multiyear mean value is 9.9×10^{-2} gC·m^{-2}·mm^{-1}; this is significantly lower than the national average, especially in a small number of regions in southern Gansu. The stability of Steppe's PUE is declined, especially in a few regions of southern Gansu, and the mean value of the standard deviation is 7.775×10^{-1}. The stability of Alpine Vegetative PUE is increased, especially in a small number of regions in eastern Tibet, and the mean value of the standard deviation is 4.78×10^{-2}. The increasing speeds of Broadleaf Forest's, Grass-forb Community's, and Alpine Vegetative PUEs are faster, with mean values of 3.1×10^{-3}, 3.3×10^{-3}, and 3.3×10^{-3}, respectively; the increasing trend is most obvious in a small number of regions in the southern Tibetan valley and northwestern Yunnan. The decreasing speed of Swamp's PUE is the fastest, with a mean value of -4.7×10^{-3}; the decreasing trend is most obvious in a small number of regions in northeastern Inner Mongolia. No desert exists in humid regions.

In semihumid regions, as shown in Figure 6, the PUE of the Mixed Coniferous and Broadleaf Forest is the highest, with an average of the multiyear mean value of 7.69×10^{-1} gC·m^{-2}·mm^{-1}; this is significantly higher than the national average, especially in a small number of regions in eastern Heilongjiang and northeastern Jilin. The Alpine Vegetative PUE is the lowest, with an average of the multiyear mean value of 1.23×10^{-1} gC·m^{-2}·mm^{-1}; this is significantly lower than the national average, especially in a small number of regions in northeastern Tibet and southwestern Qinghai. The stability of the Mixed Coniferous and Broadleaf Forest's PUE is declined, especially in a small number of regions in northeastern Jilin, and the mean value of the standard deviation is 1.801×10^{-1}. The stabilities of the Meadow and Alpine Vegetative PUEs are increased, especially in southwestern Qinghai, locally in northeastern Tibet and other regions, with mean values of the standard variations of 6.41×10^{-2} and 3.19×10^{-2}, respectively. The increasing speed of the Grass-forb Community's PUE is the fastest, with a mean value of 5.2×10^{-3}; it is the most obvious increasing trend, especially in southwestern Liaoning. The decreasing speed of Swamp's PUE is the fastest, with a mean value of -6.4×10^{-3}; it is the most obvious decreasing trend, especially in a small number of regions in Heilongjiang and in northeastern Inner Mongolia. No desert exists in semihumid regions.

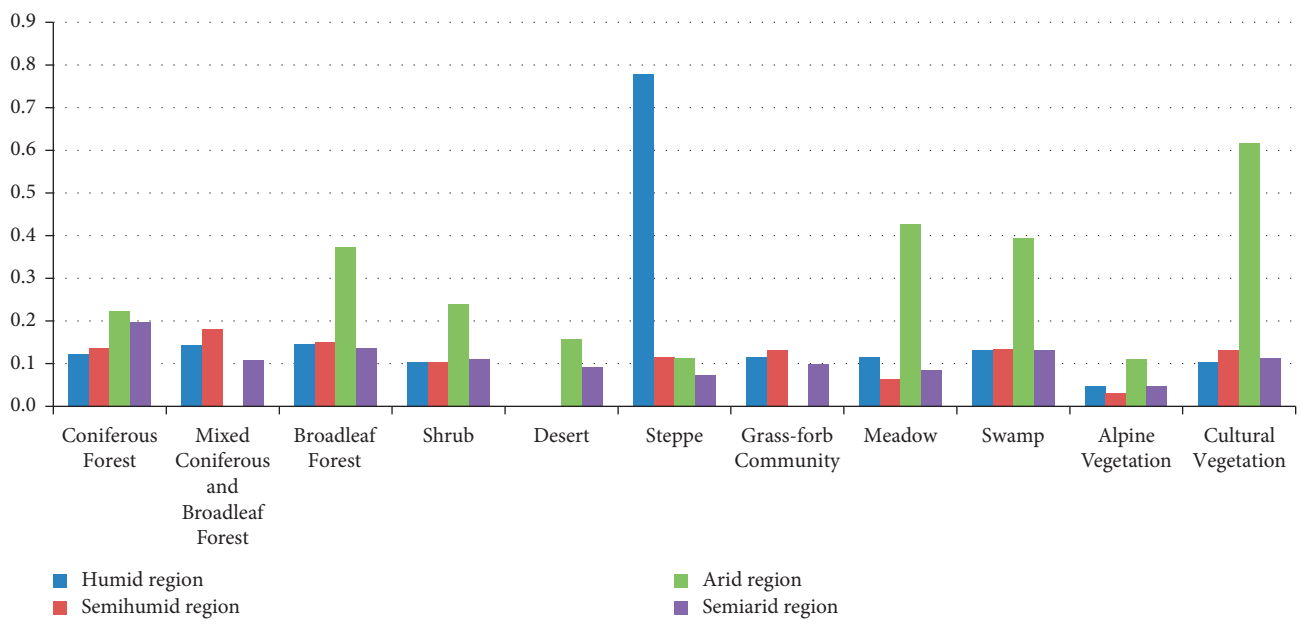
In arid regions, as shown in Figure 6, Cultural Vegetative PUE is the highest, with an average of the multiyear mean value of 1.652 gC·m^{-2}·mm^{-1}; this is significantly higher than the national average, especially in a small number of regions along the Tarim Basin's edge and in western Gansu. Alpine Vegetative PUE is the lowest, with an average of the multiyear mean value of 3.39×10^{-1} gC·m^{-2}·mm^{-1}; it is significantly lower than the national average, especially in a small number of regions in northern Tibet. The stability of Cultural Vegetative PUE is declined, especially in a small number of regions along the Tarim Basin's edge and in western Gansu, with a mean value of the standard deviation of 6.169×10^{-1}. The stability of Alpine Vegetative PUE is increased, especially in a small number of regions in northern Tibet, with a mean value of standard deviation of 1.101×10^{-1}. The increasing speed of Swamp's PUE is the fastest, with a mean value of 5.6×10^{-3}; this is the most obvious increasing trend, especially in a small number of regions in central Xinjiang. The increasing speeds of Shrub's and Cultural Vegetative PUEs are slower, with the mean values of -6×10^{-4} and -3×10^{-4}, respectively; they are the most obvious decreasing trends, especially in a small number of regions along the edge of the Tarim Basin. The mean value of the increasing speed of Steppe's PUE is 0, tending to be stable. No Mixed Coniferous and Broadleaf Forest or Grass-forb Community exists in arid regions.

In semiarid regions, as shown in Figure 6, Coniferous Forest's PUE is the highest, with an average of the multiyear mean value of 9.73×10^{-1} gC·m^{-2}·mm^{-1}; this is significantly higher than the national average, especially in a small number of regions in the southern Tibetan valley and in northern Xinjiang. Alpine Vegetative PUE is the lowest, with an average of the multiyear mean value of 1.9×10^{-1} gC·m^{-2}·mm^{-1}; this is significantly lower than the national average, especially in a small number of regions in northern Tibet and western Qinghai. The stability of Coniferous Forest's PUE is declined, with a mean value of standard deviation of 1.976×10^{-1}, especially in a small number of regions in the southern Tibetan valley and in northern Xinjiang. The stability of Alpine Vegetative PUE is increased, with a mean value of standard deviation of 4.82×10^{-2}, especially in a small number of regions in central Tibet and western Qinghai. The increasing speed of Coniferous Forest's PUE is the fastest, with a mean value of 5.5×10^{-3}; this is the most obvious increasing trend, especially in a small number of regions in the southern Tibetan valley. The lowering speeds of Mixed Coniferous and Broadleaf Forest's and Swamp's PUEs are faster, with the mean values of -7.1×10^{-3} and -7.6×10^{-3}, respectively; these are the most obvious decreasing trends, especially in a small number of regions in southwestern Heilongjiang and northwestern Jilin.

3.3.2. Variation Characteristics of the Same Vegetation Type's PUEs among Climate Zones. The averages of the multiyear mean values of the same vegetation type's PUEs among climate zones are significantly different, as shown in Figure 7. The difference in the average of Cultural



(a)



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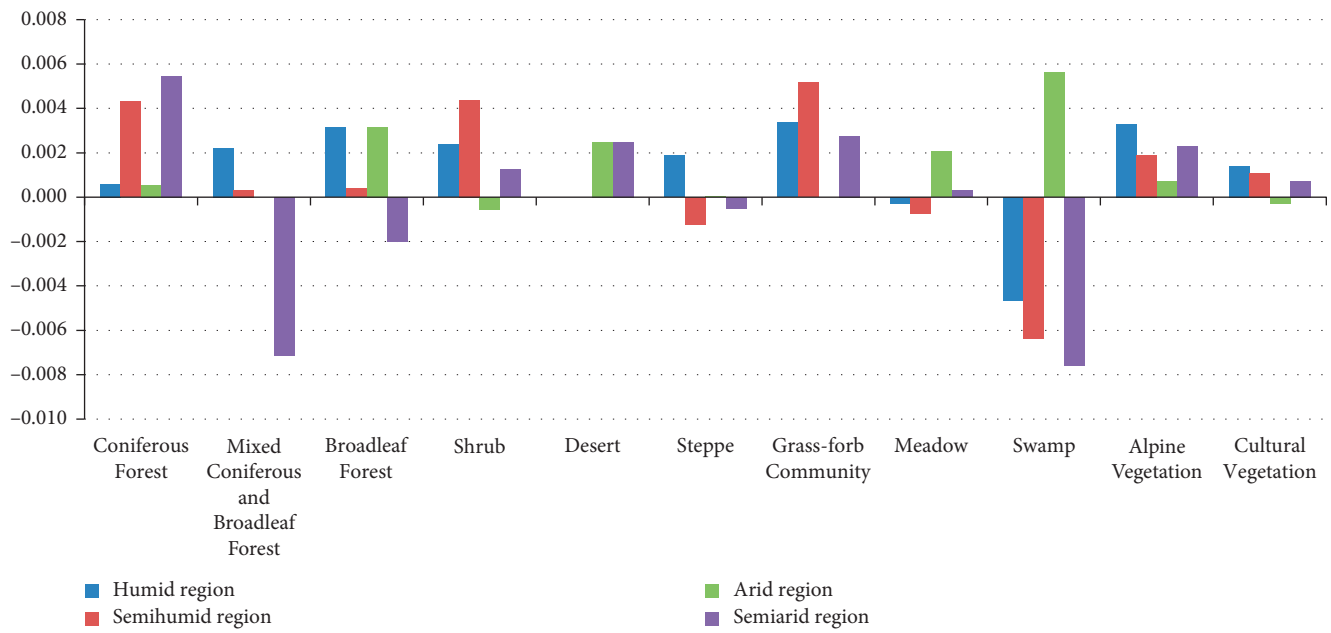

(c)

Figure 7: Statistical central tendency of the same vegetation type's PUEs among climate zones from 2000 to 2015: (a) mean values; (b) standard variations; (c) linear trends.

Vegetative PUE is the largest, with the averages of the multiyear mean values in humid, semihumid, arid, and semiarid regions are 5.35×10^{-1} gC·m^{-2}·mm^{-1}, 6.22×10^{-1} gC·m^{-2}·mm^{-1}, 1.652 gC·m^{-2}·mm^{-1}, and 5.93×10^{-1} g C·m^{-2}·mm^{-1}, respectively. The average of Cultural Vegetative PUE in arid regions is the highest, and it is significantly higher than the national average of Cultural Vegetation, especially in a small number of regions along the edge of the Tarim Basin and in western Gansu. The average of Cultural Vegetative PUE in humid regions is the lowest, and it is significantly lower than the national average of Cultural Vegetation, especially in eastern Guangxi, southern Guangdong, northern Jiangxi, and other regions. The difference in the average of Meadow's PUE is larger, and the averages of the multiyear mean values in humid, semihumid, arid, and semiarid regions are 6.08×10^{-1} gC·m^{-2}·mm^{-1}, 3.3×10^{-1} gC·m^{-2}·mm^{-1}, 1.152 gC·m^{-2}·mm^{-1}, and 4.52×10^{-1} gC·m^{-2}·mm^{-1}, respectively. The average of Meadow's PUE in arid regions is the highest, and it is significantly higher than the national average of Meadow, especially in a small number of regions along the edge of the Tarim Basin. The average of Meadow's PUE in semihumid regions is the lowest, and it is significantly lower than the national average, especially in a small number of regions in western Qinghai. The difference in the average of Grass-forb Community's PUE is the least, and the averages of the multiyear mean values in humid, semihumid, and semiarid regions are 6.08×10^{-1} gC·m^{-2}·mm^{-1}, 6.1×10^{-1} gC·m^{-2}·mm^{-1}, and 5.82×10^{-1} gC·m^{-2}·mm^{-1}, respectively. The average of Grass-forb Community's PUE in semihumid regions is the highest, and it is significantly higher than the national average of Grass-forb Community, especially in a small number of regions on the Shandong Peninsula, the Liaodong Peninsula, and in southwestern Liaoning. The average of Grass-forb Community's PUE in semiarid regions is the lowest, and it is significantly lower than the national average, especially in a small number of regions in western Shanxi. The difference in average of Mixed Coniferous and Broadleaf Forest's PUE is less, and the averages of the multiyear mean values in humid, semihumid, and semiarid regions are 6.64×10^{-1} gC·m^{-2}·mm^{-1}, 7.69×10^{-1} gC·m^{-2}·mm^{-1}, and 6.17×10^{-1} gC·m^{-2}·mm^{-1}, respectively. The average of Mixed Coniferous and Broadleaf Forest's PUE in semihumid regions is the highest, and it is significantly higher than the national average, especially in a small number of regions in eastern Heilongjiang and northeastern Jilin. The average of Mixed Coniferous and Broadleaf Forest's PUE in semiarid regions is the lowest, and it is significantly lower than the national average, especially in a small number of regions in southwestern Heilongjiang.

The interannual PUEs of the same vegetation type among climate zones is stable, but the spatial difference is relatively significant, as shown in Figure 7. The difference in stability of Steppe's PUE is the largest, and the mean values of standard deviation in humid, semihumid, arid, and semiarid regions are 7.775×10^{-1}, 1.151×10^{-1}, 1.132×10^{-1}, and 7.43×10^{-2}, respectively. The stability of Steppe's PUE in humid regions is declined, especially in a small number of regions in southern Gansu. The stability of Steppe's PUE in semiarid regions is increased, especially in northeastern Tibet, western Qinghai, and other regions. The difference in the stability of Cultural Vegetative PUE is larger, and the mean values of the standard deviation in humid, semihumid, arid, and semiarid regions are 1.042×10^{-1}, 1.317×10^{-1}, 6.169×10^{-1}, and 1.123×10^{-1}, respectively. The stability of Cultural Vegetative PUE in arid regions is declined, especially in a small number of regions along the edge of the Tarim Basin and in western Gansu. The stability of Cultural Vegetative PUE in humid regions is increased, especially in eastern Hubei, southern Anhui, and other

regions. The difference in stability of Grass-forb Community's PUE is the least, and the mean values of the standard deviation in humid, semihumid, and semiarid regions are 1.147×10^{-1}, 1.318×10^{-1}, and 9.96×10^{-2}, respectively. The stability of Grass-forb Community's PUE in semihumid regions is declined, especially in a small number of regions on the Shandong Peninsula and in southern Liaoning. The stability of Grass-forb Community's PUE in semiarid regions is increased, especially in a small number of regions in northern Shanxi and western Hubei. The difference in stability of Alpine Vegetative PUE is less, and the mean values of standard deviation in humid, semihumid, arid, and semiarid regions are 4.78×10^{-2}, 3.19×10^{-2}, 1.101×10^{-1}, and 4.82×10^{-2}, respectively. The stability of Alpine Vegetative PUE in arid regions is declined, especially in a small number of regions in southern Xinjiang. The stability of Alpine Vegetative PUE in semihumid region is increased, especially in a small number of regions in northeastern Tibet and southwestern Qinghai.

The PUEs of the same vegetation type among climate zones with overall variation trends are significantly different, as shown in Figure 7. The difference in the increasing speed of Swamp's PUE is the largest, and the mean values of the increasing speeds in humid, semihumid, arid, and semiarid regions are -4.7×10^{-3}, -6.4×10^{-3}, 5.6×10^{-3}, and -7.6×10^{-3}, respectively. The increasing speed of Swamp's PUE in arid regions is the fastest, and it is the most obvious increasing trend, especially in a small number of regions in central Xinjiang. The decreasing speed of Swamp's PUE in semiarid regions is the fastest, and it is the most obvious decreasing trend, especially in a small number of regions in southwestern Heilongjiang and northwestern Jilin. The difference in the increasing speed of Mixed Coniferous and Broadleaf Forest's PUE is larger, and the mean values of the increasing speeds in humid, semihumid, and semiarid regions are 2.2×10^{-3}, 3×10^{-4}, and -7.1×10^{-3}, respectively. The increasing speed of Mixed Coniferous and Broadleaf Forest's PUE in humid regions is the fastest, and it is the most obvious increasing trend, especially in a small number of regions in northwestern Yunnan. The decreasing speed of Mixed Coniferous and Broadleaf Forest's PUE in semiarid regions is the fastest, and it is the most obvious decreasing trend, especially in a small number of regions in southwestern Heilongjiang. The difference in the increasing speed of Desert's PUE is the least; the mean values of the increasing speeds in arid and semiarid regions are both 2.5×10^{-3}; and it is the most obvious increasing trend, especially in a small number of regions in Xinjiang and western Gansu. The difference in the increasing speed of Cultural Vegetative PUE is less, and the mean values of the increasing speeds in humid, semihumid, arid, and semiarid regions are 1.4×10^{-3}, 1.1×10^{-3}, -3×10^{-4}, and 7×10^{-4}, respectively. The increasing speed of Cultural Vegetative PUE in humid regions is the fastest, and it is the most obvious increasing trend, especially in a small number of regions in the southern Tibetan valley and in northwestern Yunnan. The decreasing speed of Cultural Vegetative PUE in arid regions is the fastest, and it is the most obvious decreasing trend, especially in a small number of regions in western Xinjiang.

4. Discussion

4.1. Analysis of Extreme Values of Vegetative PUE. The extreme value regions of vegetative PUE are mainly distributed in arid areas in Northwest China, especially along the edge areas of the Tarim Basin. This is consistent with the findings of Mu et al. [38]. The reasons for these extreme values can be explained by the following three aspects:

(1) The Tarim Basin is surrounded by mountains such as the Tianshan, Kunlun, and Altun. Regional runoff is replenished by melting snow and ice from the mountains; thus, the vegetation shows good growth with limited precipitation. Terrain factor may be one of the reasons leading to higher vegetative PUE in the area [39].

(2) Because the Taklamakan Desert is located in the center of the Tarim Basin, the sand content of the soil surface around the desert is higher; thus, the infiltration rate of precipitation also increases, increasing the vegetative PUE [27, 38].

(3) In arid areas, the vegetative root system is well developed, with a lower canopy conductance being able to utilize the soil moisture in the lower layer; thus, the production volume of consumed water per unit of vegetation is higher [40]. In particular, some dominant plant communities have lower transpiration and higher photosynthetic rates in arid environments, so vegetative PUE may also be higher [41–43].

4.2. Influencing Factors on Spatial Variation in Vegetative PUE. The variation in vegetative PUE is closely related to climate zones, soil factors, and vegetation types [16, 27]. Due to the differences in precipitation, soil factors, and vegetation types in different climatic zones, in discussing the influencing factors on spatial variations in vegetative PUE, this study obtained the following four results:

(1) The difference in vegetative PUE may be affected by different vegetation types. The differences in biological community structure, photosynthetic efficiency, and fractional vegetation cover of different vegetation types can result in different PUEs among different vegetation types [44, 45].

(2) The difference in vegetative PUE may be affected by different climatic zones. For example, a significant spatial difference in the PUEs of the same vegetation type among climatic zones may be due to the distribution of climate conditions, such as heat and moisture, being different in different climatic zones, which can determine vegetative PUE as a zonal distribution [25, 46].

(3) The difference in vegetative PUE may be affected by precipitation, and water is an important factor that limits vegetative growth in arid areas [45]. For example, along the edge area of the Tarim Basin, the vegetation is replenished by melting snow and ice in the mountains, making the vegetative PUE in this area higher than that of other arid areas [39, 47].

(4) The difference in vegetative PUE may be affected by soil factors in humid areas. Generally, in humid regions, the soil moisture is in a saturation condition with sufficient precipitation, but the biological activity of the soil will be lower. In addition, a superfluous amount of precipitation will result in surface runoff, washing away key nutrient substances that are easily affected by eluviations, such as nitrogen and phosphorus, creating an indirect impact on vegetative growth [48]. In humid regions, improving soil fertility and permeability can be beneficial to vegetative PUE [16].

4.3. Limitations and Prospects of the Study. The meteorological stations used in this study are rare in the western China, with a generally uneven distribution that may affect the accuracy of the spatial interpolation of the precipitation data. In the future, the use of remote-sensing data to perform supplemental interpolation of spatial data based on DEM may be preferable to improve the spatial data quality of precipitation. The NPP directly uses the product of MODIS NPP because of the limitation of scale and the lack of measured data verification, which may result in errors when using NPP to calculate PUE. In the future research, we should use this model or improve the relevant model, carry out NPP simulation calculations, and use the measured data for verification, which may improve the accuracy of NPP. In further PUE studies, the NDVI can be used instead of NPP to enable PUE calculations, which may improve PUE quality and provide better data for further research on the spatiotemporal variations of PUE.

Due to the limitations of the research scale and data in this paper, it is impossible to deeply discuss the influencing factors for the evolution of the spatiotemporal patterns of vegetative PUE. As for the relationship between the evolution process of vegetative PUE and climatic change, altitude, biological characters of vegetation, soil, human activities, and so on, we can assess these factors from the following aspects: the driving relationship between changes in vegetative PUE and precipitation and temperature, the difference in vegetative PUE at different altitudes, the correlation between fractional vegetation cover (FVC), leaf area index (LAI) and spatial distribution and interannual fluctuations of vegetative PUE, and the impact of different soil types on spatial differences of vegetative PUE. In future research, other statistical models and analysis methods should be used to further improve the research effectiveness of PUE. In addition, the different influencing factors of vegetative PUE in arid and humid regions also need further in-depth study to gain important findings.

5. Conclusions

This paper starts from the national scale, using time-series MODIS NPP data and meteorological precipitation data from 2000 to 2015 in China to calculate the Chinese vegetative PUE from 2000 to 2015. Then, it analyzes the changes and spatiotemporal patterns of the Chinese terrestrial vegetative PUE in the most recent 16 years. The main conclusions are as follows:

(1) The multiyear mean value of China's vegetative PUE shows obvious spatial variation characteristics. It is relatively stable interannually, with an overall slightly increasing trend. The regions with extreme values, declined stability, and the most obvious decreasing trends of China's vegetative PUE all appear along the edge areas of the Tarim Basin.

(2) There is a significant difference in the PUEs among different vegetation types. Broadleaf Forest's PUE is the highest, and Alpine Vegetative PUE is the lowest. The stabilities of Mixed Coniferous and Broadleaf Forest's and Broadleaf Forest's PUEs are declined, and the stabilities of Steppe's and Alpine Vegetative PUEs are increased. The increasing speed of Grass-forb Community's PUE is the fastest, the decreasing speed of Swamp's PUE is the fastest, and the increasing speed of Meadow's PUE tends to be stable.

(3) There is a significant difference in the PUEs among different vegetation types in climate zones. No desert exists in humid and semihumid regions. No Mixed Coniferous and Broadleaf Forest or Grass-forb Community exists in arid regions. It includes all vegetation types in semiarid regions. The PUEs of the same vegetation type are significantly different among climate zones. The difference in the average of Cultural Vegetative PUE is the largest, and the difference in the average of Grass-forb Community's PUE is the least. The difference in the stability of Steppe's PUE is the largest, and the difference in the stability of Grass-forb Community's PUE is the least. The difference in the increasing speed of Swamp's PUE is the largest, and the difference in the increasing speed of Desert's PUE is the least.

Research on the spatiotemporal patterns of vegetative PUE in China will help us gain an in-depth understanding of the mechanism of vegetation response to global climate change, and we can more clearly recognize the formation process of the productivity of different vegetation types in different climatic zones. The spatiotemporal variation characteristics of vegetative PUE in arid regions, especially the possible influencing factors of vegetative PUE in extreme regions, can provide important references for many researchers of vegetative PUE in arid regions. A relatively comprehensive study of China's vegetative PUE, based on different vegetation types and different climate zones, can accumulate valuable information for other researchers of China's vegetative PUE in the future. Vegetative PUE has extensive application prospects in the assessment of vegetation degradation and regional water-carbon cycles. PUE has important practical and theoretical significance for the scientific study of China's ecological safety constructs, land-vegetation ecosystems, and reaction to global changes.

Data Availability

The vector data of the climate zones and vegetation types in China used to support the findings of this study are included within the article. The MODIS NPP data are downloaded

from [NASA, https://ladsweb.nascom.nasa.gov/search/]. The meteorological precipitation data used to support the findings of this study were supplied by [the China Meteorological Data Service Center] under license and so cannot be made freely available. Requests for access to these data should be made to [the China Meteorological Data Service Center, http://data.cma.cn/].

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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