Hindawi
Advances in Meteorology
Volume 2019, Article ID 8659138, 15 pages
https://doi.org/10.1155/2019/8659138

Research Article

The Variations of Satellite-Based Ecosystem Water Use and Carbon Use Efficiency and Their Linkages with Climate and Human Drivers in the Songnen Plain, China

Bo Li, Fang Huang, Shuai Chang, and Ning Sun

School of Geographical Sciences, Northeast Normal University, Changchun 130024, China

Correspondence should be addressed to Fang Huang; huangf835@nenu.edu.cn

Received 11 November 2018; Revised 13 February 2019; Accepted 4 April 2019; Published 28 April 2019

Academic Editor: James Cleverly

Ecosystem water use efficiency (WUE) and carbon use efficiency (CUE), as two of the most important ecological indicators of an ecosystem, represent the carbon assimilation rate of unit water consumption and the capacity of transferring carbon from the atmosphere to potential carbon sinks. Revealing WUE and CUE changes and their impact factors is vital for regional carbon-water interactions and carbon budget assessment. Climate affects carbon and water processes differently. Compared to WUE, the variations in CUE in response to climate factors and human activity remain inadequately understood. In this study, ecosystem-level WUE and CUE variations in the Songnen Plain (SNP), Northeast China, during 2001–2015, were investigated using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data. The relationships between WUE, CUE, main climate factors, and human impacts were explored. The results showed that ecosystem WUE and CUE have fluctuated over time, with regional average values of 1.319 $gC{\cdot}kg^{-1}H_2O$ and 0.516, respectively. Deciduous broad-leaved forests had the highest average WUE but the lowest CUE. The multiyear average CUE of grassland ranked in first place, while the lowest WUE indicated that a lesser capacity of net productivity was generated by the use of limited water supply. WUE and CUE showed a downward trend in most areas of the SNP, indicating that the carbon sequestration capacity of the terrestrial ecosystem became weaker in the past 15 years. Annual precipitation and relative humidity had positive influences on WUE and CUE in more than 60% of the study area. The total annual sunshine duration and annual average temperature negatively affected WUE and CUE in most areas. Human activities had a positive effect on ecosystem WUE changes in the SNP but might inhibit CUE variations. Our findings aid in understanding the biological regulation mechanisms of carbon-water cycle coupling and provide a scientific basis for formulating sustainable regional development strategies and guiding water and land resources management.

1. Introduction

Water use efficiency (WUE) is defined as the carbon assimilation rate of unit water consumption [1], which links the photosynthetic production of ecosystems to evapotranspiration and reflects ecosystem carbon and water cycles and their interactions. Carbon use efficiency (CUE) is the ratio of net primary productivity (NPP) to gross primary productivity (GPP), which indicates ecosystem capacity to transfer atmospheric CO_2 into biomass and carbon sequestration. CUE changes strongly affect ecosystem carbon budgets and turnover. Because WUE and CUE are related to the processes of ecosystem evapotranspiration and photosynthesis, they are regarded as the important indicators for characterizing the carbon-water coupling of ecosystems. The quantitative analysis of spatial-temporal changes of WUE and CUE and their influencing factors will aid in better understanding the effects of future climate change on the water and carbon processes of ecosystems [2].

Although the lack of continuous ground observations may hinder the long-term analysis of the dynamics of vegetation development, satellite remote sensing provides useful information for investigating large-scale and long-term variabilities of ecosystem WUE and CUE. In 1999, Bastiaanssen analyzed crop WUE in India based on estimates of crop yields and evaporation (ET) using remote sensing data for the first time [3]. Mo et al. integrated a soil plant atmospheric transmission crop growth model with remote sensing data to predict crop yield, water consumption, and WUE in Hebei Province, China [4]. Zwart et al. indicated that remote sensing data could be used as input data in a water productivity model and estimated the WUE of wheat from a local to global scale [5]. Teixeira et al. calculated regional evapotranspiration with remote sensing data in the middle and lower reaches of the San Francisco River in Brazil and studied the spatial distribution of crop WUE [6]. Based on crop yields derived from remote sensing images and meteorological data, Li et al. estimated large-scale ET and WUE levels of winter wheat and summer corn in the Haihe River watershed [7]. Hu et al. found that there were significant differences in daily WUE of forest and grassland ecosystems [8]. Many attempts have been made to address the relationship between temporal-spatial variations in WUE and climatic factors using ecosystem models or satellite observations. Gang et al. evaluated the spatiotemporal dynamics of global grassland WUE from 2000 to 2013 and revealed the different responses of each grassland type to climate variations [9]. Zhang et al. applied the ecosystem model CEVSA to estimate the spatiotemporal changes of WUE in high mountainous regions in southwest China from 1954 to 2010 and analyzed its response to climate change [10]. Sun et al. posited that global WUE produced different spatial relationships with climate variables [11]. By means of continuous eddy covariance (EC) measurements and time-series MODIS data, Tang et al. investigated the seasonal variations in WUE for grassland and cropland ecosystems in China's arid and semiarid regions and contended that the dominant climate factors were linked by temperature and precipitation [12].

In many studies, CUE has been considered a constant value regardless of ecosystem type or species [13–15], but that assumption at global scale might be controversial because it ignores the influence of environmental factors [16, 17]. Piao et al. demonstrated that the CUE of different vegetation differed greatly from the south temperate zone to the tropics [18]. Nemani et al. calculated CUE at a global scale using remote sensing data [19]. Zhang et al. found that the NPP/GPP ratio exhibited a pattern that did not depend only on the main climatic characteristics (i.e., temperature and precipitation) and geographical factors (namely, latitude and altitude) [20]. Khalifa et al. revealed that WUE and CUE of the different land cover types in Ethiopia had higher magnitudes than their counterparts in Sudan, and both of them exhibited higher sensitivity to drought and variations in precipitation [21]. He et al. investigated the spatial variations in CUE from different process-based carbon cycle models in comparison with those from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data to analyze the responses of CUE to mean annual precipitation and temperature [22]. To our knowledge, the analysis of the relationships of CUE with other climatic factors, such as relative humidity, solar duration, and the comprehensive impacts of human activities, has not been well explored.

The Songnen Plain (SNP) is located in the temperate semihumid to semiarid transition ecological fragile zone in Northeast China, which is highly sensitive to global change. Historically, the SNP fostered both agricultural and nomadic cultures. The combined effects of vulnerable physical basis and excessive irrational human activities have made the region suffer from a high risk of land degradation for the past century. Due to concerns over aggravating desertification, many measures for ecological and environmental protection have been taken by the Chinese government and have achieved preliminary effectiveness. Previous studies have mostly focused on the land cover and use changes and effects of agricultural activities on the environment. Little is known about the spatial-temporal patterns of ecosystem-level WUE and CUE and their response to climate change and human impacts in the SNP.

The objectives of this study are to explain (1) how ecosystem WUE and CUE in the SNP varied during 2001–2015 with MODIS satellite observations and (2) how climatic factors and human activities affected variations of ecosystem WUE and CUE in the SNP. The results and conclusions complement our knowledge of coupled carbon-water cycles and carbon budgets of the temperate semiarid and semihumid transitional zone ecosystem and their underlying driving mechanisms.

2. Materials and Methods

2.1. Study Area. The SNP is located in the central part of Northeast China, with a range of 121°38′ to 128°33′E and 42°49′ to 49°12′N and a total area of 22.35×10^4 km^2 (Figure 1). It is an alluvial plain across which the Songhua and Nenjiang rivers flow and is situated in the central Songliao Basin between the Xiaoxing'an Mountains, Changbai Mountains, and the Songliao Watershed. It is also known as one of the world's three major black soil regions and soda salinized land areas. The altitude ranges from 101 to 1632 meters above sea level but is mostly below 200 meters [23]. The main landform types include those of low mountains, alluvial plains, tablelands, and intervals. The SNP belongs to a temperate continental semihumid and semiarid monsoon climate zone that is characterized by significant winds and four seasons with a hot, rainy summer and a cold, dry winter. The average temperature is from −16°C to −26°C in January and 21.2°C to 23°C in July. The annual precipitation ranges between 350 and 800 mm and gradually decreases from east to west [24]. Soils are fertile, with black soil, meadow soil, and chernozem being widely distributed in this plain. From east to west, the natural vegetation types are forest steppe, meadow steppe, and typical grassland. As a typical agropastoral transitional zone, the SNP is more sensitive to climate change. Administratively, the SNP includes 54 county-level cities in the central and western parts of Jilin Province and the southwest of Heilongjiang Province. It is among the important grain commodity bases in China.

2.2. Data and Processing

2.2.1. MODIS Data. MOD17A3 yearly NPP and GPP products with 1-km spatial resolution were the basis of this

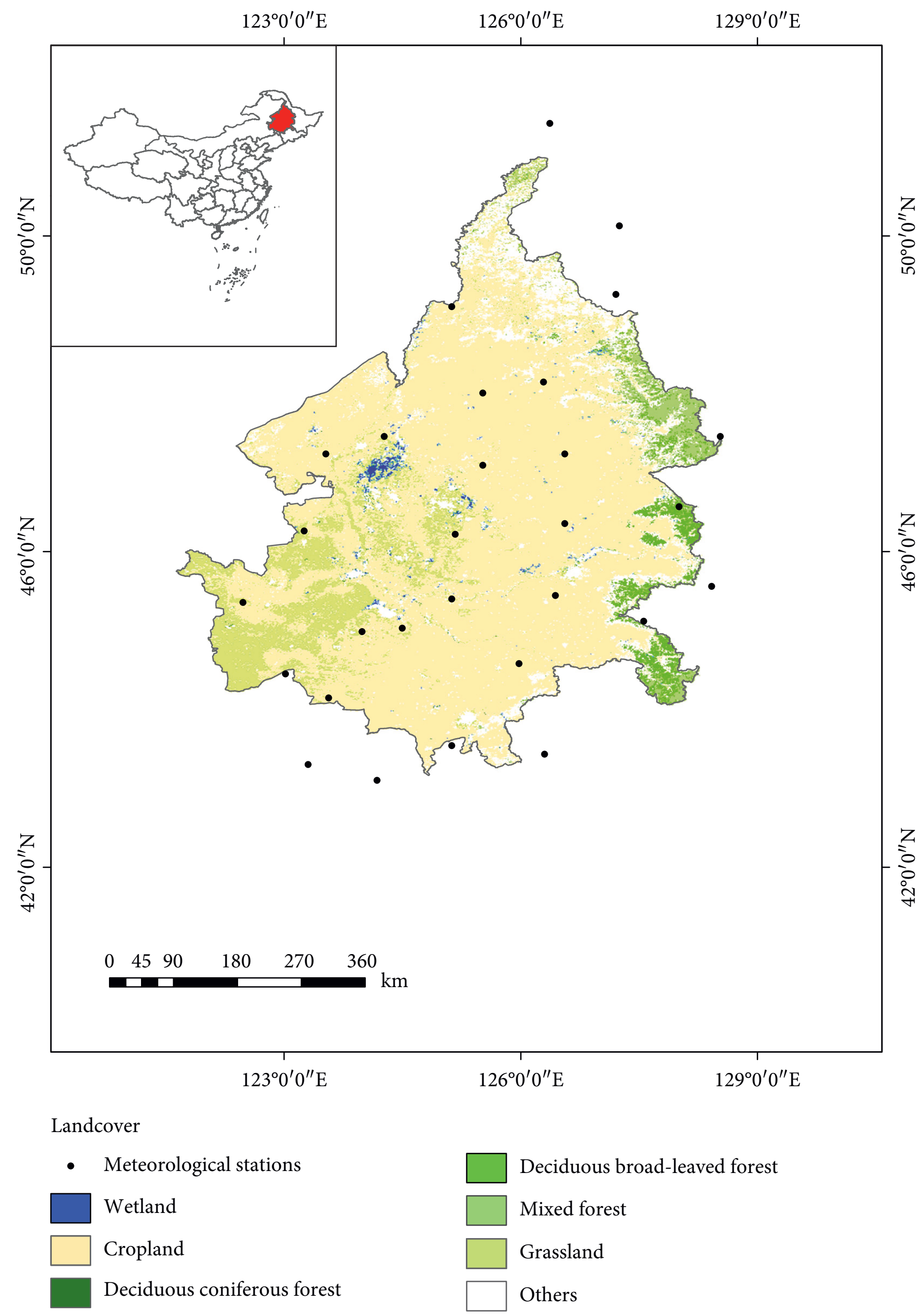


Figure 1: Location and land cover of the SNP.

study. Based on the Biome-BGC (biogeochemical cycles) model, NPP data are produced by the Numerical Terradynamic Simulation Group (NTSG) and the University of Montana (UST) (https://ladsweb.modaps.eosdis.nasa.gov/). This dataset's accuracy and reliability have been widely verified. There are no overall bias and continuous overestimation or underestimation at global scale compared with the field measured values [25, 26]. The annual actual evapotranspiration (ETa) product (MOD16A3), with spatial resolution of 1 km and estimation based on the Penman–Monteith model, was accessed at http://ntsg.umt.edu/project/mod16. The images were a subset for the SNP in ArcGIS.

The MODIS land cover type dataset (MCD12Q1) is provided by the Land Processes Distributed Active Archive Center (LP DAAC) (https://lpdaac.usgs.gov/) [27]. This product includes global land cover data from 2001 to 2016 with a spatial resolution of 500 m and adopts five different classification schemes. In this study, 2009 land cover data were used. According to the IGBP class scheme and the regional characteristics of the SNP, vegetation types were summarized as follows: deciduous coniferous forest, deciduous broad-leaved forest, mixed forest, grassland, cropland, and wetland. The data were then resampled to the 1 km resolution of MODIS products.

2.2.2. Meteorological Data. Monthly meteorological data of 29 weather stations in and near the SNP from 2001 to 2015 were acquired from the National Meteorological Information Center of China (http://data.cma.cn/). Yearly average precipitation (mm), total duration of sunshine (h), average temperature (°C), and average relative humidity (%) were computed. A previous study found that Kriging interpolation had high numerical precision at different resolutions, but the results could not show the details of actual terrain and were unsuitable for the plains [28]. The inverse distance weighting (IDW) spatial interpolation technique showed better adaptability in plain areas, with relatively high accuracy of interpolation. Therefore, the gridded precipitation, sunshine hours, temperature, and humidity data with spatial resolution of 1 km were produced by the IDW interpolation method in ArcGIS in this study.

2.3. Calculation of WUE and CUE. Ecosystem WUE refers to the rate of carbon assimilation per unit water loss, which is an important indicator of ecological function and carbon-water cycle coupling [29]. Due to differences in research purposes and data acquisition approaches, the calculation of the "water loss" of the ecosystem differs across studies, which may cause different understandings of ecosystem WUE variability mechanisms. In this study, WUE is calculated by the following equation [30]:

$$\mathrm{WUE} = \frac{\mathrm{NPP}}{\mathrm{ET}}, \tag{1}$$

where NPP and ET is the net primary productivity and evapotranspiration, respectively.

Ecosystem CUE describes the relationship between photosynthesis and respiration, which is an important indicator of the ability of plants to transfer carbon [31]. CUE is a key controlling factor for ecosystem carbon storage and can be used to compare carbon cycles in different ecosystems. The calculation of CUE is performed as follows:

$$\mathrm{CUE} = \frac{\mathrm{NPP}}{\mathrm{GPP}}, \tag{2}$$

where GPP is the gross primary productivity, representing the ability to capture energy and carbon through photosynthetic plants and the total amount of C assimilation, and NPP reveals the energy of plants stored after losing C from GPP through autotrophic respiration [32].

2.4. Trend Analysis. Spatial trends of WUE and CUE were examined by applying a simple linear regression model with time as the independent variable and WUE or CUE as the dependent variables. The outputs of the trend analysis are the maps of regression slope values, as expressed by the following formula:

$$\mathrm{slope} = \frac{n \times \sum_{i=1}^{n} i \times A_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} A_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2}, \tag{3}$$

where slope is the slope of the fitted regression line at each pixel; n represents year range; i is 1 for the first year, 2 for the second year, and so on; and A_i represents the WUE or CUE of the year i. A negative regression coefficient ($\mathrm{slope} < 0$) indicates a decline of WUE or CUE, whereas a positive value ($\mathrm{slope} > 0$) depicts an increase trend. F test was used to determine the significance of change trend.

2.5. Correlation Analysis. To analyze the intensity of linear correlation between WUE, CUE, and climate factors from 2001 to 2015, the correlation analysis (CA) method was used. The Spearman correlation coefficient (ρ) of each pixel was calculated by the formula as follows [33]:

$$\rho = 1 - \frac{6 \sum d_i^2}{n^3 - n}, \tag{4}$$

where ρ is the correlation coefficient ranging from 0 to 1; n is the number of levels; and d is the rank difference of the two pairs of variables. The rank sum test is used to test its significance.

2.6. Multiple Regression Residual Analysis. The multivariate regression residuals analysis method was proposed by Evans and Geerken to discriminate land degradation driven by climate and human drivers [34, 35]. In this study, by the regression analysis of WUE, CUE, and climatic factors at the pixel scale, the values of WUE and CUE were predicted, which could be regarded as the impact of climate on WUE and CUE. Residual values were estimated by the differences between observed WUE, CUE, and their predicted values, and thereby, the effect of climate change and human activities on WUE and CUE could be distinguished. The residual can be expressed as follows:

$$\varepsilon = D_1 - D_2, \tag{5}$$

where D_1 and D_2 are the observed and predicted values of WUE or CUE, respectively. ε indicates the human impacts on WUE or CUE. A positive residual ($\varepsilon > 0$) indicates positive effects of human activities on WUE or CUE, whereas a negative value ($\varepsilon < 0$) depicts the negative roles of anthropogenic causes. The significance of the residual sequence variation trend was also analyzed.

3. Results and Discussion

3.1. Temporal Dynamics of WUE and CUE

3.1.1. Interannual Changes. The multiyear average WUE in the SNP fluctuated with time, as shown in Figure 2. Average WUE peaked in 2003 (3.881 $\mathrm{gC{\cdot}kg^{-1}H_2O}$) in association with higher NPP. Subsequently, the regional WUE kept decreasing and dropped to the lowest value in 2009 (0.551 $\mathrm{gC{\cdot}kg^{-1}H_2O}$), possibly due to high evapotranspiration in that year. WUE started to increase in 2009 and rose to 1.127 $\mathrm{gC{\cdot}kg^{-1}H_2O}$ in 2013. It declined again after 2013, and a lower WUE value of 0.940 $\mathrm{gC{\cdot}kg^{-1}H_2O}$ was found in 2015.

By comparison, the regional CUE was relatively stable, with an average value of 0.516. The average CUE was 0.495 in 2001 and dropped to 0.467 in 2003. It showed an upward trend for the period 2001–2005. The maximum CUE (0.552)

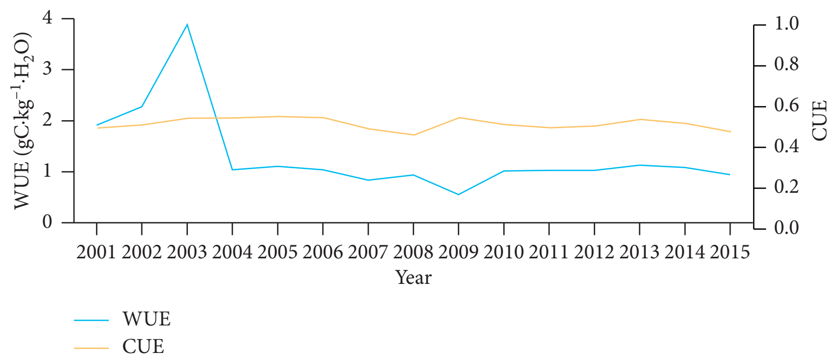


Figure 2: Annual average WUE and CUE in the SNP for the period of 2001–2015.

was observed in 2005. It decreased to its lowest value (0.461) in 2008, implying the worst level of CUE. Ecosystem CUE increased from 2010 to 2013 and decreased during 2013–2015.

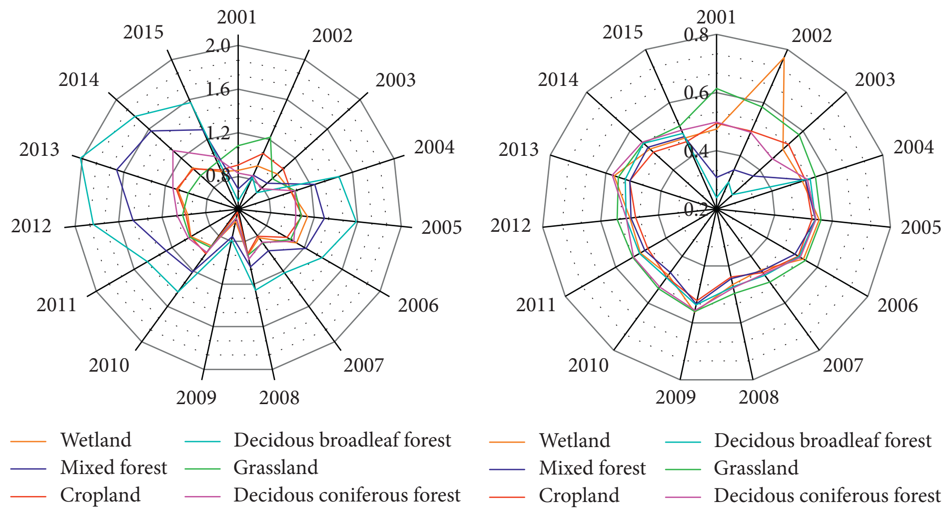
3.1.2. WUE Variations of Different Ecosystems. During 2001–2015, the average WUE of different ecosystems followed a descending order of deciduous broadleaf forest > mixed forest > grassland > deciduous coniferous forest > cropland > wetland. The highest WUE in the SNP was found in the deciduous broad-leaved forest, with a multiyear average value of 1.328 $gC\cdot kg^{-1}H_2O$. The wetland showed the lowest WUE (0.954 $gC\cdot kg^{-1}H_2O$). The maximum WUE values of deciduous broad-leaved forest and mixed forest were both found in 2013 (2.019 $gC\cdot kg^{-1}H_2O$ and 1.669 $gC\cdot kg^{-1}H_2O$, respectively), whereas the minimum values were 0.577 $gC\cdot kg^{-1}H_2O$ and 0.685 $gC\cdot kg^{-1}H_2O$ in 2001, respectively. The average WUE of mixed forest was 1.158 $gC\cdot kg^{-1}H_2O$. The interannual average WUEs of grassland and cropland were 0.984 $gC\cdot kg^{-1}H_2O$ and 0.961 $gC\cdot kg^{-1}H_2O$, respectively. In deciduous coniferous forest, the multiyear average WUE was 0.972 $gC\cdot kg^{-1}H_2O$, with the highest value (1.304 $gC\cdot kg^{-1}H_2O$) in 2014 and the lowest value (0.584 $gC\cdot kg^{-1}H_2O$) in 2009. The interannual WUE mean of wetland was 0.954 $gC\cdot kg^{-1}H_2O$, and the maximum and minimum WUEs were observed in 2005 (1.138 $gC\cdot kg^{-1}H_2O$) and 2009 (0.615 $gC\cdot kg^{-1}H_2O$), separately. Due to the significantly increased evapotranspiration in 2009, the average WUEs of all ecosystems were relatively low.

Regarding the temporal variation of WUE in different vegetation types, the decreasing trend followed the order of deciduous coniferous forest (2.43%) > grassland (1.53%) > wetland (1.37%) > cropland (0.42%). In contrast, the increased trends of WUE were for deciduous broadleaf forest (6.98%) and mixed forest (4.53%). The increased WUE in deciduous broadleaf forest and mixed forest indicated that WUE improved and that greater net productivity might be generated by using a limited water supply. The WUE of deciduous coniferous forest, grassland, wetland, and cropland revealed the opposite trend.

3.1.3. CUE Variations of Different Ecosystems. Figure 3(b) illustrates the CUE changes of different ecosystems from 2001 to 2015. Grassland showed the highest CUE, with a multiyear average CUE of 0.567. The CUE of deciduous broad-leaved forest was the lowest. CUE of different ecosystems followed a descending order of grassland > wetland > deciduous coniferous forest > cropland > mixed forest > deciduous broad-leaved forest. The multiyear average CUE of deciduous coniferous forest was 0.533. The highest (0.597) and lowest (0.472) CUEs were observed in 2013 and 2003, respectively. Deciduous broad-leaved forest and mixed forest showed a similar change tendency of annual CUE, with average interannual values of 0.479 and 0.480, respectively. The highest CUE (0.560) value occurred in 2005, while their lowest values of 0.239 and 0.308 were found in 2001.

The annual average CUE values of the deciduous broad-leaved forest and the mixed forest were low before 2003, but they suddenly increased in 2004 (Figure 3(b)). This might be attributed to the lower annual NPP during 2001–2003, whereas GPP showed a small difference. The average CUE of cropland was 0.510, with the peak of 0.551 in 2003 and the trough of 0.452 in 2008. The multiyear average CUE of wetland was 0.542. It was found that wetland CUE peaked in 2002 (0.801) and that the minimum value occurred in 2007 (0.472). The reason was that NPP of wetland in 2002 reached 579.2 g/m^2, an increase of 27.56% from that in 2001.

CUE can quantitatively depict the ability of vegetation to fix atmospheric CO_2 in the surface ecosystem [34–36]. During the past 15 years, the CUE of deciduous broad-leaved forest and mixed forest showed an increasing trend, with that for deciduous broad-leaved forest rising most obviously. However, average CUE values of deciduous coniferous forest, grassland, cropland, and wetland tended to decrease in the following sequence: deciduous coniferous forest > wetland > grassland > cropland. From 2001 to 2015, deciduous coniferous forest, grassland, cropland, and wetland CUE dropped, indicating their enhanced vegetation respiration. The respiration decomposed organic matter into simple inorganic substances such as water and carbon dioxide; thereby, ecosystems might release more carbon dioxide. In contrast, the CUE of deciduous broad-leaved forest and mixed forest increased, suggesting that these ecosystems were more efficient in assimilating CO_2 and reducing the CO_2 in the atmosphere. Given the greater absorption of carbon dioxide, carbon sequestration was more likely.



(a) (b)

Figure 3: WUE (a) and CUE (b) of different ecosystems in the SNP from 2001 to 2015.

3.2. Spatial Distribution and Change Trend of WUE and CUE. Figures 4(a) and 4(b) show the spatial distributions of multiyear average WUE and CUE, respectively, in the SNP from 2001 to 2015. The linear trends of the WUE and CUE were also calculated at the 99% confidence level (Figures 4(c) and 4(d)). Spatially, average WUE ranged from 0.178 to 8.445 $gC{\cdot}kg^{-1}H_2O$; higher values were mainly found in the eastern part of the SNP. The average CUE values in the southwest were greater than in other regions.

The WUE in the SNP showed a general downward trend during the past 15 years. The area of decreased WUE occupied 99.82% of the landscape, showing a concentrated spatial pattern. Among those regions where WUE decreased, cropland and grassland constituted 81.14% and 12.06% of the total land, respectively. The pixels of increased WUE showing in a dotted pattern only accounted for 0.18% of the study area, which was mostly covered by deciduous coniferous forest, deciduous broad-leaved forest, and mixed forest in the northeastern and southwestern fringes.

CUE also showed a decreasing trend. Increased CUE was mainly observed in the eastern deciduous coniferous forest, deciduous broad-leaved forest, and mixed forest area, accounting for 0.11%. Ecosystem CUE tended to decrease in 99.89% of the total area. Among those areas, 81.19% and 12.07% were occupied by cropland and grassland, respectively.

3.3. Direct Effects of Local Climate Factors on WUE and CUE Changes. The spatial distribution of the correlation coefficients between climatic factors, WUE, and CUE is illustrated in Figures 5 and 6. In general, WUE and CUE had more obvious correlation with yearly average precipitation, annual total sunshine hours, average relative humidity, and annual average temperature (Table 1).

WUE was positively correlated with average annual precipitation in two-thirds of the total study area. Precipitation had a positive effect on WUE in more than 70% of the areas covered by mixed forest, deciduous broad-leaved forest, and cropland but was negatively correlated to WUE in 54% of the grassland areas. The duration of sunshine had an inhibitory effect on the WUE in 58.63% of the vegetation areas. The longer the total sunshine duration was, the lower WUE might be. A positive correlation between the total sunshine hours and WUE was mainly observed in the southeastern part of the SNP, but the duration of sunshine in these regions had decreased during the past 15 years. Sunshine duration was significantly and negatively correlated with WUE in the eastern area, where the total sunshine hours increased. The duration of sunshine had a negative impact on more than 60% of wetland WUE. In all, 90% of the areas in the SNP showed a positive correlation between annual average relative humidity and WUE. The positive correlation between relative humidity and WUE was mainly found in the northern part of the SNP, while there was negative correlation in the southeastern and central regions. The annual average humidity had a positive impact on approximately 98% of mixed forest WUE, and negative correlations were observed in 24% of the areas covered by deciduous coniferous forest. The annual average temperature also played a role in regulating WUE. In more than 65% of the SNP, ecosystem WUE had a negative feedback on temperature. The negative correlation areas were mainly observed in the southeast. Except for the deciduous coniferous forest, average temperature had a negative effect on the WUE of other ecosystem types.

The average annual precipitation in the SNP had a positive impact on CUE in approximately 72% of the total landscape and especially in mixed forest and wetland. However, negative correlation was found in approximately 52% of areas covered by grassland. The annual total sunshine duration was negatively correlated with ecosystem CUE in the eastern region, whereas it had a positive influence on the CUE of ecosystems in the southeast region. Sunshine duration increased in approximately 85% of areas covered by mixed forest where the CUE was relatively higher. More

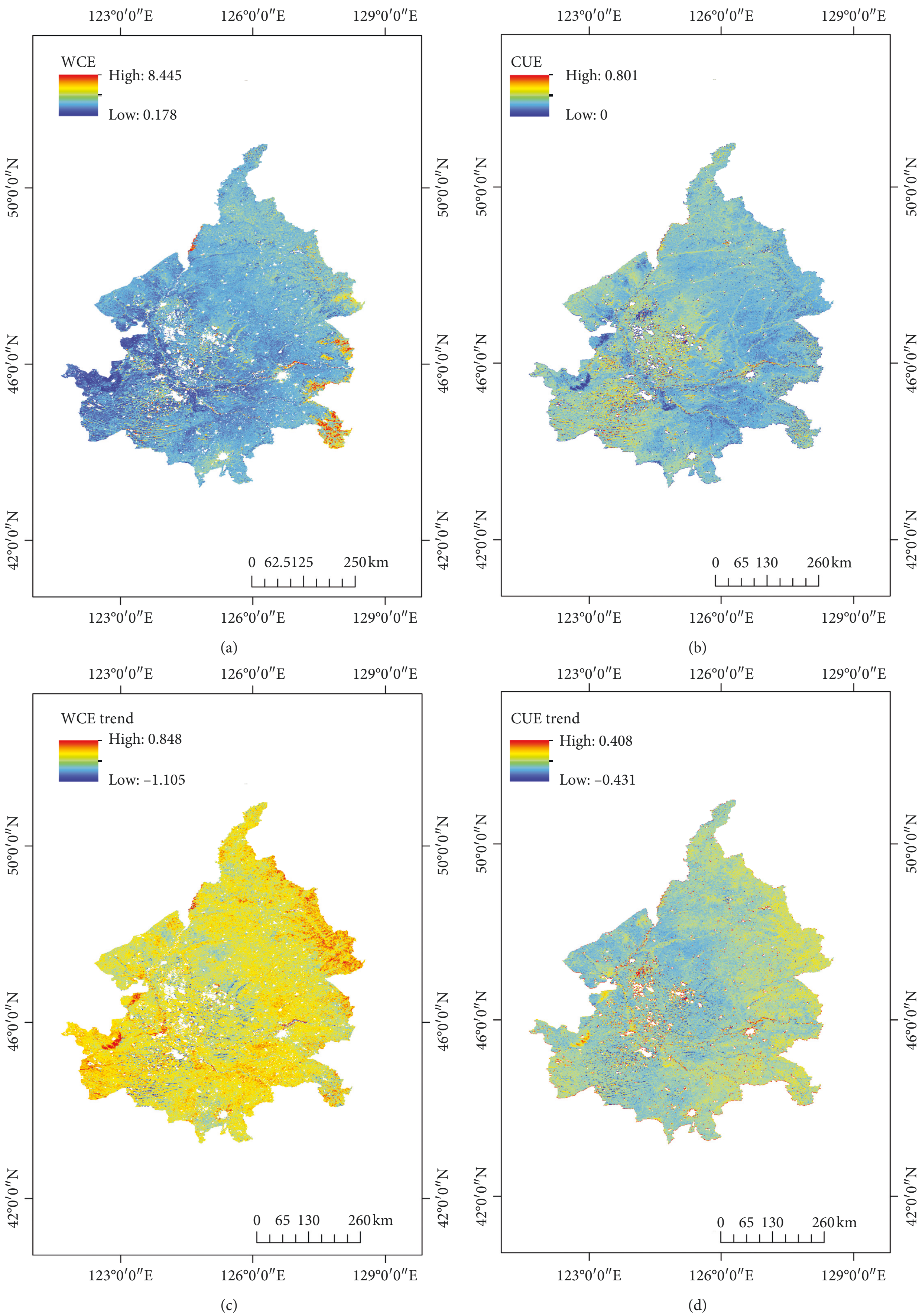


Figure 4: Spatial distribution and trend of WUE and CUE in the SNP (2001–2015). (a) Annual average WUE, (b) annual average CUE, (c) WUE change trend, and (d) CUE change trend.

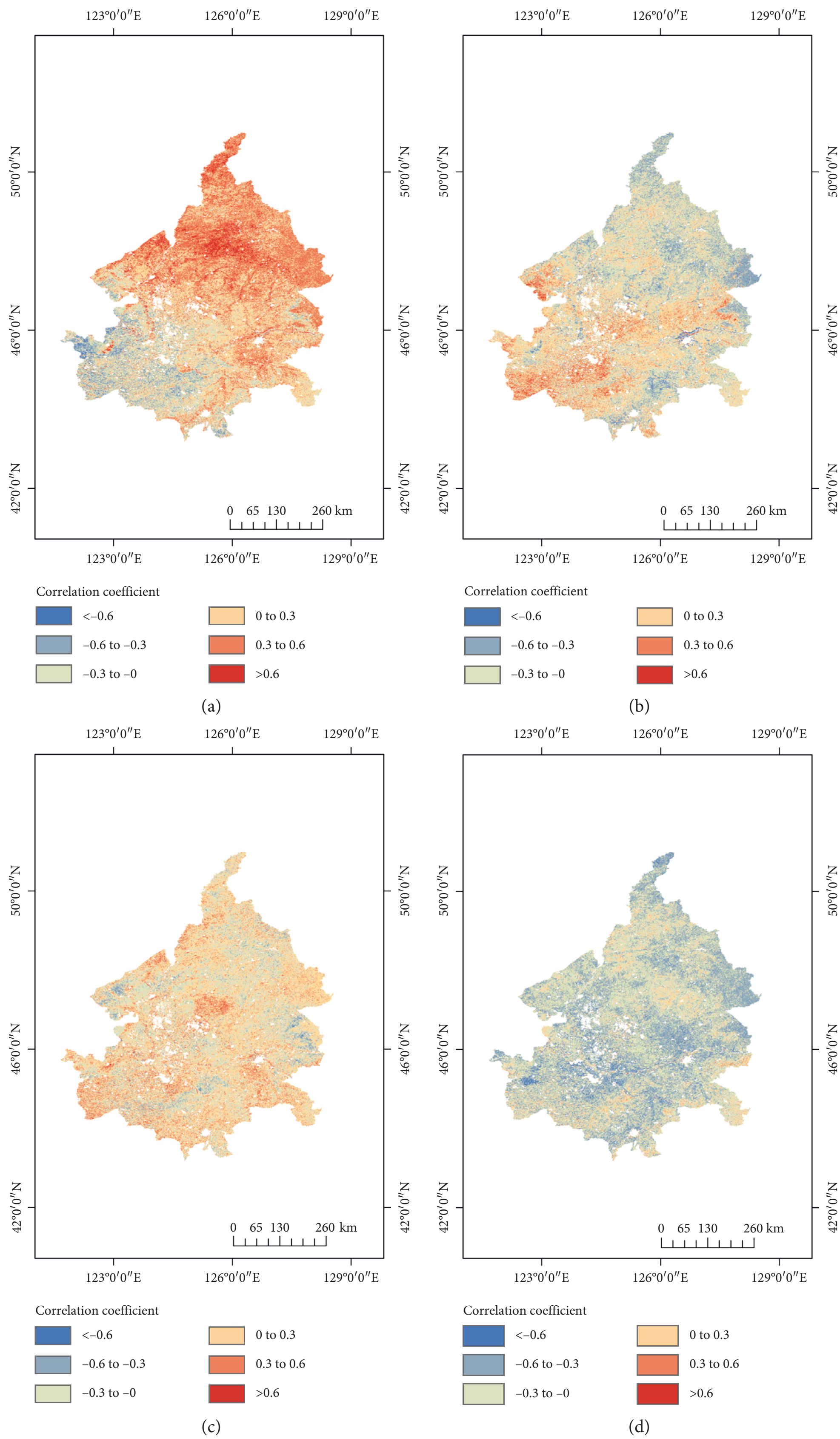


Figure 5: Correlation coefficients between WUE and major climatic factors: (a) annual precipitation, (b) total annual sunshine duration, (c) annual average relative humidity, and (d) annual average temperature.

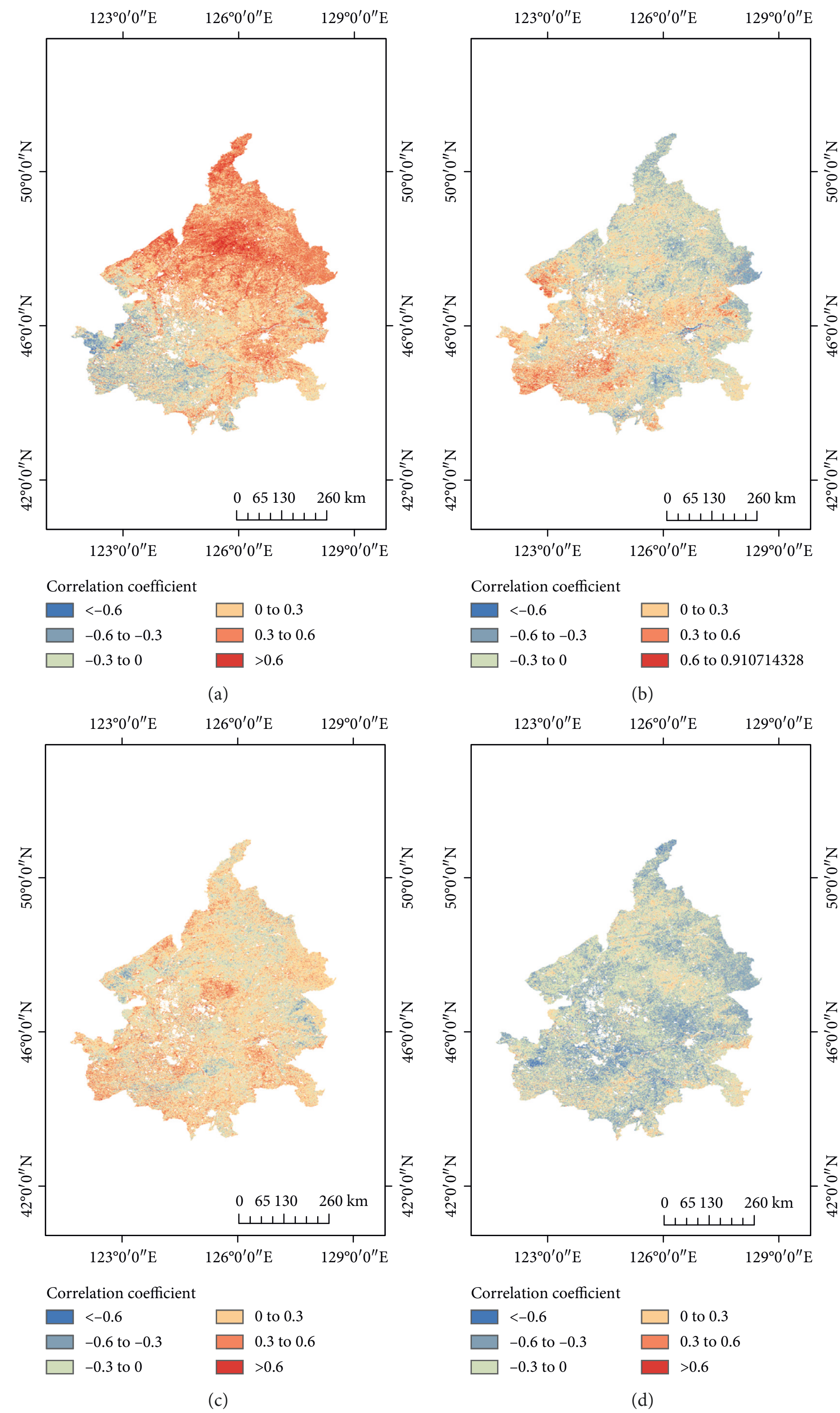


Figure 6: Correlation coefficients between CUE and major climatic factors: (a) annual precipitation, (b) total annual sunshine duration, (c) annual average relative humidity, and (d) annual average temperature.

than 65% of the wetlands showed increased sunshine, while CUE declined. The annual relative humidity was positively correlated with ecosystem CUE in the Northeast fringe and the southwestern region. By contrast, CUE values in more than 60% of the pixels had positive responses to annual relative humidity. The annual average temperature had a

Table 1: Area percentages of the correlation coefficients between WUE, CUE, and climate factors (significant positive correlation ($r > 0$, $p < 0.05$): no significant positive correlation ($r > 0$, $p < 0.05$), no significant negative correlation ($r < 0$, $p > 0.05$), and significant negative correlation ($r < 0$, $p < 0.05$)).

	Correlation	Precipitation	Sunshine duration	Relative humidity	Temperature
WUE	Significant positive correlation	8.21	1.99	17.48	0.27
	No significant positive correlation	67.18	32.11	73.28	33.62
	No significant negative correlation	24.06	59.15	9.22	64.54
	Significant negative correlation	0.55	6.75	0.02	1.57
CUE	Significant positive correlation	10.45	1.59	1.42	0.04
	No significant positive correlation	61.82	41.45	59.54	12.98
	No significant negative correlation	26.29	54.39	38.61	80.30
	Significant negative correlation	1.44	2.57	0.43	6.68

negative correlation with the CUE of ecosystems over most of the area (87% of the pixels).

Overall, it might be concluded that annual precipitation could improve WUE and CUE of the forestland but inhibited the grasslands' WUE and CUE. The total annual sunshine duration had a negative impact on wetland WUE and CUE changes. The annual relative humidity was not only positively correlated with the CUE of all the vegetation types in the SNP but also played a positive role in the WUE of most forestland. This indicated that the forestland WUE was improved with increased rainfall. Therefore, the net productivity generated by limited water resources would be increased. The lower wetlands WUE and CUE were potentially correlated with longer sunshine hours. The respiration of vegetation might be enhanced, and more carbon dioxide would be released. In areas with relatively lower temperatures, greater WUE and CUE of vegetation generally could be observed while vegetation respiration decreased.

3.4. Human Influence on WUE and CUE Changes. To analyze the impact of human activities on WUE and CUE changes, the residual trend method was adopted. Based on the results of correlation analysis, there was a weak linkage between temperature and WUE and CUE variations at an annual scale. We selected precipitation, total annual sunshine duration, and annual average relative humidity to perform a regression analysis. Pixel-scale predicted WUE and CUE were calculated by a linear regression model using WUE, CUE, and the above three climatic factor maps. The predicted WUE or CUE indicated the climatic impacts, whereas their observed values were the combined results of climatic and anthropogenic factors. Thus, the residual value between the predicted and observed values might be regarded as the human influence on WUE or CUE.

According to Figure 7, the regional average residual value of WUE in the SNP declined with an undulating trend during the past 15 years. It kept increasing in the first two years and started to decrease from the year 2003. During 2001–2015, the residual was positive ($\varepsilon > 0$), indicating that human activities played a positive role in WUE changes. The decreasing trend in WUE residual might be associated with a weakening human impact. Except for 2003, the CUE residual values were negative, implying the negative effects of anthropogenic factors on CUE changes. The declined trend of the CUE residual suggested that the effects of human activities might decrease.

Spatially, the regions showing positive trends of WUE and CUE residuals accounted for 0.49% and 0.4% of the total area, indicating that the impacts of human activities on ecosystem WUE and CUE might increase (Figures 8(a) and 8(b)). Conversely, the areas showing negative trends of residuals occupied more than 99% of the SNP, implying the human effects on ecosystem WUE and CUE tended to weaken. The pixels showing declined residuals were mainly found in the western part of the study area, dominated by cropland, grassland, and wetland. The trends of WUE and CUE residuals passed the significance level test at $p < 0.1$ and $p < 0.05$, respectively.

4. Discussion

4.1. Variations of WUE and CUE. As an important indicator of terrestrial ecosystems responding to global change, WUE links carbon and hydrological cycles of vegetation ecosystems [37]. Due to the varied photosynthesis capabilities of different types of vegetation, there should exist certain differences in WUE and CUE [38]. We compared the WUE estimated by different research studies (Table 2). Lu and Li quantitatively estimated and analyzed the spatial and temporal dynamic patterns and seasonal variations of WUE for different vegetation ecosystems in western China in 2002. They found that the average annual WUE of the main vegetation ecosystems in this region showed a downward trend as follows: mountain forest > desert shrub > irrigated farmland > alpine grassland > cold desert and Gobi [42]. Qiu et al. reported that the annual average WUE of woodland was significantly higher than for other vegetation types in China. The annual average WUE of the mixed forest and deciduous broad-leaved forest was the highest, while the annual average WUE of the shrubs and grasslands was lower ($<1\ gC \cdot kg^{-1}H_2O$) [43]. In our current study, the annual average WUE of the main vegetation ecosystem in the SNP followed a descending order of deciduous broad-leaved forest > mixed forest > grassland > deciduous coniferous forest > cropland > wetland. The regional average WUE in the SNP was $1.073\ gC \cdot kg^{-1}H_2O$ for the period of 2001–2015, which was consistent with the threshold of estimated WUE in China [43]. Liu et al. found that annual average WUE of the forest or grassland in Northeast China showed less interannual variability during 2002–2013 [44]. In this

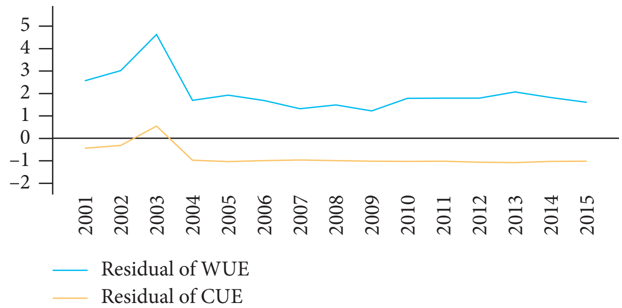


Figure 7: Trends of WUE and CUE residuals in the SNP from 2001 to 2015.

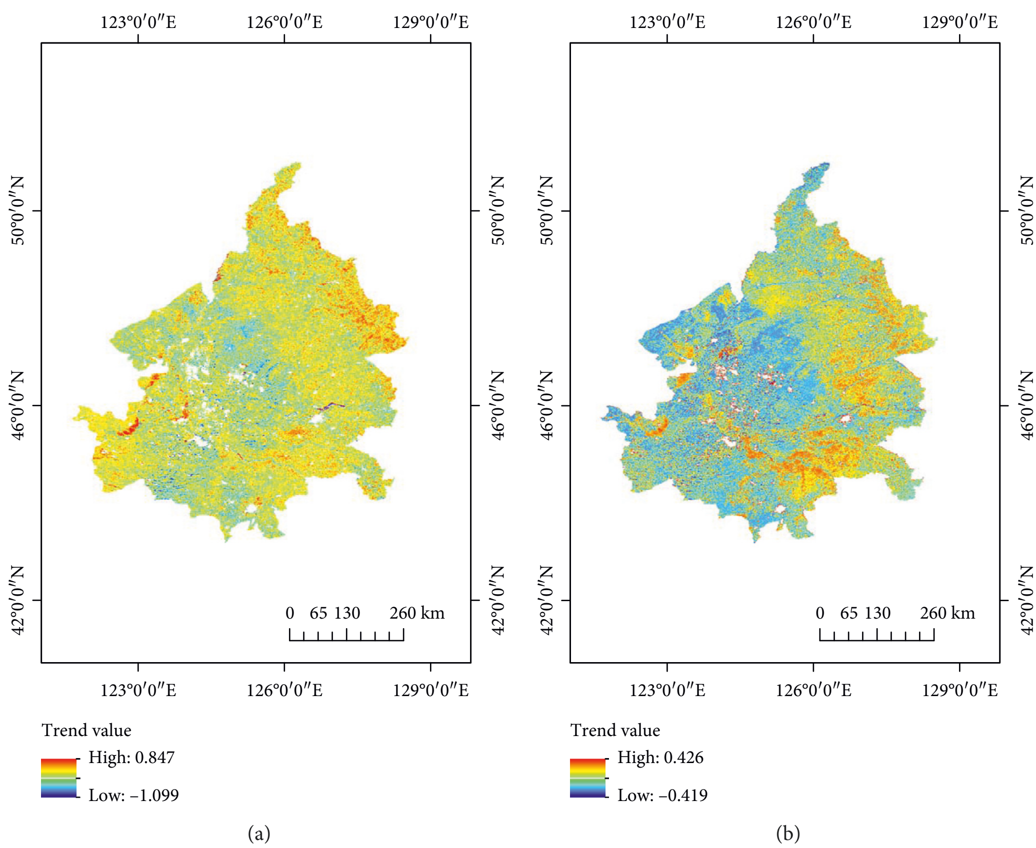


Figure 8: Spatial distribution of WUE and CUE residuals in the SNP from 2001 to 2015: (a) spatial distribution of WUE residual changes and (b) spatial distribution of CUE residual changes.

temperate semihumid to semiarid transitional region of Northeast China, we found that the interannual differences in the annual average WUE were relatively large from 2001 to 2015. The average WUE of the cropland decreased by 1%, while the average WUE of mixed forest, deciduous broad-leaved forest, and deciduous coniferous forest increased by 40%, 32.9%, and 19.6%, respectively.

CUE is sensitive to environmental conditions and climate change [45]. As the function of GPP, NPP, and respiration, the CUE of vegetation (for instance, forest) may be affected by many factors such as temperature, precipitation, photosynthetically active radiation, and soil nutrients [46]. CUE showed significant spatial variations associated with different ecosystems, geographical location, and climate [20]. Chambers et al. revealed that the CUE of temperate forests was approximately 0.50 [47]. Khalifa et al. estimated the CUE of different vegetation in the sub-Saharan area and found that the annual average CUE decreased in the following sequence: cropland > wetland > grassland > mixed forest > evergreen broad-leaved forest > deciduous broad-leaved forest [21]. Our results showed that the average annual CUE of different vegetation in the SNP followed a descending order of grassland (0.567) > wetland (0.542) > deciduous coniferous forest (0.533) > cropland (0.510) > mixed forest (0.480) > deciduous broad-leaved forest (0.479). The CUE of grassland was higher than those of the deciduous coniferous and broad-leaved forest, possibly due to the lesser investment in respiring plant tissue relative to

Table 2: Comparison of WUE estimated by different researches.

Vegetation type	WUE ($gC{\cdot}kg^{-1}H_2O$)	Data source
Wetland	—	Wei [39]
	—	DLEM model [40]
	0.869	Xia [41]
	0.954	Our article
Cropland	0.82	Wei
	0.54	DLEM model
	0.908	Xia
	0.961	Our article
Grassland	0.77	Wei
	0.75	DLEM model
	0.827	Xia
	0.978	Our article
Mixed forest	0.85	Wei
	0.96	DLEM model
	1.077	Xia
	1.158	Our article
Deciduous broad-leaved forest	1.04	Wei
	0.91	DLEM model
	1.018	Xia
	1.328	Our article
Deciduous coniferous forest	0.71	Wei
	0.96	DLEM model
	0.943	Xia
	0.972	Our article

forests; the same result was reported by Law et al. [48]. The annual average CUE of the SNP was 0.520 and showed a steady trend, which was consistent with the threshold value of the global terrestrial ecosystem CUE estimated by Zhang et al. [20]. During the past 15 years, the increase in CUE of forest ecosystems in the SNP could be a positive sign of an enhancement of their efficiency, which has great potential for carbon sequestration. However, the decreased CUE of grassland, cropland, and wetland ecosystems in the SNP indicated their diminished efficiency in assimilating CO_2 and reducing the CO_2 in the atmosphere for the period of 2001–2015.

4.2. Relationships between WUE and CUE Changes, Climate Factors, and Human Activity. Climate factors could affect the changes of carbon fluxes. There have been different conclusions about the effect of precipitation on vegetation WUE to date. In the current study, we found that the WUE of ecosystems in the SNP was significantly and positively correlated with annual average precipitation and relative humidity, while it was negatively correlated with total sunshine duration and annual average temperature. In the regions with more annual average precipitation, annual total sunshine hours tend to be shorter, possibly resulting in less evapotranspiration and higher WUE. Han and Wan noted that temperature had an inhibitory effect on WUE in the grassland region of northern China, whereas precipitation might promote WUE on the ecosystem scale [49]. The annual average relative humidity can reflect the annual average precipitation to a certain extent, and its impact mechanism on vegetation WUE and CUE is similar to that of precipitation. Jiang found that, as the drought increased, the WUE of vegetation in the Northeast China Transect (NECT) gradually increased to a certain value and then decreased, indicating that there was a specific threshold of plant WUE in terms of the drought degree [50]. However, few studies on the relationship between precipitation and WUE at a regional scale in China have been conducted. This may result in a vague understanding of whether ecosystem WUE in China shows a trend of increasing first and then decreasing with the increase of annual precipitation. It is also unclear how high the annual precipitation will be when WUE reaches its peak [51].

Zhang et al. indicated that CUE tended to decrease with the increase of precipitation in the regions with annual precipitation less than 2300 mm at the global scale. Illumination is one of the driving forces of plant photosynthesis. Photosynthesis of plants can only be performed within a certain range of radiation [20]. With light intensity decreasing, the maintenance respiratory rate decreased, while the growth respiration coefficient increased, resulting in the decrease of plant CUE [52]. Marthews et al. simulated the carbon balance of six tropical forest plots in the Andes-Amazon. They indicated that forest CUE did not show a consistent trend with changing altitude and temperature. The CUE value was close to a median of 0.5, which was mainly related to the balance between growth respiration and maintenance respiration of the forest canopy [53]. Zhang et al. analyzed the global pattern of NPP to GPP ratio and noted that the ratio might increase as the temperature decreased between 20°C and 27°C [20], which is roughly similar to our finding.

Human interference and management measures may also have an impact on WUE and CUE changes. According to the study of Liu and Ren, the increases of vegetation coverage and WUE in the Loess Plateau were mainly attributable to ecological restoration projects such as returning cropland to forest [54]. Hirata et al. thought that carbon sequestration of forest ecosystems was primarily sensitive to the influence of climate, given the low intensity of human disturbances [55]. On the other hand, human activities such as fertilization and irrigation may affect vegetation CUE. Ryan et al. demonstrated that biomass and respiration of plant fine roots decreased due to irrigation and fertilization, and forest CUE increased through experiments on a 20-year-old *Pinus radiat*a plantation [56]. The increase in soil nutrient use efficiency may reduce the growth of fine roots, promote dry wood production, and increase the aboveground part of CUE, suggesting that human intervention and management measures can cause a transient increase in aboveground CUE [57]. In this study, our results revealed the opposite effects of human activities on WUE and CUE variations in the SNP. Anthropogenic causes might play positive roles in WUE changes but had negative influences on CUE. Tian et al. indicated that a total of 9155.53 km^2 of grassland was converted into cropland in the SNP during 1986–2010 [58]. By using MCD12Q1 land cover data, the major vegetation type changes in the SNP from 2001 to 2015

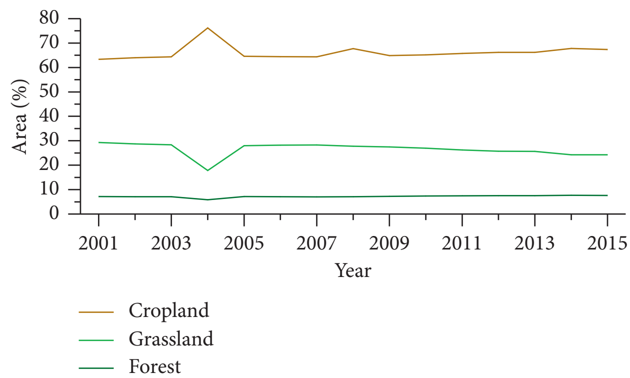


Figure 9: Changes in major vegetation types in the SNP from 2001 to 2015.

were extracted (Figure 9). The cropland increased, the grassland decreased, and the forest remained relatively stable. It was found that the grassland, accounting for approximately 4% of the total pixels, was converted into cropland, which might provide evidence for our hypothesis. The average CUE of grasslands was higher. When the grassland was reclaimed as cropland, the regional CUE thereby decreased. Spatially, due to the high percentage of areas showing the negative residual trends of WUE and CUE, the intensity of human impact tended to weaken in the SNP during the past 15 years.

4.3. Uncertainty. This study investigated spatial and temporal patterns of WUE and CUE in SNP, using time-series remote sensing data with a spatial resolution of 1 km. Generally, uncertainty may be involved while estimating WUE and CUE using public-domain data [59]. The relatively lower spatial resolution of the available remote sensing data may affect the accuracy, especially for high heterogeneous ecosystems. Due to the lack of ground-based measurements, the regional WUE and CUE estimates in this study could not be accurately validated. Precipitation, temperature, sunshine duration, and relative humidity were chosen as the influencing climate factors of regional ecosystem WUE and CUE variations, but solar radiation and CO_2 concentration were not taken into account. The mechanism of the environmental controls of variations in ecosystem WUE and CUE is more complicated. Although a residual analysis may be used to distinguish human influence from climate change influence on WUE and CUE, the effects of other factors, such as management and technology, need to be evaluated further.

5. Conclusions

In this study, spatial and temporal variations of ecosystem WUE and CUE and their relationship with climate and human activity in the SNP were assessed. WUE and CUE differed in different terrestrial ecosystems in the SNP. The multiyear average WUE of the SNP fell in the range of 0.178–8.445 $gC{\cdot}kg^{-1}H_2O$ for the period of 2001–2015, with a mean value of 1.319 $gC{\cdot}kg^{-1}H_2O$. From 2001 to 2015, regional multiyear average CUE values varied from 0 to 0.801. Average WUE of deciduous broad-leaved forest ranked in first place, whereas grasslands possessed the lowest WUE. In contrast, grassland CUE was the highest, while deciduous broad-leaved forest had the lowest CUE. The decreases in WUE and CUE of grassland, cropland, and wetland indicated that their capability of water resources use weakened, and their efficiency in assimilating CO_2 and reducing the CO_2 in the atmosphere decreased. Spatially, the ecosystems' WUE and CUE in almost the entire study area exhibited a decreasing trend over the past 15 years. The regions with a decrease in both WUE and CUE were mainly distributed in cropland and grassland, respectively.

In most areas of the SNP, ecosystem WUE and CUE were positively correlated with annual precipitation and annual average relative humidity for the period of 2001–2015. In contrast, total sunshine duration and annual average temperature had significantly negative correlations with ecosystem WUE and CUE. In the past 15 years, human impact might have facilitated the increase of ecosystem WUE while oppositely restraining the CUE in the SNP, but the extent of these effects decreased.

Data Availability

The whole data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

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

Acknowledgments

This research was supported by the National Natural Science Foundation of China (Grant nos. 41571405 and 41571115) and the key project of the National Natural Science Foundation of China (Grant no. 41630749).

References

[1] R. A. Fischer and N. C. Turner, "Plant productivity in the arid and semiarid zones," *Annual Review of Plant Physiology*, vol. 29, no. 1, pp. 277–317, 1978.

[2] G.-R. Yu, Q.-F. Wang, and J. i. e. Zhuang, "Modeling the water use efficiency of soybean and maize plants under environmental stresses: application of a synthetic model of photosynthesis-transpiration based on stomatal behavior," *Journal of Plant Physiology*, vol. 161, no. 3, pp. 303–318, 2004.

[3] W. G. M. Bastiaanssen, *Remote Sensing in Water Resources Management: The State of the Art*, Iwmi Books Reports, 1998.

[4] X. Mo, S. Liu, Z. Lin, Y. Xu, Y. Xiang, and T. R. Mcvicar, "Prediction of crop yield, water consumption and water use efficiency with a SVAT-crop growth model using remotely sensed data on the north china plain," *Ecological Modelling*, vol. 183, no. 2-3, pp. 301–322, 2005.

[5] S. J. Zwart, W. G. M. Bastiaanssen, C. de Fraiture, and D. J. Molden, "WATPRO: a remote sensing based model for mapping water productivity of wheat," *Agricultural Water Management*, vol. 97, no. 10, pp. 1628–1636, 2010.

[6] A. H. d. C. Teixeira, W. G. M. Bastiaanssen, M. D. Ahmad, and M. G. Bos, "Reviewing SEBAL input parameters for assessing evapotranspiration and water productivity for the Low-Middle São Francisco river basin, Brazil," *Agricultural and Forest Meteorology*, vol. 149, no. 3-4, pp. 462–476, 2009.

[7] F. Li, Z. Zhan, S. Jiang, and J. Xiong, "Remote sensing monitoring on regional crop water productivity in the Haihe river basin," *Journal of Geographical Sciences*, vol. 23, no. 6, pp. 1080–1090, 2013.

[8] Z. M. Y. Hu, G. R. Wang, and F. H. Zhao, "Research progress of water use efficiency in ecosystem," *Acta Ecologica Sinica*, vol. 29, pp. 1498–1507, 2009.

[9] C. Gang, Z. Wang, W. Zhou et al., "Assessing the spatio-temporal dynamic of global grassland water use efficiency in response to climate change from 2000 to 2013," *Journal of Agronomy and Crop Science*, vol. 202, no. 5, pp. 343–354, 2016.

[10] Y. D. P. Zhang, F. X. Gu, and S. R. Liu, "Temporal-spatial variations of WUE and its response to climate change in alpine area of southwest china," *Acta Ecologica Sinica*, vol. 36, pp. 1515–1525, 2016.

[11] G. C. Sun and P. Noormets, "Upscaling key ecosystem functions across the conterminous United States by a water-entric ecosystem model," *Journal of Geophysical Research-Biogeosciences*, vol. 116, p. 2011, 2015.

[12] X. Tang, M. Ma, Z. Ding et al., "Remotely monitoring ecosystem water use efficiency of grassland and cropland in China's arid and semi-arid regions with MODIS data," *Remote Sensing*, vol. 9, no. 6, p. 616, 2017.

[13] S. W. Running and J. C. Coughlan, "A general model of forest ecosystem processes for regional applications I. Hydrologic balance, canopy gas exchange and primary production processes," *Ecological Modelling*, vol. 42, no. 2, pp. 125–154, 1988.

[14] R. Coughlan, "The global carbon cycle: a viewpoint on the missing sink," *Functional Plant Biology*, vol. 21, no. 1, pp. 1–15, 1994.

[15] J. J. Landsberg and R. H. Waring, "A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning," *Forest Ecology and Management*, vol. 95, no. 3, pp. 209–228, 1997.

[16] R. C. Dewar, B. E. Medlyn, and R. E. Mcmurtrie, "Acclimation of the respiration/photosynthesis ratio to temperature: insights from a model," *Global Change Biology*, vol. 5, pp. 615–622, 2010.

[17] C.-W. Xiao, J. C. Yuste, I. A. Janssens et al., "Above- and belowground biomass and net primary production in a 73-year-old Scots pine forest," *Tree Physiology*, vol. 23, no. 8, pp. 505–516, 2003.

[18] S. Piao, S. Luyssaert, P. Ciais et al., "Forest annual carbon cost: a global-scale analysis of autotrophic respiration," *Ecology*, vol. 91, no. 3, pp. 652–661, 2010.

[19] R. R. Nemani, C. D. Keeling, H. Hashimoto et al., "Climate-driven increases in global terrestrial net primary production from 1982 to 1999," *Science*, vol. 300, no. 5625, pp. 1560–1563, 2003.

[20] Y. J. Zhang, M. Xu, H. Chen, and J. Adams, "Global pattern of NPP to GPP ratio derived from modis data: effects of ecosystem type, geographical location and climate," *Global Ecology and Biogeography*, vol. 18, pp. 280–290, 2010.

[21] M. Khalifa, N. A. Elagib, and K. Schneider, "Spatio-temporal variations in climate, primary productivity and efficiency of water and carbon use of the land cover types in Sudan and Ethiopia," *Science of the Total Environment*, vol. 624, pp. 790–806, 2018.

[22] Y. He, S. Piao, X. Li, A. Chen, and D. Qin, "Global patterns of vegetation carbon use efficiency and their climate drivers deduced from MODIS satellite data and process-based models," *Agricultural and Forest Meteorology*, vol. 256-257, pp. 150–158, 2018.

[23] H. Chen, W. Zhang, H. Gao, and N. Nie, "Climate change and anthropogenic impacts on wetland and agriculture in the Songnen and Sanjiang Plain, Northeast China," *Remote Sensing*, vol. 10, no. 3, p. 356, 2018.

[24] B. Zhang, X. Song, Y. Zhang et al., "Hydrochemical characteristics and water quality assessment of surface water and groundwater in Songnen Plain, Northeast China," *Water Research*, vol. 46, no. 8, pp. 2737–2748, 2012.

[25] M. Zhao, F. A. Heinsch, R. R. Nemani, and S. W. Running, "Improvements of the MODIS terrestrial gross and net primary production global data set," *Remote Sensing of Environment*, vol. 95, no. 2, pp. 164–176, 2005.

[26] D. P. Turner, W. D. Ritts, W. B. Cohen et al., "Evaluation of MODIS NPP and GPP products across multiple biomes," *Remote Sensing of Environment*, vol. 102, no. 3-4, pp. 282–292, 2006.

[27] M. A. Ahl, D. Sulla-Menashe, B. Tan et al., "Modis collection 5 global land cover: algorithm refinements and characterization of new datasets," *Remote Sensing of Environment*, vol. 114, no. 1, pp. 168–182, 2010.

[28] Z. C. Zhang Xiaoping and S. Wang, "Quantitative analysis of interpolation DEM accuracy in plain area," *Geospatial Information*, vol. 4, pp. 75–77, 2014.

[29] J. Jin, Y. Wang, Z. Zhang, V. Magliulo, H. Jiang, and M. Cheng, "Phenology plays an important role in the regulation of terrestrial ecosystem water-use efficiency in the northern hemisphere," *Remote Sensing*, vol. 9, no. 7, p. 664, 2017.

[30] N. J. Rosenberg, B. L. Blad, and S. B. Verma, *Microclimate: The Biological Environment*, Wiley, Hoboken, New Jersey, USA, 1974.

[31] J. M. O. Scurlock and D. O. Hall, "The global carbon sink: a grassland perspective," *Global Ecology and Biogeography*, vol. 4, no. 2, pp. 229–233, 2010.

[32] Y. Kwon and C. P. S. Larsen, "Effects of forest type and environmental factors on forest carbon use efficiency assessed using MODIS and FIA data across the eastern USA," *International Journal of Remote Sensing*, vol. 34, no. 23, pp. 8425–8448, 2013.

[33] J. Sun, "Rank correlation coefficient is used to analyze the trend of atmospheric environment change in main cities of our province," *Fujian Environment*, no. 1, pp. 11-12, 1995.

[34] J. Evans and R. Geerken, "Discrimination between climate and human-induced dryland degradation," *Journal of Arid Environments*, vol. 57, no. 4, pp. 535–554, 2004.

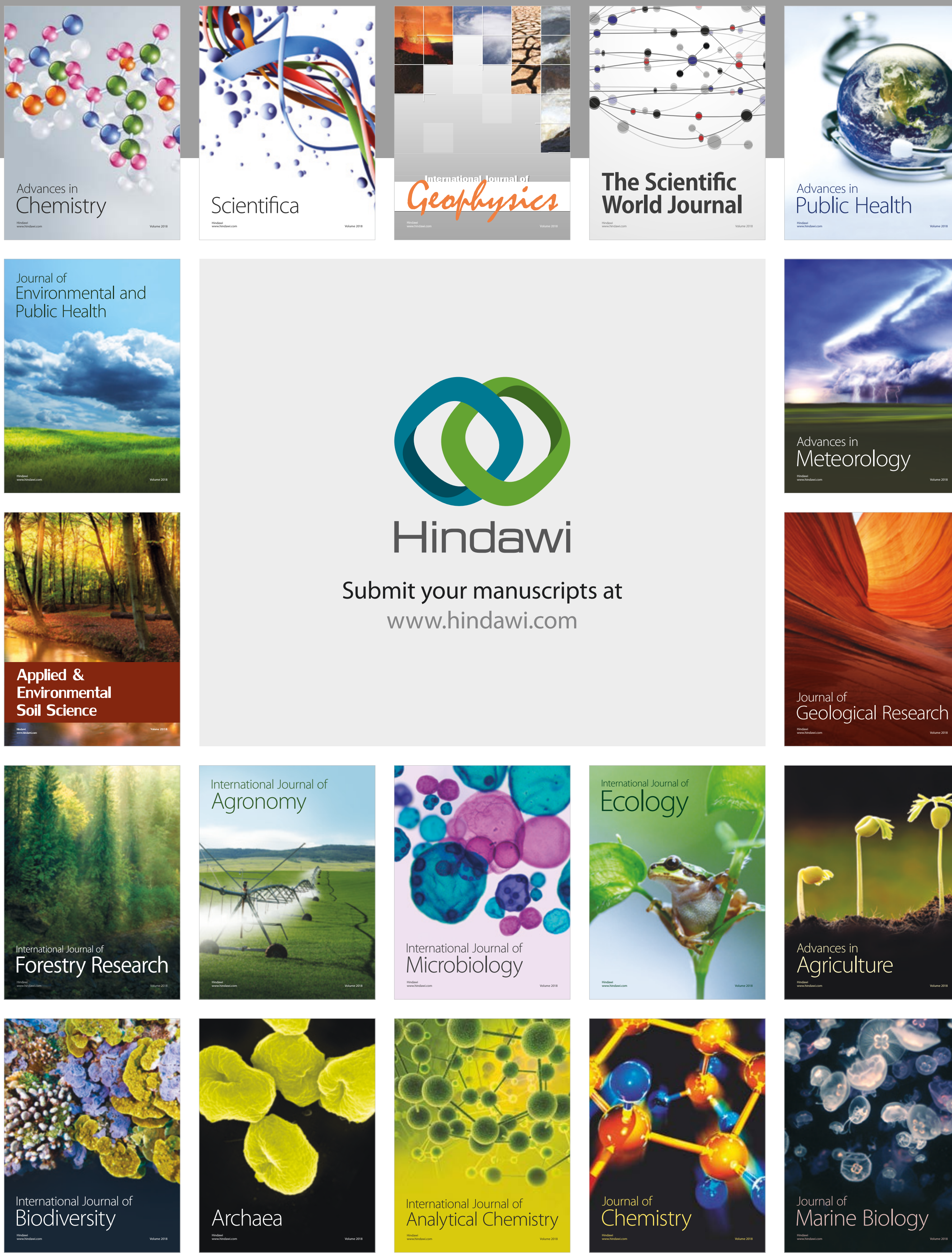
[35] R. Geerken and M. Ilaiwi, "Assessment of rangeland degradation and development of a strategy for rehabilitation," *Remote Sensing of Environment*, vol. 90, no. 4, pp. 490–504, 2004.

[36] Y. Li, J. Fan, and Z. Hu, "Comparison of carbon-use efficiency among different land-use patterns of the temperate steppe in the Northern China pastoral farming ecotone," *Sustainability*, vol. 10, no. 2, p. 487, 2018.

[37] M. G. Ryan, S. Linder, J. M. Vose, and R. M. Hubbard, "Dark respiration of pines," *Ecological Bulletins*, vol. 43, pp. 50–63, 1994.

[38] J. Jin, W. Zhan, Y. Wang et al., "Water use efficiency in response to interannual variations in flux-based photosynthetic onset in temperate deciduous broadleaf forests," *Ecological Indicators*, vol. 79, pp. 122–127, 2017.

[39] Z. Y. Wei Hejie, X. Dong, N. Lu, and X. Wang, "Estimating the spatio-temporal characteristic of vegetation water use efficiency over Weihe River Basin," *Journal of Natural Resources*, vol. 31, pp. 1275–1288, 2016.
[40] A. Ito and M. Inatomi, "Water-use efficiency of the terrestrial biosphere: a model analysis focusing on interactions between the global carbon and water cycles," *Journal of Hydrometeorology*, vol. 13, no. 2, pp. 681–694, 2012.
[41] X. Lei, *Estimation of water use efficiency of global terrestrial ecosystem and heat effect of vegetation loss in man-made land*, Ph.D. thesis, University of Chinese Academy of Sciences, Beijing, China, 2015.
[42] L. Lu and X. H. C. L. Li, "Temporal and spatial characteristics of water use efficiency of vegetation in Western China," *Journal of Glaciology and Geocryology*, vol. 29, pp. 777–784, 2007.
[43] K. B. Qiu, *Estimation of Temporal and Spatial Changes in Total Primary Productivity, Evapotranspiration, and Water Use Efficiency of Vegetation in China*, Beijing Forestry University, Beijing, China, 2015.
[44] D. Liu, C. Yu, and F. Zhao, "Response of the water use efficiency of natural vegetation to drought in Northeast China," *Journal of Geographical Sciences*, vol. 28, no. 5, pp. 611–628, 2018.
[45] M. A. Bradford and T. W. Crowther, "Carbon use efficiency and storage in terrestrial ecosystems," *New Phytologist*, vol. 199, no. 1, pp. 7–9, 2013.
[46] P. Cox, "Description of the 'TRIFFID' dynamic global vegetation model," *Hadley Centre Technical Note*, vol. 24, 2001.
[47] J. Q. T. Chambers, E. S., L. C. Toledo et al., "Rrepiration from a tropical forest ecosystem: partitioning of sources and low carbon use efficiency," *Ecological Applications*, vol. 14, pp. S72–S88, 2004.
[48] B. E. Law, E. Falge, L. Gu et al., "Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation," *Agricultural and Forest Meteorology*, vol. 113, no. 1-4, pp. 97–120, 2015.
[49] Y. Han and S. Wan, "Water-mediated responses of ecosystem carbon fluxes to climatic change in a temperate steppe," *New Phytologist*, vol. 177, pp. 209–219, 2010.
[50] G. M. D. Jiang, "A comparative study on photosynthesis and water use efficiency between clonal and non-clonal plant species along the Northeast China Transect (NECT)," *Acta Botanica Sinica*, vol. 42, pp. 855–863, 2000.
[51] L. X. Zhang and Z. M. F. Hu, "Advances in the spatiotemporal dynamics in ecosystem water use efficiency at regional scale," *Advances in Earth Science*, vol. 29, pp. 691–699, 2014.
[52] J. M. Frantz and B. Bugbee, "Acclimation of plant populations to shade: photosynthesis, respiration, and carbon use efficiency," *Journal of the American Society for Horticultural Science*, vol. 6, 2005.
[53] T. R. Marthews, Y. Malhi, C. A. J. Girardin et al., "Simulating forest productivity along a neotropical elevational transect: temperature variation and carbon use efficiency," *Global Change Biology*, vol. 18, no. 9, pp. 2882–2898, 2012.
[54] X. F. H. Liu and Z. Y. Ren, "Spatiotemporal variation of water use efficiency and its driving forces on the loess plateau during 2000–2014," *Scientia Agricultura Sinica*, vol. 51, pp. 302–314, 2018.
[55] R. Hirata, N. Saigusa, S. Yamamoto et al., "Spatial distribution of carbon balance in forest ecosystems across East Asia," *Agricultural and Forest Meteorology*, vol. 148, no. 5, pp. 761–775, 2008.
[56] M. G. Ryan, R. M. Hubbard, S. Pongracic, R. J. Raison, and R. E. Mcmurtrie, "Foliage, fine-root, woody-tissue and stand respiration in Pinus radiata in relation to nitrogen status," *Tree Physiology*, vol. 16, no. 3, pp. 333–343, 1996.
[57] H. V. A. Mäkelä, "Modeling forest stand dynamics from optimal balances of carbon and nitrogen," *New Phytologist*, vol. 194, p. 961, 2012.
[58] Y. N. Tian, X. D., and S. Y. Zang, "The research on the spatial pattern change of land use degree in songnen plain from 1986 to 2010," *Natural Science Journal of Harbin Normal University*, vol. 32, pp. 101–107, 2016.
[59] X. Tang, H. Li, A. R. Desai et al., "How is water-use efficiency of terrestrial ecosystems distributed and changing on earth?," *Scientific Reports*, vol. 4, p. 7483, 2014.


Advances in Chemistry
Scientifica
International Journal of Geophysics
The Scientific World Journal
Advances in Public Health
Journal of Environmental and Public Health
Advances in Meteorology
Applied & Environmental Soil Science
Hindawi
Submit your manuscripts at
www.hindawi.com
Journal of Geological Research
International Journal of Forestry Research
International Journal of Agronomy
International Journal of Microbiology
International Journal of Ecology
Advances in Agriculture
International Journal of Biodiversity
Archaea
International Journal of Analytical Chemistry
Journal of Chemistry
Journal of Marine Biology