RESEARCH ARTICLE

Assessing the spatiotemporal variation of NPP and its response to driving factors in Anhui province, China

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Abstract

Net primary productivity (NPP) of terrestrial ecosystems is an important metric of ecosystem functioning; however, the understanding of response mechanism of NPP to influencing factors and driving mechanisms are still limited. In this study, taking Anhui province as an example, spatio-temporal changes of NPP and its response to influencing factors were investigated for evaluating the effects of climate change and land use and land cover change (LUCC) on regional NPP. The Carnegie–Ames–Stanford Approach (CASA) model was employed for NPP simulation by using the MODIS normalized difference vegetation index (NDVI) data and meteorological data over 2001–2016. Combined domestic LUCC, the spatiotemporal distribution pattern and dynamic change characteristics of NPP under a long time series and its response to climate factors and human activities were analyzed in the Anhui province. The results indicated that from 2001 to 2016, total NPP had a fluctuated and decreased trend with the variation range between 30.52 and 38.07 TgC in Anhui province. The multi-year average of total NPP was about 34.62 TgC. The highest value was in 2008 and the lowest value was in 2011. Among them, amount of forestland NPP was the most. The spatial distribution of NPP shows that the high value area was mainly distributed in southern Anhui mountain areas and western Anhui Dabie mountain areas; the lower value was distributed in the middle in the study area. The area of which the NPP showed a slight decrease and essentially unchanged accounted for 59.35% and 31.82%, respectively. In general, the correlation between vegetation NPP and temperature was greater than that between precipitation. The vegetations NPP of eight land use types were all positively correlated with temperature. However, the other seven types of land use were negatively correlated with precipitation except cultivated land. In the past 16 years, the decrease of cultivated land areas and the increase of urban and construction land areas contributed a lot to the decrease of vegetation NPP in Anhui province. The NPP changes of different land use types were closely related to climatic factors, land cover area, and vegetation types.

Keywords Anhui province · NPP · CASA model · Climatic factors · Land use types

Introduction

Net primary productivity (NPP) of vegetation refers to the difference between the amount of organic matter produced by green plants through photosynthesis and the amount of organic matter consumed by autotrophic respiration per unit

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time and area ((Lijun et al., 2002); Lieth and (Dengkai et al., 2018; Helmut & Whittaker Robert, 1975)). NPP not only represents the growth status and health degree of vegetation in the ecosystem (Fujun et al., 2011; Wei et al., 2018; Jun et al., 2018), but also is an important indicator to measure the exchange of CO_2 between the atmosphere and the surface and a major factor to regulate the process of the ecosystem (Bao et al., 2016; Dengkai et al., 2018; Wang et al., 2018a; Wang et al., 2018b; Wang et al., 2018c; Wang et al., 2018d). It plays an important role in global change and the carbon cycle (Field Christipher et al., 1998; Ruimy et al., 1994). Since the 1960s, a number of NPP estimation models have been developed around the world (Shilong et al., 2001; Chengming et al., 2015). Due to different operating mechanisms, these models can be divided into four categories: climate models (such as Miami model and Thornthwaite Memorial model, Chikugo

model, Beijing model, and Zhou Guangsheng model, etc.), ecological process model (such as the BEPS model, Biome-BGC model, the CENTURY model, etc.), light energy utilization model (such as GLO PEM model, the VPM model, CASA model and C-Fix model, etc.), and ecological remote sensing coupled model (Changqiao et al., 2017; Bunkei et al., 2004; Potter Christopher et al., 1993; Veroustraete et al., 2002). Among them, the improved CASA model is widely adopted by domestic scholars. CASA model is used to calculate NPP based on vegetation physiological process, photosynthetic effective radiation absorbed by vegetation and light energy utilization rate. Compared with other models, it has the advantage of requiring fewer remote sensing biophysical input parameters, reducing errors, and achieving more accurate dynamic monitoring of NPP in different regions and at different times.

The dynamic change of NPP is the result of multiple factors such as climate factors, topographic conditions, soil characteristics, vegetation types, human activities, and so on (Wang et al., 2018a; Wang et al., 2018b; Wang et al., 2018c; Wang et al., 2018d; Meiling et al., 2016). However, NPP is more sensitive to change of climate and disturbance of human activities (Xuejia et al., 2018; Yanbiao et al., 2018; Huan et al., 2018).

Climate change affects vegetation growth, which in turn has a greater impact on vegetation NPP. Since the mid-nineteenth century, a large number of scholars have been gradually engaged in the relative research of NPP response to climate factors. Numerous studies have analyzed the response characteristics of terrestrial ecosystem NPP in grassland and sandy land to climate factors, and demonstrated that precipitation was the main influencing factor and had a greater impact on the growth of grassland vegetation than temperature (Shaojie et al., 2013; Zhihui et al., 2017; Wei et al., 2017).

The final impact of human activities is mainly reflected in the change of land use patterns. Change of land use types leads to changes in vegetation growth environment, which in turn leads to changes in vegetation NPP (Yuan, 2018; Yi et al., 2017). The increase of urban construction land caused by urbanization was the main reason for the loss of NPP (Yanbiao et al., 2018). Moreover, human activities played a significant positive role in the increase of NPP in the region, especially the increase of woodland area in land use/cover change driven by the ecological restoration project (Yang et al., 2014a, b). In some sensitive areas, the impact of land use change on vegetation NPP was analyzed, and it demonstrated that land use change was obvious in different periods and landscape types, and NPP difference was significant in Chongqing section of the Three Gorges Reservoir area from 2001 to 2015 (Zhao et al., 2018).

In China, relevant researches on NPP mainly focus on the sensitive and fragile areas of ecological environment, such as the grassland of Inner Mongolia and the alpine grassland of Qinghai-Tibet plateau. Anhui province is located in the central and eastern parts of China, where the terrain conditions are complex and the topography is different from north to south. To a certain extent, the zonal distribution of vegetation is not obvious, resulting in a variety of difficulties in the study, which is rarely studied. Especially in the context of global climate change, climate fluctuations have a significant impact on Anhui's fragile ecosystem. After the great flood occurred in the Yangtze river basin in 1998, the role of land use and cover change (LUCC) in various sections of the basin has attracted the attention of the government and researchers. Anhui province was one of 25 provinces that the Chinese government officially launched in 2000 to convert farmland to forest and grass. In 2010, the Chinese government officially approved the "planning of Wanjiang river city belt to undertake industrial transfer demonstration zone," and the construction of Anhui river city belt to undertake industrial transfer demonstration zone entered the national development strategy. During the 12th 5-year plan period, the strategy of "revitalizing northern Anhui" was carried out. During the research period, many national policies had important influence on land use change in Anhui province. In recent years, some scholars have gradually begun to study the response of NPP to climatic change and land use patterns' change in Anhui province (Wang et al., 2018a; Wang et al., 2018b). Wang et al. estimated the vegetation NPP and its response to climate change in Anhui province from 2018 to 2099 based on CMIP5 model, and the results showed that the correlation between vegetation NPP and precipitation was higher than that between vegetation NPP and temperature (Wang et al., 2018b). It is of great significance to grasp objectively the spatio-temporal process of the change of vegetation NPP and clarify the key factors driving this process in Anhui province, for the development and utilization of land resources in a protective way, as well as the protection of regional ecological environment and the smooth implementation of sustainable development strategy of regional society and economy.

The purposes of this paper are (1) to investigate the spatio-temporal changes of vegetation NPP in Anhui province from 2001 to 2016; (2) to analyze the climate change in Anhui province during 2001–2016 and evaluate the response of vegetation NPP to the climate change in the same period; and (3) to analyze the land use and land cover change in Anhui province from 2001 to 2016 and evaluate the impact of LUCC on vegetation NPP.

Materials and methods

Study area

Anhui province is located in the hinterland of east China with a vast territory which is close to the Yangtze River delta economic zone with Shanghai as the center and radiated by the transfer

demonstration zone of Wanjiang City Belt (Fig. 1). It is the transitional belt between China's coastal and inland hinterland. The Yangtze River and the Yellow River are across the whole territory from west to east. The province is located in between 114° 54′–119° 27′ E and 29° 41′–34° 38′ N with a total area of 139,600 km^2, accounting for about 1.45% of China's land area, ranking the third in the east China and the 22nd in China. It has a remarkable monsoon climate, the climatic feature of which is warm and humid with distinct four seasons. With the Huaihe River as the boundary, the north is for the warm temperate semi-humid monsoon climate, the south is for the subtropical humid monsoon climate zone. Average annual temperature and precipitation on the regional scale is between 14 and 17 °C and 800–1600 mm, respectively. Average frost-free period is 200–250 days. In the study area, plain, hills, and mountains alternate with each other with diversity. The terrain of the province is high in the south and low in the north. The southern terrain is dominated by hills and mountains, while the northern terrain is dominated by plains. Anhui province can be divided into five geomorphic areas: Huaihe plain area, Jianghuai hilly area, Dabieshan mountain area in western Anhui province, Yangtze River impact plain area in central Anhui province, and southern Anhui mountain area, respectively. In recent years, with the development of society, land use, and land cover in Anhui province have changed significantly under the joint influence of natural factors and social factors.

Data and methods

Data source and preprocessing

MODIS-derived composite vegetation indices (MOD13A1) NDVI data with spatial resolution of 500 m and temporal resolution of 16d were obtained from NASA's Web site (https://ladsweb.modaps.eosdis.nasa.gov) from 2001 to 2016. Spatial splicing, resampling, format transformation, and projection transformation of the dataset were performed by using MODIS Reprojection Tools (MRT). Convert original HDF format into Tiff format. Convert original map projection into Albers Equal Area projection. Maximum value composite (MVC) was used to obtain monthly NDVI data. Combined with the administrative zoning map of Anhui province, ArcGIS 10.2 software was used to extract the mask of NDVI data in Anhui province from 2001 to 2016, and the raster images of NDVI were obtained month by month.

　　Climate data was obtained from the monthly dataset of China's surface climate data and the monthly dataset of basic elements of China's meteorological radiation in China meteorological data network (http://data.cma.cn), including temperature, precipitation, and solar radiation during 2001–2016. Meteorological data were interpolated by IDW method with ArcGIS 10.2 software. The raster images of average monthly temperature, monthly precipitation, and monthly solar radiation were extracted with mask by the administrative zoning map of Anhui province.

　　Land cover data (MCD12Q1) from NASA's Web site (https://ladsweb.modaps. eosdis.nasa.gov), with the spatial resolution of 500 m. Based on MRT software and IGBP global vegetation classification scheme, 17 land cover categories were determined. Based on ArcGIS10.2 software and combined with the reality of land use in Anhui province, land cover data from 2001 to 2016 were reclassified into 8 land types, which were cultivated land, woodland, grassland, water area, urban and construction land, wetland, ecotones of natural vegetation, and areas with low vegetation cover, respectively.

CASA model

CASA model is classified as light use efficiency models. It is based on the principle of vegetation remote sensing. The normalized difference vegetation index (NDVI) calculated by remote sensing is used to obtain the fractional photosynthetically active radiation (FPAR). The photosynthetically active radiation (PAR) and FPAR are used to calculate the absorbed photosynthetically active radiation (APAR) to estimate NPP. In the model, NPP is mainly determined by APAR and a light-use efficiency factor (ε) (Zhu, Pan and Zhang, 2007). With the month as the time step, the expression is:

$$NPP(x, t) = APAR(x, t) \times \varepsilon(x, t) \tag{1}$$

　　where x represents spatial position and t represents time; NPP(x,t) is the net primary productivity of vegetation of pixel x in month t (unit, gC/m^{2}M); APAR (x,t) is the absorbed photosynthetically active radiation by pixel x in month t (unit, gC/m^{2}M). $\varepsilon(x,t)$ is the actual light energy utilization rate for the pixel x under t month.

　　APAR depends on the total solar radiation and the characteristics of vegetation itself, which can be expressed by the following formula:

$$APAR(x, t) = SOL(x, t) \times FPAR(x, t) \times 0.5 \tag{2}$$

　　where SOL(x, t) represents the total solar radiation of pixel x in month t (MJ/m^2); constant 0.5 represents the proportion of effective solar radiation (400~700 nm) that can be utilized by vegetation in total solar radiation. The specific calculation method of FPAR(x,t) is shown in the literature (Zhu et al., 2019).

$\varepsilon(x,t)$ estimation According to the points of Potter et al. (1993), the maximum light energy utilization rate of vegetation under ideal conditions is mainly affected by temperature, moisture, and other factors. The calculation formula is as follows:

$$\varepsilon(x, t) = \varepsilon^* \times T_\varepsilon(x, t) \times W_\varepsilon(x, t) \tag{3}$$

where ε^* is the maximum light energy utilization rate of vegetation under ideal conditions, $T_\varepsilon(x,t)$ represents the stress coefficient of temperature on the light energy utilization rate, and $W_\varepsilon(x,t)$ represents the water stress coefficient (Zhu et al., 2019).

Trend analysis

Trend analysis method was employed to analyze the spatial pattern of vegetation NPP change in Anhui province from 2001 to 2016. The calculation formula was as follows:

$$\theta_{slope} = \frac{n \times \sum\limits_{j=1}^{n} j \times NDVI_j - \sum\limits_{j=1}^{n} j \sum\limits_{j=1}^{n} NDVI_j}{n \times \sum\limits_{j=1}^{n} j^2 - \left(\sum\limits_{j=1}^{n} j\right)^2} \qquad (4)$$

In the formula, θ_{slope} was the slope of trend change; n was the research year; NPP_j was the total NPP in year j. When $\theta_{slope} > 0$, it indicated that vegetation NPP showed an upward trend from 2001 to 2016 in Anhui province, and vice versa. According to the variation range of trend, it was divided into five levels, which were significantly decreased ($\theta_{slope} < -5$), slightly decreased ($-5 \leq \theta_{slope} < -1$), essentially unchanged ($-1 \leq \theta_{slope} < 1$), slightly increased ($1 \leq \theta_{slope} < 5$), and significantly increased ($\theta_{slope} \geq 5$).

Correlation analysis

Pearson correlation coefficient was calculated for bivariate correlation analysis of NPP with monthly mean temperature and annual precipitation in Anhui province from 2001 to 2016. The calculation formula was as follows:

$$R_{xy} = \frac{\sum\limits_{i=1}^{n} [(x_i - \bar{x})(y_i - \bar{y})]}{\sqrt{\sum\limits_{i=1}^{n} (x_i - \bar{x})^2 \sum\limits_{i=1}^{n} (y_i - \bar{y})^2}} \qquad (5)$$

In the formula, R_{xy} was the correlation coefficient of two variables x and y; n was the research year; x_i was the total NPP of vegetation in year i; $\bar{x}$ was the average value of vegetation NPP; y_i was the climate factor value in year i; $\bar{y}$ was the average value of climate factor.

Validation of CASA model

To verify the estimation accuracy of the CASA model, the observed NPP values (field-measured NPP) for Anhui grassland vegetation (39 data points) from April to August 2016 was compared with the simulated NPP. Figure 2 presents the results of the correlation analysis between the observed NPP data and estimated NPP ($R^2 = 0.695$, $P < 0.001$), which indicates that the estimation accuracy is satisfactory and that the

CASA model could be used to support research on changes in NPP in Anhui province.

Results

### Spatial and temporal changes of vegetation NPP during the study periods

Interannual variation characteristics of total vegetation NPP

Figure 3 intuitively showed the slight downward trend of annual total NPP in Anhui province from 2001 to 2016. During the 16 years, amount of total NPP ranged from 30.52 to 38.07 TgC. During the study period, there were three peaks and three troughs. The peaks existed in 2005, 2008, and 2013 whose NPP were 37.03 TgC, 38.07 TgC, and 35.14 TgC, respectively. The troughs appeared in 2003, 2006, and 2011 whose NPP value were 33.82 TgC, 36.06 TgC, and 30.52 TgC, respectively. The multi-year average of total NPP was about 34.62 TgC. In 2004, 2005, 2006, 2007, 2008, 2009, and 2013, the total NPP was higher than the multi-year average. In 2016, the total amount of NPP was about 3.12 TgC less than that in 2001.

Spatial distribution characteristics of vegetation NPP

The spatial distribution characteristics of NPP in Anhui province exhibited a nonrandom pattern. Figure 4 shows the spatial variation characteristics of vegetation NPP in Anhui province from 2001 to 2016. Figure 5 shows land use types in Anhui province. On the whole, the features were that the vegetation NPP was more in the south and north and that was less in the middle. The variation range of vegetation NPP was 30.09–345.33 gC/m^2 in the study area. Specifically, the mean NPP was highest in Wannan and Wanxi Dabie mountain areas compared to that in other areas. The main reason may be that these areas were located in the subtropical monsoon humid climate zone with high temperature, rainfall and good hydrothermal conditions. In addition, the mountainous area was large and the altitude was high, and the number of vegetation such as woodland and grassland was more in these regions. Meanwhile, there are a large number of evergreen broadleaved forests in these areas. Among them, the NPP in Huangshan area in Wannan mountains areas was the highest. Besides the reasons listed above, there were also the following two reasons. On the one hand, there were many national key scenic spots in this area with a lot of rare tree species. On the other hand, local people had a strong sense of environmental protection, and the phenomenon of local deforestation was not common. The median area of NPP was distributed in Huaibei plain, which was the main body of Anhui plain with flat terrain and fertile soil. It covered an area of 38,000 km^2. Except

Fig. 1 Location of the study area with the distribution of rivers and weather stations
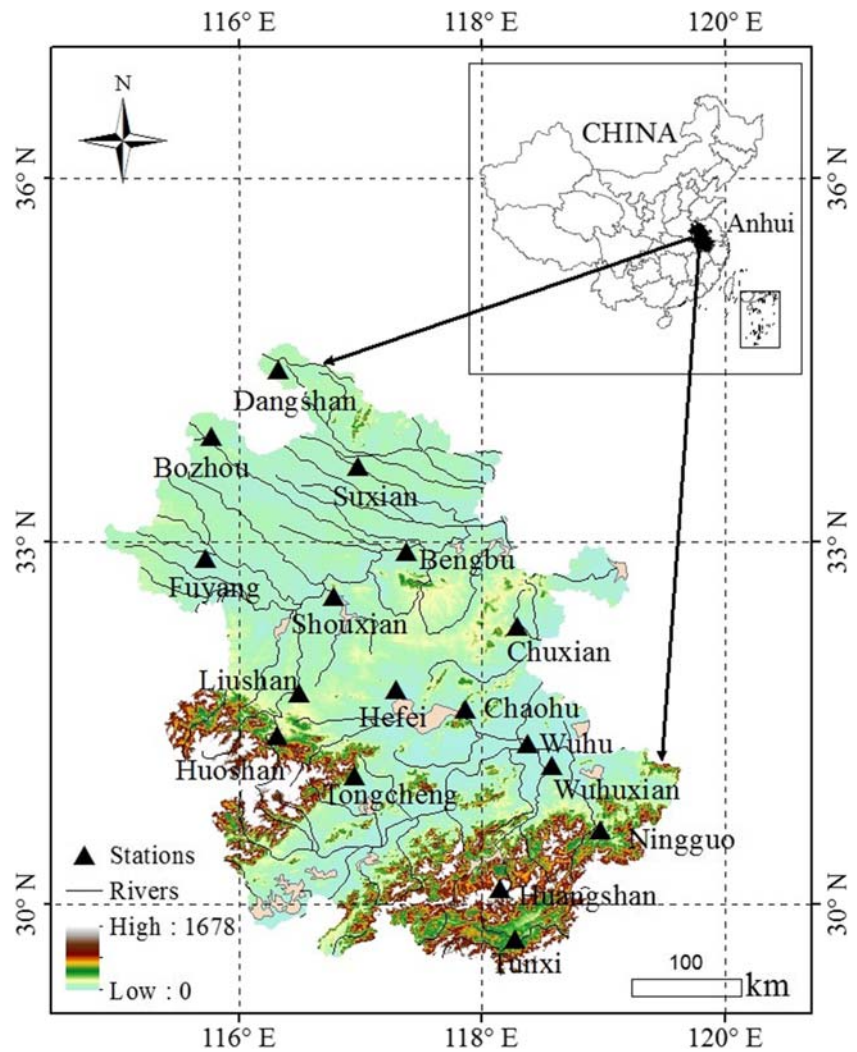
for the small hills in the northeast, most of the area was plain with an elevation of 15–50 m. It also had numerous tributaries throughout the Huaihe River where abundant irrigation water,
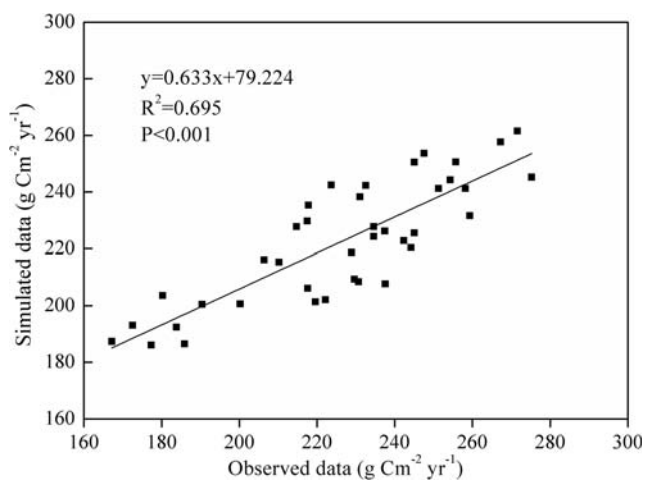

Fig. 2 Correlation between simulated NPP and observed NPP for Anhui province

and unique geographical advantages made it the main grain crop growing area in Anhui province. The representative crops were mainly wheat and corn in this place. The region was located in the humid monsoon climate zone of the warm temperate zone where the climatic conditions determine the vegetation type. The vegetation was mainly deciduous broad-leaved forest. The low value area of NPP was located in the Jianghuai hills and plain areas along the river. The reason for the low NPP was mainly due to the large area of cultivated land, water area, town and construction land, and the areas with low vegetation coverage. In addition, the vegetation was mainly composed of deciduous broad-leaved and ever-green broad-leaved mixed forests.

Trend analysis

Figure 6 shows the spatial distribution characteristics of change trend of vegetation NPP in Anhui province from 2001 to 2016. During these 16 years, about 59.35% of the regions in Anhui province showed a slight decrease in NPP

$$y = -0.2562x + 36.798$$
$$R^2 = 0.2589$$

— Total NPP ——— Average value ········ Trend line(Total NPP)
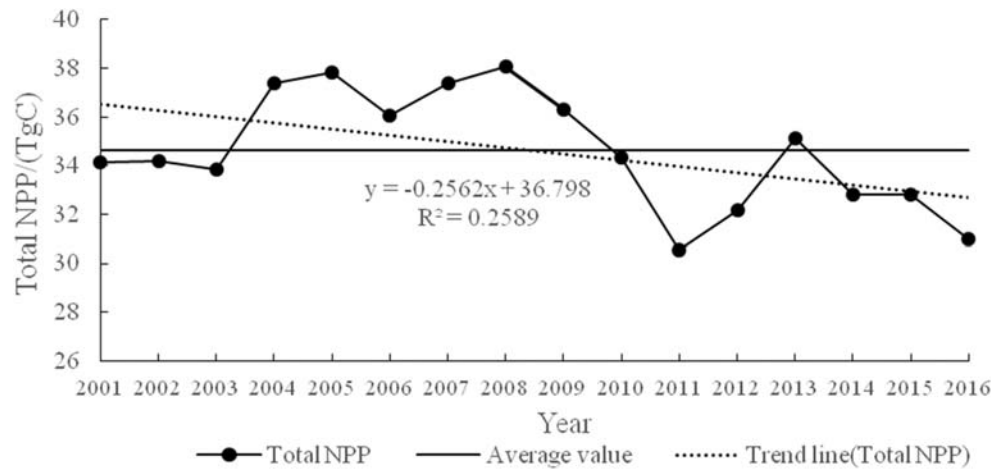
where was scattered throughout the rest of the province except for the sporadic distribution in Dabie mountain areas in western Anhui. The land area of NPP with a significant decreasing trend was less than 1/10 of the province's area which mainly distributed in the plain area along the river and evenly

scattered in the plain area of Huaibei and the hilly area of Jianghuai. About 31.82% of the land area of Anhui province in NPP was in a basically unchanged state which was mainly distributed in the central and southern part of Dabie mountain areas in the west of Anhui province, the northern part of

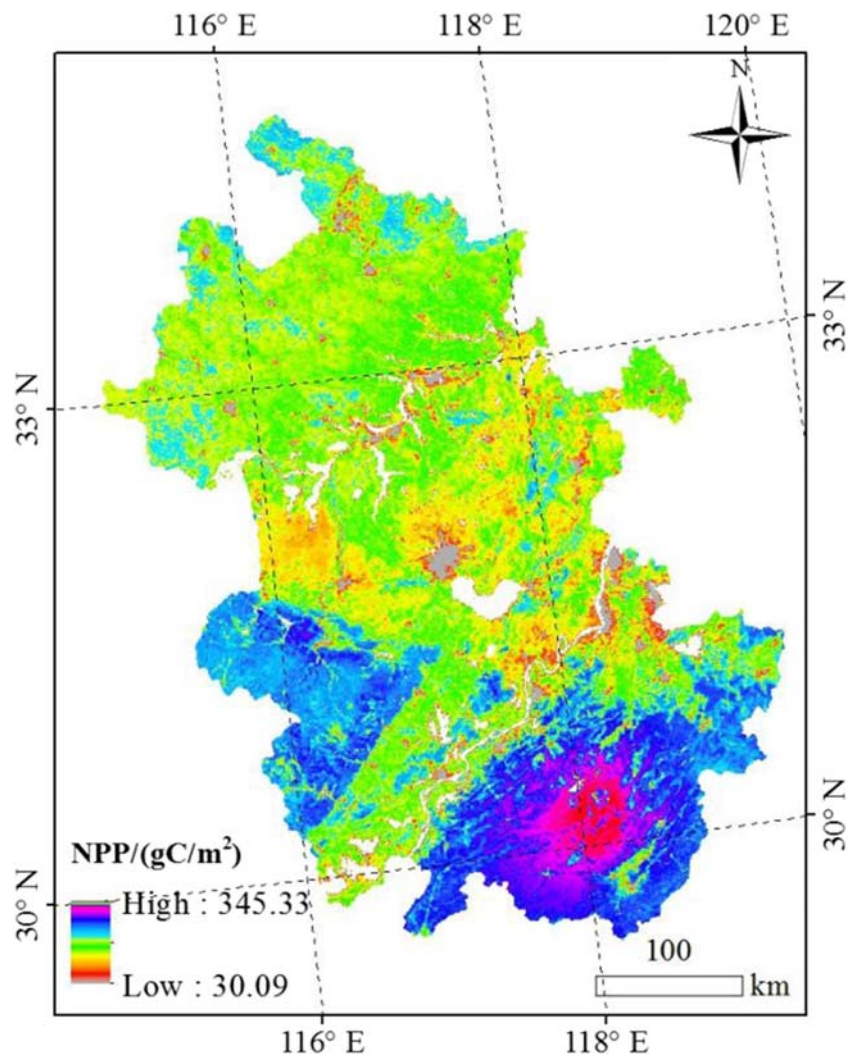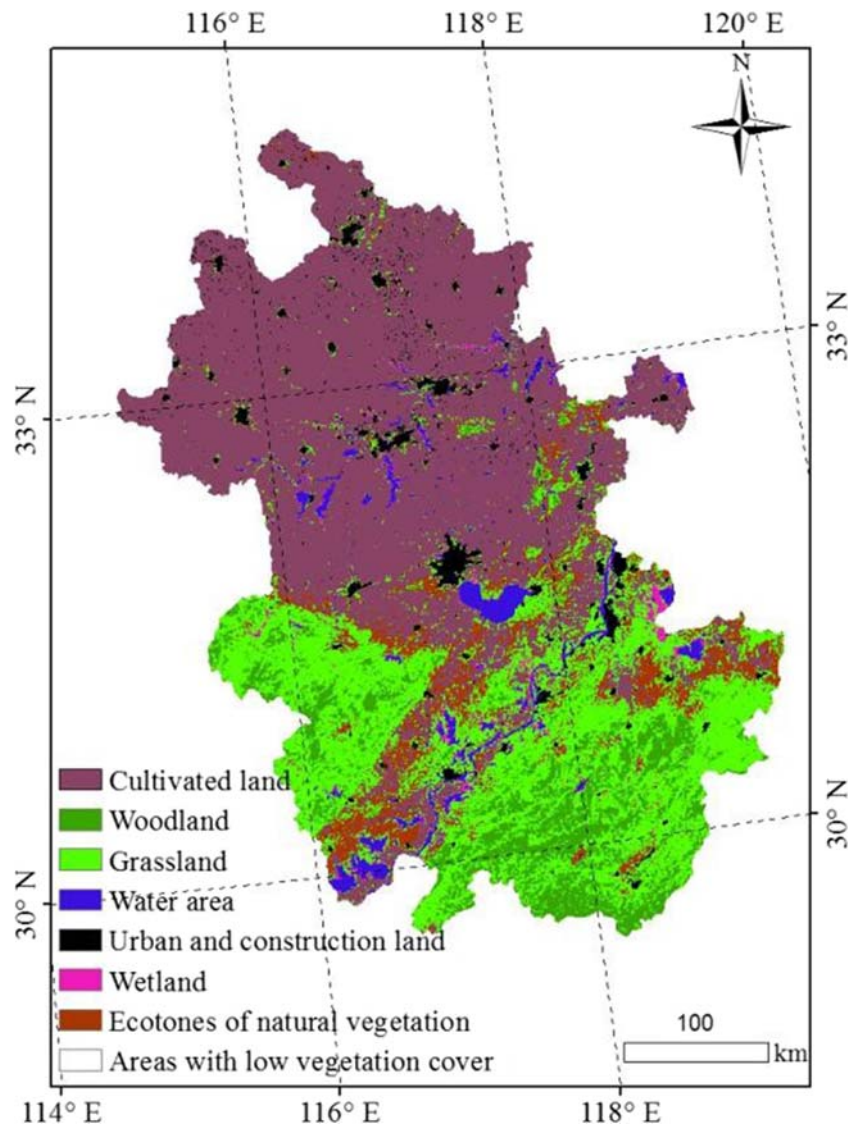Fig. 4 Spatial distribution of vegetation NPP from in Anhui province from 2001 to 2016

NPP/(gC/m²)

High : 345.33

Low : 30.09

Fig. 5 Land use types in the study area

Huaibei plain areas, and the Jianghuai hilly area. Scattered distribution also existed in mountainous areas in the south of Anhui province. The area of NPP with slight increase accounted for 2.14% of the whole province which mainly distributed in the northern part of Dabie mountain areas in western Anhui. However, the areas of land where NPP showed a significant increase were very small, which were only about 0.01% of the province's land area.

Climate change in Anhui province during 2001–2016

The interannual variation characteristics of temperature and precipitation

The average temperature of 16 years was between 15.33 and 16.43 °C with the highest value appeared in 2007 and the lowest value appeared in 2011 (Fig. 7). In 16 years, the average value of monthly mean temperature was about 15.86 °C. The average

annual precipitation from 2001 to 2016 was between 927.97 and 1663.95 mm with the highest value in 2016 and the lowest value in 2001. The average annual precipitation over the years was about 1228.52 mm. During these 16 years, the monthly mean temperature and annual precipitation in Anhui province were in a fluctuating state, with the monthly mean temperature being in a fluctuating downward trend and the annual precipitation being in a fluctuating upward trend. The rate of annual precipitation increased faster than that of the monthly average temperature decreased. This result was consistent with the findings of Wang et al. (2018).

Spatial distribution characteristics of precipitation and temperature

Figures 8 and 9 reveal that there were obvious regional differences in annual precipitation and monthly mean temperature between 2001 and 2016 in Anhui province. The spatial

Fig. 6 Spatial distribution of change trend of vegetation NPP during 2001–2016
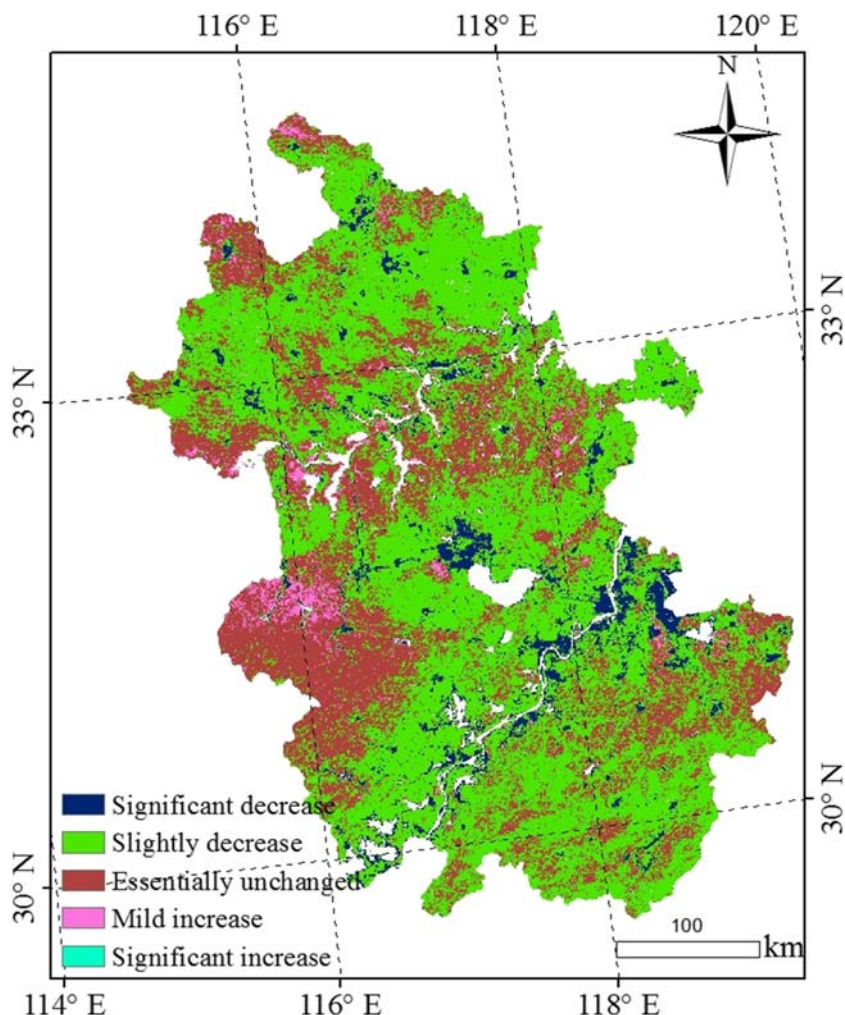

difference of annual precipitation was mainly reflected that in the south was more than that in the north. Except for some parts of Dabie mountain areas, the annual precipitation decreased from south to north in the whole province. The spatial characteristics of monthly mean temperature were that the temperature was low in most parts of southern Anhui mountainous areas and some parts of Dabie mountainous areas due to the influence of higher terrain. And the temperature distribution in other areas exhibited

the distribution characteristic of gradual decrease from the central part to the north and south.

Land use and land cover change in Anhui province from 2001 to 2016

Table 1 shows the land area of each land use type and its percentage in Anhui province during 2001–2016. Four types

Fig. 7 The interannual trend of monthly mean temperature and annual precipitation in Anhui province from 2001 to 2016
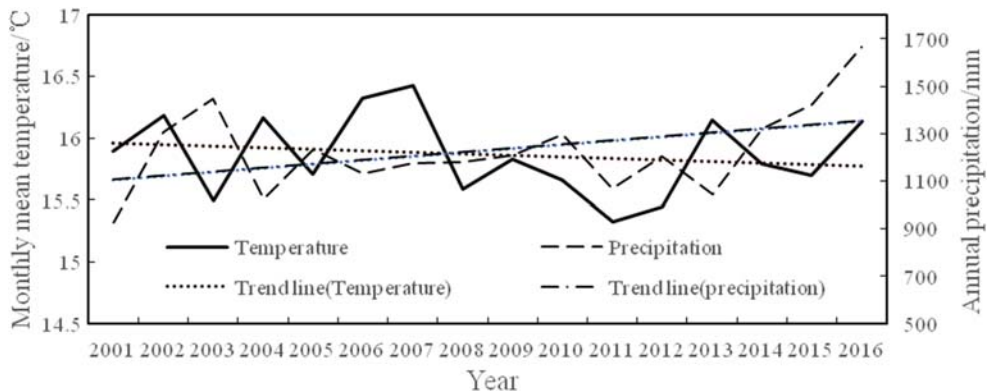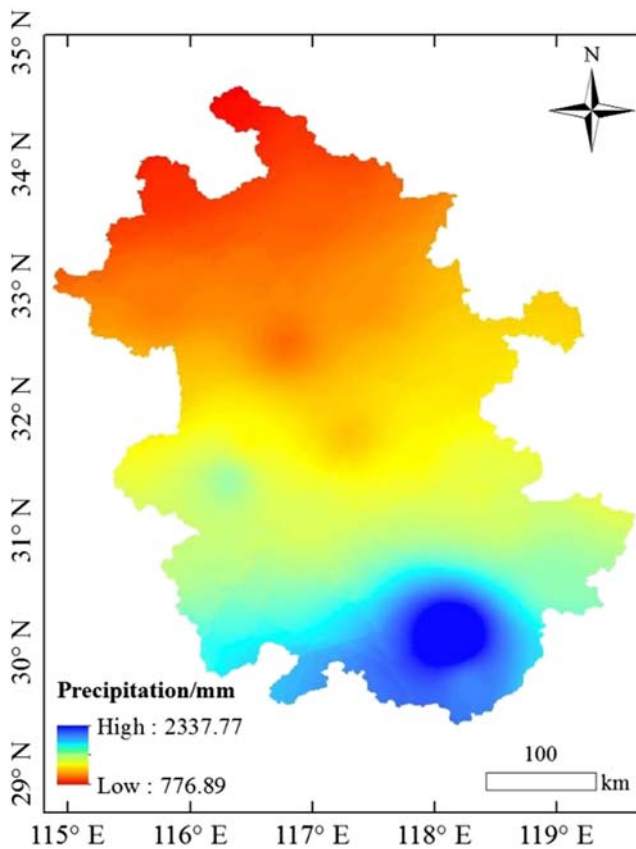
Fig. 8 Spatial distribution of precipitation in Anhui province during 2001–2016
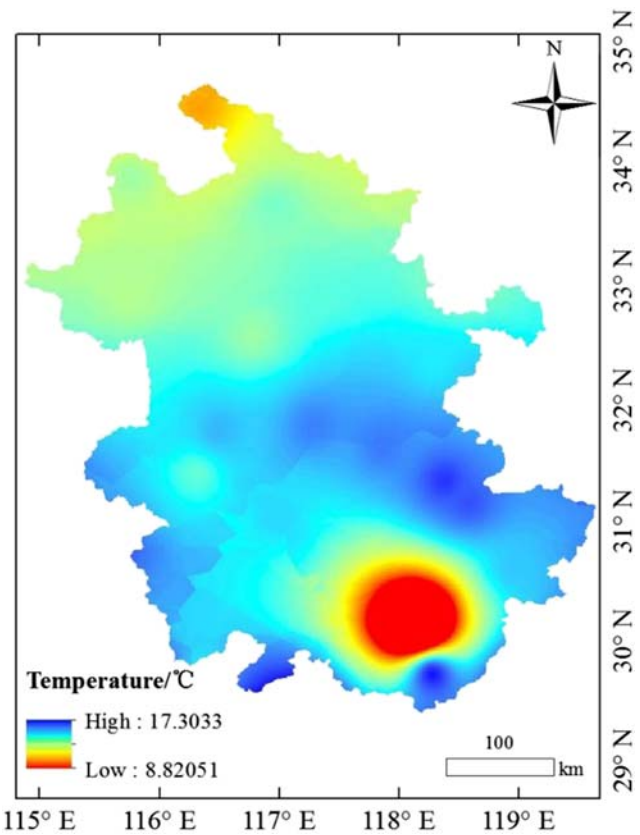

Fig. 9 Spatial distribution of temperature in Anhui province during 2001–2016

of land use with the highest proportion were cultivated land, grassland, woodland, and ecotones of natural vegetation, respectively. Among them, the area of cultivated land was about more than half of the study area. In 2005, the cultivated land's area was the most which was about 72,675.25 km^2 with accounting for 53.43% of the province's land area. The land area with low vegetation coverage was the least. Since 2002, its proportion in the land area of the whole province had remained at 0.01%. During the whole research period, the area of the cultivated land and ecotones of natural vegetation showed the fluctuation and decrease trend of different rates, while the land area of the woodland, grassland, water area, urban and construction land, wetland and areas with low vegetation cover showed the fluctuation and increase trend of different rates.

By comparing the area data of various land use types in 2016 and 2001, the area of cultivated land, grassland, ecotones of natural vegetation, and low vegetation cover land reduced by 2085.75 km^2, 580 km^2, 918.25 km^2, and 4.5 km^2, respectively. However, the area of woodland, water area, urban and construction land and wetland increased by 1666.25 km^2, 30.25 km^2, 1004.25 km^2, and 749.75 km^2, respectively. Among them, the land with the fastest reduction rate and the largest reduction area was cultivated land, the cultivated land areas reduced by 1.44% compared to that in 2001.

Decreased areas of cultivated land were mainly distributed in Huaibei plain areas, Jianghuai hilly areas, and plain areas along the river. The area of woodland, urban, and construction land increased the most with accounting for 1.21% and 0.72% of the province's area, respectively. The increased areas of woodland were mainly distributed in the southern Anhui mountain areas and the Dabie mountain areas in the west of Anhui province. The increased areas of urban and construction land were mainly distributed in the plain area along the river and the Jianghuai hilly areas. The main reason of land use and land cover for the obvious change was that under the support of national policies such as the construction of industrial transfer demonstration zone of Wanjiang City Belt and the implementation of northern Anhui revitalization strategy and northern Anhui rising strategy and so on, the process of new-type industrialization and urbanization was accelerating and the areas of industrial land and urban construction land were increasing in the areas along the river and northern Anhui province. At the same time, Anhui province also belonged to the scope of the national project of returning farmland to forests. On the one hand, people responded positively to the national policies. On the other hand, people's awareness of environmental protection was also increasing. A series of vegetation construction practices such as afforestation and

Table 1   Change of land use area in Anhui province during 2001–2016

Area (km²)	Cultivated land	Woodland	Grassland	Water area	Urban and construction land	Wetland	Ecotones of natural vegetation	Areas with low vegetation cover
2001	72,179	11,402.75	37,256.75	4248	3355.25	1006	10,186.25	22.5
	51.68%	8.16%	26.68%	3.04%	2.40%	0.72%	7.29%	0.02%
2002	72,347.5	11,639	36,853.25	4253.25	3374.25	1046.5	10,122	20.75
	51.80%	8.33%	26.39%	3.05%	2.42%	0.75%	7.25%	0.01%
2003	71,522.75	11,921.75	36,109.5	1144.5	3388.5	694.75	10,198.75	10
	52.98%	8.83%	26.75%	0.85%	2.51%	0.51%	7.56%	0.01%
2004	72,579.75	12,259	35,519.25	1436	3448	768.25	10,203.25	10.25
	53.28%	9.00%	26.07%	1.05%	2.53%	0.56%	7.49%	0.01%
2005	72,675.25	12,700.5	34,727	1351.25	3478	678.5	10,399.25	11
	53.43%	9.34%	25.53%	0.99%	2.56%	0.50%	7.65%	0.01%
2006	72,730.25	12,918.25	34,657.5	1649.75	3527.5	749.75	10,301	12.25
	53.26%	9.46%	25.38%	1.21%	2.58%	0.55%	7.54%	0.01%
2007	72,550.75	13,134.75	35,112	1507.5	3659.5	786.25	9467.75	10
	53.26%	9.64%	25.77%	1.11%	2.69%	0.58%	6.95%	0.01%
2008	72,662	13,137.5	35,095.25	1446.5	3655.5	744.75	9467.25	9.75
	53.34%	9.64%	25.76%	1.06%	2.68%	0.55%	6.95%	0.01%
2009	72,577.25	13,160	35,596	4261	3789.5	1068.2	9191.25	13.25
	51.97%	9.42%	25.49%	3.05%	2.71%	0.76%	6.58%	0.01%
2010	72,638.75	13,174.75	35,791.75	4263.5	3878.5	1125.75	8770.75	12.75
	52.01%	9.43%	25.63%	3.05%	2.78%	0.81%	6.28%	0.01%
2011	72,333	13,109.75	35,998	4255.25	3972	1175.75	8662.5	12.25
	51.84%	9.40%	25.80%	3.05%	2.85%	0.84%	6.21%	0.01%
2012	71,897.5	12,961.25	35,967	4258.75	4052.75	1286.75	9080.25	14.25
	51.53%	9.29%	25.78%	3.05%	2.90%	0.92	6.51%	0.01
2013	71,511.75	12,749.5	36,308.5	4258.5	4129.5	1383.25	9160	17.5
	51.26%	9.14%	26.02%	3.05%	2.96%	0.99%	6.57%	0.01%
2014	71,079	12,777.25	36,575.75	4265.25	4217.5	1478.25	9107.25	18.25
	50.95%	9.16%	26.22%	3.06%	3.02%	1.06%	6.53%	0.01%
2015	70,629	13,015.5	36,568.25	4276.25	4286.25	1610	9113.75	19.5
	50.62%	9.33%	26.21%	3.07%	3.07%	1.15%	6.53%	0.01%
2016	70,093.25	13,069	36,676.75	4278.25	4359.5	1755.75	9268	18
	50.24%	9.37%	26.29%	3.07%	3.12%	1.26%	6.64%	0.01%

conversion of farmland to forest and grass were increasingly practiced making the area of forest land, water area and wetland continuously expand.

Discussion

Response of vegetation NPP to climate change

#### Effects of meteorological factors on vegetation NPP

According to the variation trends of monthly mean temperature, annual precipitation, and total NPP in Anhui province from 2001 to 2016 (Fig. 10), monthly mean temperature showed a slight decline trend, annual precipitation exhibited an upward trend, and total NPP showed a downward trend. Thus, the cold and wet climate was not conducive to the increase of total NPP of vegetation. The results of previous

studies had proved that the warming and wetting of climate was conducive to the increase of total NPP of vegetation. The years 2004, 2005, 2007, 2008, and so on followed this principle. However, there were exceptions in some special years. For example, the monthly mean temperature and annual precipitation in 2013 were similar with 2011, while the total amount of NPP was quite different from each other. The main reason for this phenomenon was caused by the transitional interference of human activities.

Correlation between vegetation NPP and climate factors

The spatial distribution of temperature and precipitation was significantly different under the influence of various factors. Therefore, the correlation between NPP and climate factors was also obviously different in space. Figures 11 and 12 show the spatial distribution of the correlation coefficient between NPP and annual precipitation and monthly mean temperature

Fig. 10 Effects of meteorological factors on vegetation NPP
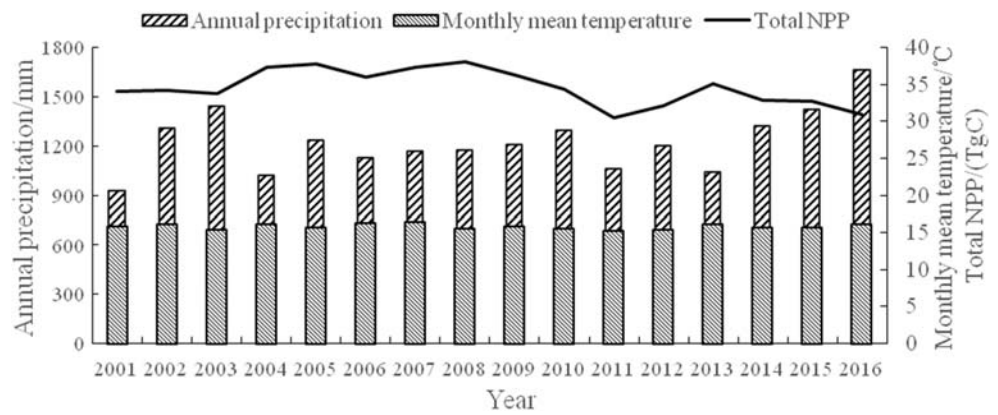
in Anhui province during 2001–2016. As could be seen from the two figures, there were positive and negative correlations between vegetation NPP and annual precipitation and monthly mean temperature. However, the correlation between NPP and monthly mean temperature was greater than that between NPP and annual precipitation (R_T, 0.102; R_P, −0.180). In the study area, the area of positive correlation between NPP and annual precipitation was smaller than that of positive correlation between NPP and monthly mean temperature (positive correlation: R_P, 36.39%; R_T, 63.73%). The area of negative correlation between NPP and annual precipitation was larger than that of negative correlation between NPP and monthly mean temperature (negative correlation: R_P, 63.61%; R_T,

36.27%). The areas of positive correlation between NPP and annual precipitation were mainly distributed in plain areas of Huaibei and hilly areas of Jianghuai. Because these areas were mainly arid areas in Anhui province where the increase of precipitation could alleviate the drought and benefit the growth of crops. The areas of negative correlation between NPP and annual precipitation were mainly distributed in southern Anhui mountains. Because the mountainous areas in southern Anhui were mainly a forest distribution area where the increase of precipitation was not conductive to plant photosynthesis and had an inhibitory effect on the productivity of this region. The regions of positive correlation between NPP and monthly mean temperature were mainly distributed in the
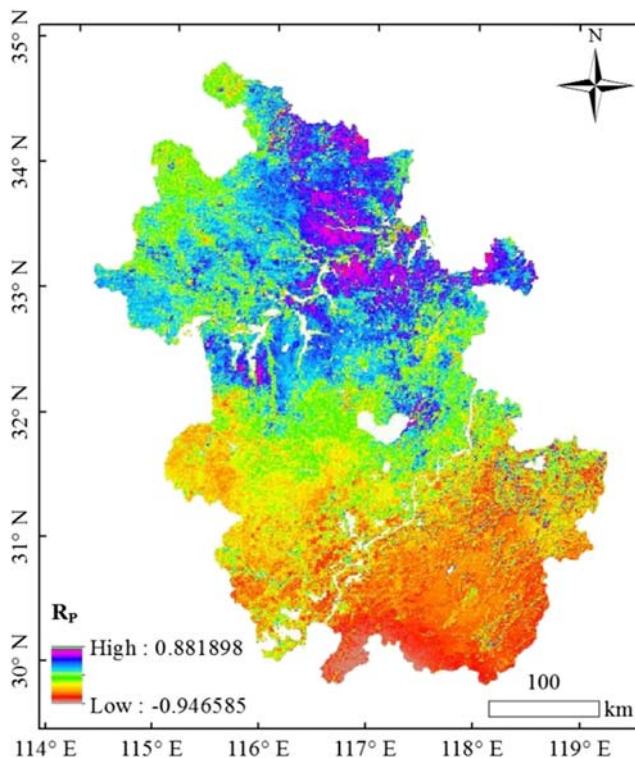

Fig. 11 Correlation relationship between vegetation NPP and annual precipitation in Anhui province during 2001–2016
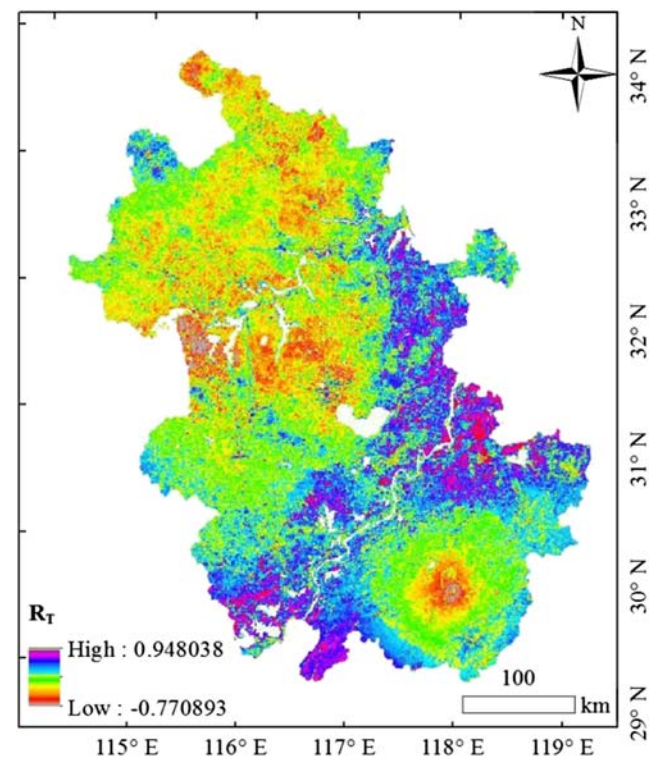

Fig. 12 Correlation relationship between vegetation NPP and monthly mean temperature in Anhui province during 2001–2016

plain area along the river. Because the plain area along the river was mainly the distribution area of high-yield paddy fields in Anhui province where the representative crop was rice (Yuan et al., 2016). According to the growth habit of crops, under the condition of sufficient irrigation water, the increase of temperature was beneficial to the growth of crops. The regions with negative correlation between NPP and monthly mean temperature were mainly distributed in the mountainous areas of southern Anhui and the hilly areas of Jianghuai. Due to the influence of topography, rising temperature would strengthen air convection, leading to increased precipitation, and thus decrease the NPP of vegetation. In general, the increase of annual precipitation is the main climatic factor for the decrease of total NPP.

Response of vegetation NPP to land use types

Vegetation NPP of different types of land use

The vegetation NPP of different land use types is obviously different due to the different coverage area and ecosystem structure. Figure 13 shows the NPP of cultivated land, woodland, grassland, water area, urban and construction land, wetland, ecotones of natural vegetation, and areas of low vegetation coverage of 8 types of land use had obvious gap between the total NPP from 2001 to 2016 in Anhui province, from big to small in the order: woodland, grassland, ecotones of natural vegetation, cultivated land, urban and construction land, wetland, water area, and areas with low vegetation cover. This was mainly related to their vegetation type and coverage area. The areas of woodland in Anhui province was broad where

mainly distributed with evergreen broad-leaved forest, deciduous broad-leaved forest, and evergreen broad-leaved mixed forest, which was the main reason why forest vegetation NPP took the first place among many land types. In 2013, the amount of forest vegetation NPP was the largest which was about 242.27 gC/m^2. The reason that the cultivated land area was the largest and the vegetation NPP was not the most was mainly affected by the variety and ripening of crop.

Figure 13 also shows the change of NPP of 8 land use types in Anhui province in a long time series from 2001 to 2016. The amount of NPP in these 8 types of land use all showed a downward trend, but the rate of decline was different from each other. The descending rates were ranked from the largest to the smallest: water area, areas with low vegetation cover, wetland, urban and construction land, grassland, cultivated land, ecotones of natural vegetation, and woodland. The areas of woodland in Anhui province were on the rise while the NPP of forestland NPP was on the decline. The main reason was the reduction of original trees and the increase of secondary forests and economic forests. During the study period, the NPP in woodland, grassland, ecotones of natural vegetation, and cultivated land had little interannual fluctuation and the change range was similar. However, the following four types of land use, wetland, urban and construction land, water area and areas with low vegetation cover, the annual variation range of total NPP were large. Among them, the NPP of water area was the most, followed by wetland. By comparing the amount of NPP of 8 land use types in 2001 and 2016, the descending value of NPP was ranked from largest to smallest as wetland, water area, urban and
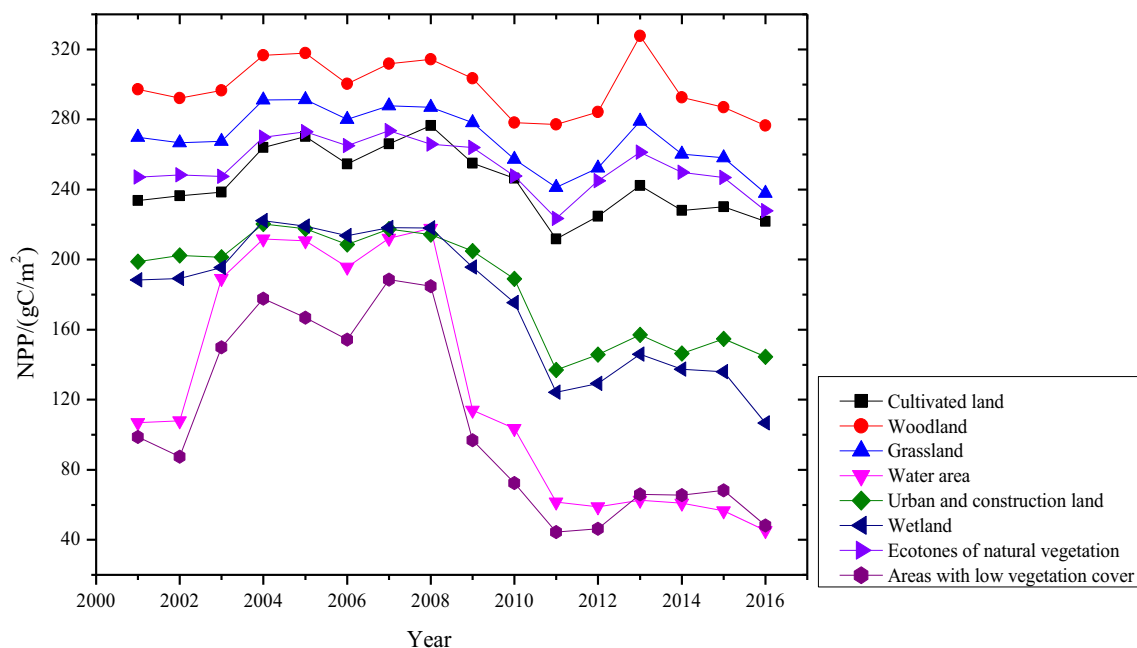

Fig. 13 Vegetation NPP of 8 land use types in Anhui province during 2001–2016

construction land, areas with low vegetation cover, grassland, woodland, ecotones of natural vegetation, and cultivated land. Accordingly, their decrease values were 81.66 gC/m^2, 61.58 gC/m^2, 54.33 gC/m^2, 50.55 gC/m^2, 32.01 gC/m^2, 20.72 gC/m^2, 19.20 gC/m^2, and 11.76 gC/m^2.

Land use type conversion in Anhui province from 2001 to 2016

Under the common influence of natural environment and human activities, land use and land cover types had mostly changed each other. Table 2 summarizes the change of land use types in Anhui province from 2001 to 2016. As shown in the Table 2, during the 16 years, the total transferred areas between land use types were up to 19,455.08 km^2 in Anhui province with accounting for 13.90% of the total area of the province. Cultivated land, woodland, grassland, water area, urban and construction land, wetland, ecotones of natural vegetation, and areas with low vegetation cover had transferred to the outside for 5511.64 km^2, 1507.20 km^2, 7349.03 km^2, 98.42 km^2, 82.44 km^2, 238.79 km^2, 4653.28 km^2, and 14.29 km^2, accounting for 3.94%, 1.08%, 5.25%, 0.07%, 0.06%, 0.17%, 3.32%, and 0.01% of the land area of the whole province, respectively. Grassland had the most outward transferring area and the areas with low vegetation coverage had the least outward transferring area. In addition to woodland, urban and construction land, ecotones of natural vegetation and areas with low vegetation cover, cultivated land, grassland, water area and wetland were all converted with other 7 land use types. The cultivated land was mainly converted to grassland and ecotones of natural vegetation with accounting for 44.89% and 39.72% of the total transferred area of cultivated land, respectively. Woodland was mainly transformed to grassland whose transferring areas accounted for 99.46% of the total transferring areas of woodland.

Grassland was mainly converted to woodland with accounting for 43.31% of the total areas of grassland transfer. The water area was mainly converted to wetland, and its transferring areas accounted for 37.15% of the total transfer area of the water area. The urban and construction land was mainly converted to farmland and grassland with accounting for 53.73% and 38.56% of the total transfer area of urban and construction land, respectively. The wetland was mainly turned into grassland, and its transfer area accounted for 60.47 of the total transfer area of the wetland. The ecotones of natural vegetation were mainly converted to grassland and woodland, which accounted for 55.62% and 41.71% of the total transferred area, respectively. The areas with low vegetation coverage were mainly converted into wetland with accounting for 59.52% of its total transferred area.

During the whole research period, the land area transferred into the cultivated land, woodland, grassland, water area, urban and construction land, wetland, ecotones of natural vegetation, and areas with low vegetation cover were 3460.37 km^2, 3199.91 km^2, 6770.97 km^2, 146.81 km^2, 1089.96 km^2, 970.77 km^2, 3808.84 km^2, and 10.46 km^2, respectively. They covered 2.47%, 2.29%, 4.84%, 0.10%, 0.78%, 0.69%, 2.72%, and 0.01% of the total land use area in Anhui province, respectively. The areas transferred into grassland were the most, and the areas transferred into areas with low vegetation cover were the least. The transferring areas of cultivated land were mainly ecotones of natural vegetation and grassland, which accounted for 56.09% and 41.04% of the total transferring area of cultivated land, respectively. The transfer-in areas of woodland were mainly grassland, which accounted for 99.47% of the total transfer-in area of woodland. The grassland was mainly transferred to the ecotones of natural vegetation and cultivated land, which respectively accounted for 38.33% and 36.54% of the total transferred grassland areas. Grassland and wetland were the main transfer-in areas, which accounted for 37.38% and 36.75% of the total transfer-in area,

Table 2 Transfer matrix of land use type in Anhui province during 2001–2016

Area (km^2)	Cultivated land	Woodland	Grassland	Water area	Urban and construction land	Wetland	Ecotones of natural vegetation	Areas with low vegetation cover	Total
Cultivated land	67,270.00	10.24	2474.00	31.90	644.00	160.50	2189.00	2.00	72,781.64
Woodland	0.02	9779.00	1499.00				8.18		11,286.20
Grassland	1420.00	3183.00	30,130.00	54.88	325.60	755.40	1605.00	5.15	37,479.03
Water area	23.49	0.10	32.82	4149.00	5.02	36.56	0.02	0.4	4247.42
Urban and construction land	44.29	0.22	31.79	1.91	3124.00	0.62	3.60		3206.44
Wetland	31.52	1.54	144.40	53.95	4.45	716.00	0.03	2.90	954.79
Ecotones of natural vegetation	1941.00	4.81	2588.00	1.09	109.20	9.19	5336.00		9989.28
Areas with low vegetation cover	0.05		0.96	3.09	1.69	8.50		6.93	21.22
Total	70,730.37	12,978.91	36,900.97	4295.81	4213.96	1686.77	9141.84	17.39	139,966.01

respectively. The transfer of urban and construction land was mainly cultivated land and grassland with accounting for 59.08% and 29.87% of the total transfer areas, respectively. The transferred areas of wetland were mainly grassland with accounting for about 77.81% of the total transferred areas of wetland. Cultivated land and grassland were the main transfer-in areas of the ecotones of natural vegetation, which accounted for 57.52% and 42.17% of the total transfer-in areas, respectively. The areas with low vegetation cover were mainly converted to grassland whose transferring areas accounted for 49.25% of its total transferred areas. The areas transferred in and out of Anhui province by land use types in 2001 and 2016 were compared. It can be concluded that in the past 16 years, there were the main characteristics of land use type transformation that areas of Anhui province mainly turned out from cultivated land (-2051.27 km^2), grassland (-578.06 km^2), ecotones of natural vegetation (-847.44 km^2), and areas with low vegetation cover (-3.83 km^2) and turned into from woodland (1692.71 km^2), water area (48.39 km^2), urban and construction land (1007.52 km^2), and wetland (731.98 km^2). The largest amount of land transferred was from woodland to urban and construction land. It indicated that the urbanization process was accelerating in Anhui province. And people pay special attention to environmental protection while they were developing economy. The decrease of land use type area with higher vegetation NPP such as cultivated land, grassland and ecotones of natural vegetation and the increase of land use type area with lower vegetation NPP such as water area, urban and construction land and wetland were the main reasons for the decrease of total vegetation NPP in Anhui province. Although the areas of forest ecosystem with high net primary productivity were on the rise, the increase of its vegetation NPP was still not enough to offset the decrease of vegetation NPP in the whole province.

Figure 14 shows the spatial distribution of NPP changes using the difference of NPP data in Anhui province from 2001 to 2016. As could be seen from Fig. 14, the fluctuation range of vegetation NPP's difference was about between -288.39 and 200.19 gC/m^2. Amount of vegetation NPP increased the most in the Jianghuai hills and Huaibei plain. The reason was that the areas of cultivated land were widespread due to the unique natural conditions in these areas. With the development of urbanization and the implementation of the policy of returning farmland to forest and grassland, the land type conversion in this region was mainly the conversion of cultivated land to woodland, grassland, urban and construction land that resulted in the increase of vegetation NPP. The vegetation degradation was the most serious in the plain area along the river where the vegetation NPP decreased the most.

The vegetation degradation was the most serious and the vegetation NPP decreased the most in the plain area along the river. The reason was that this region had superior location and rapid economic development. It was the main population

concentration area in Anhui province. There were less areas of cultivated land and forest land and larger areas of ecotones with natural vegetation. During the study period, with the establishment of the Wanjiang City Belt to undertake transfer demonstration area, along the river plains' urbanization entered a stage of rapid development. As industrial land, residential land, and infrastructure land increased rapidly, vegetation degradation declines seriously in those regions. Especially in some cities along the river, such as Anqing, Chizhou, Tongling, Chaohu, Wuhu, Maanshan, and so on, the decrease of vegetation NPP were the most significant (Wang, Wang and Zhang, 2018). With the development of the cities and the change of people's lifestyle, the farmers who used to work at home may gave up planting a series of cash crops with slow growth cycle, such as cotton and rice, and instead planted vegetables with fast growth rate, short growth cycle and high economic benefits in order to meet the needs of the urban population and pursue more economic benefits. It was also the essential reason for the decline of vegetation NPP in the plain area along the river.

Correlation between vegetation NPP of different land use types and climatic factors

As shown in the Fig. 15, the correlation coefficient between NPP and annual precipitation of 8 land use types in Anhui province was ranked from the largest to the smallest in the order of cultivated land, urban and construction land, water area, wetland, areas with low vegetation coverage, ecotones of natural vegetation, grassland, and woodland. Among them, cultivated land was the only one that was positively correlated with annual precipitation, while the rest were negatively correlated. In the long time series, the correlation coefficients of cultivated land, urban and construction land, water area, ecotones of natural vegetation, grassland and woodland and precipitation did not change much. The correlation coefficient between wetland and precipitation fluctuated and increased. The correlation coefficient between precipitation and areas with low vegetation coverage fluctuated and decreased. Among them, the correlation coefficient between cultivated land and annual precipitation was the largest, while that between woodland and annual precipitation was the smallest. The main reason may be that the growth of crops on cultivated land was closely related to precipitation. Crop plant was small and its root system was not developed, which went against itself store moisture. Therefore, the growth of crops was closely affected by precipitation. In addition to extreme weather, moderate rainfall in Anhui province was conducive to the growth of crops. On the contrary, due to the extensive distribution of evergreen broad-leaved forest, deciduous broad-leaved forest and evergreen and deciduous mixed forest in the study region, these vegetation types had large plants, wide leaf surface, developed root system and inherent ability to

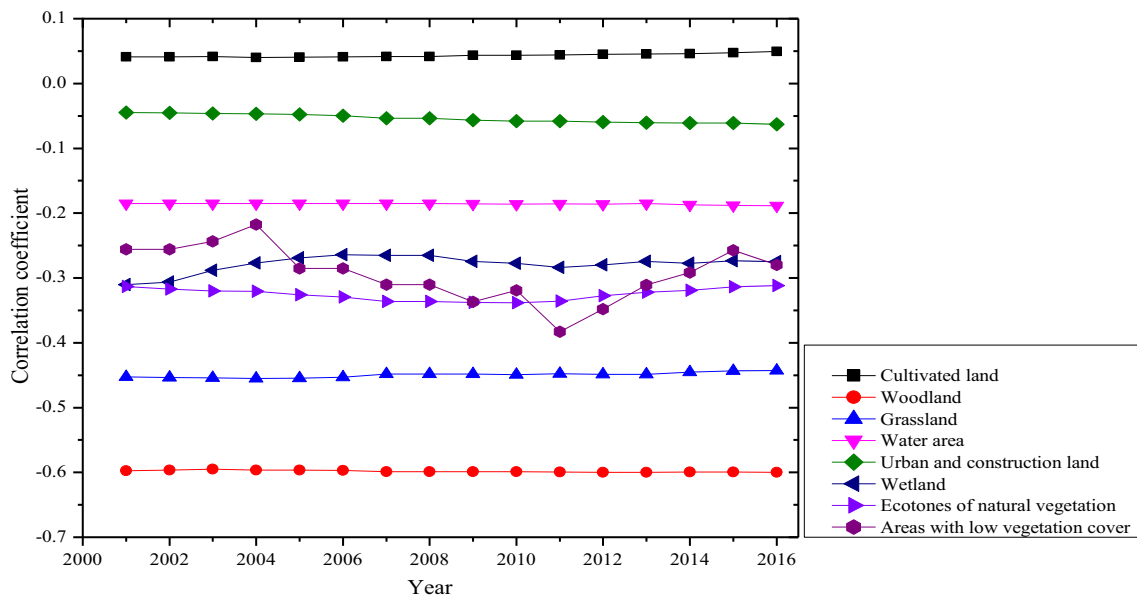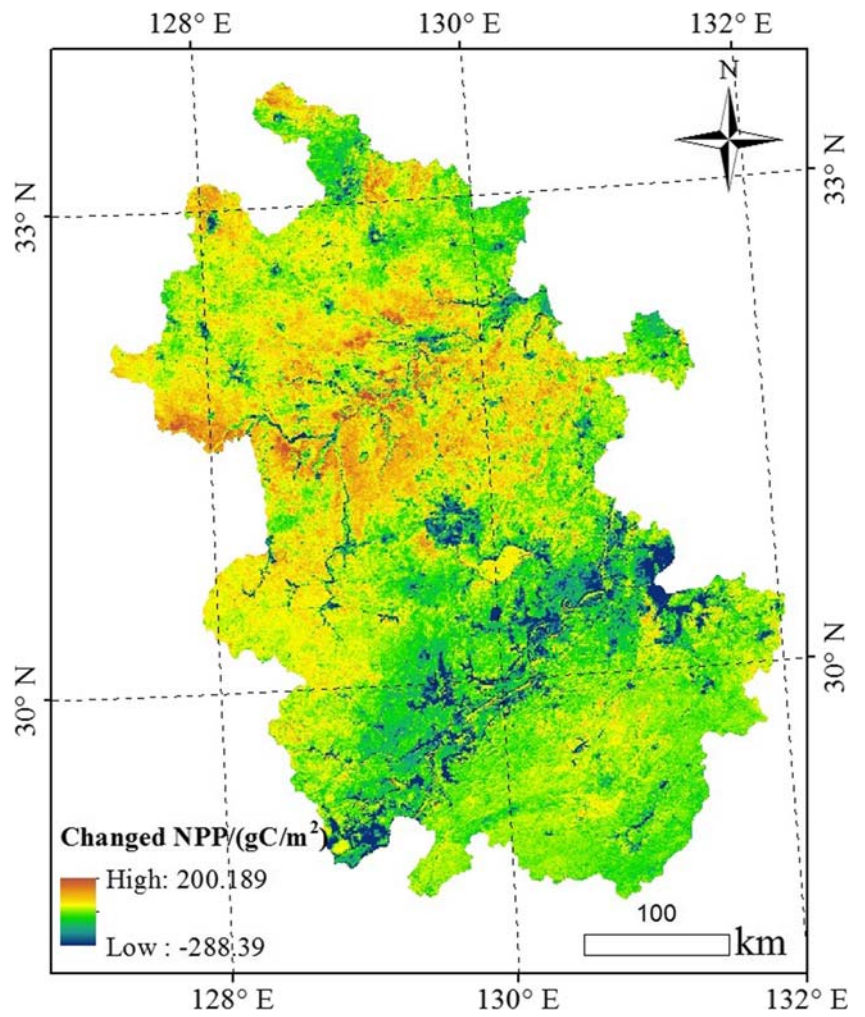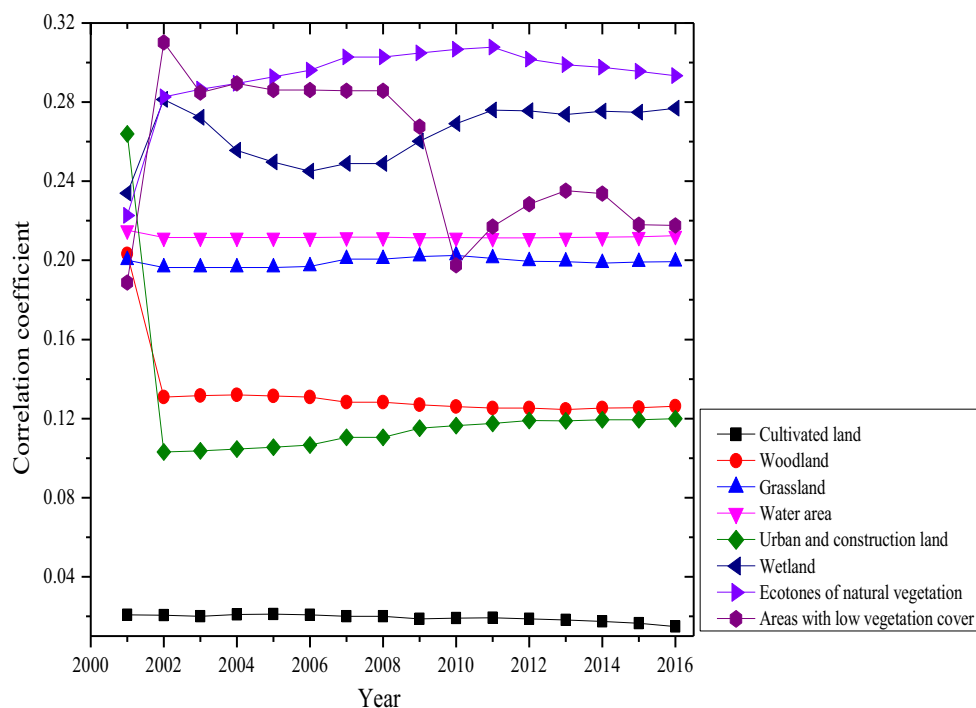**Fig. 14** Spatial distribution of changed NPP in Anhui province during 2001–2016

Fig. 15 Correlation coefficient between vegetation NPP of different land use types and annual precipitation

Fig. 16 Correlation coefficient between vegetation NPP of different land use types and monthly mean temperature

store water. Thus, woodland was less affected by precipitation. In addition, due to the influence of climatic conditions, Anhui province had more precipitation. Excessive precipitation was not conducive to the growth of forest vegetation. It could be said that precipitation was the limiting factor for the increase of forest vegetation NPP.

The correlation coefficient between vegetation NPP and temperature and precipitation were significantly different in Anhui province. As shown in Fig. 16, in Anhui province, the NPP of the 8 types of land use were positively correlated with the monthly mean temperature. It indicated that the temperature conditions were conducive to the growth of vegetation in Anhui province. During the study period, the correlation coefficient between the vegetation NPP of water area, grassland and cultivated land and temperature did not change significantly. From 2001 to 2002, the correlation coefficient between urban and construction land, woodland, and temperature dropped sharply. Meanwhile, the correlation coefficients between areas with low vegetation cover, ecotones of natural vegetation, wetland, and temperature rose sharply. Since 2002, the correlation coefficient between woodland, urban and construction land, and temperature had fluctuated in a small range. Woodland was in the fluctuation decline trend, while urban and the construction lands were in the fluctuation rise trend. The former was due to the decrease of natural forest and the increase of secondary forest and young forest. The latter was because of the rapid expansion of urban land and improvement of urban greening work such as urban afforestation, planting flowers and grass, and so on. In contrast, the correlation coefficient between ecotones of natural vegetation,

areas with low vegetation cover, wetland, and temperature were relatively higher and the variation range of their correlation coefficients were larger. For 16 years, the correlation coefficient between cultivated land and temperature had been at a minimum. The main reason for this phenomenon was the particularity of cultivated land vegetation—crop short stature. Even at the same temperature, the net primary productivity of crops was less than that of trees, shrubs, and grasslands.

The research results in this paper were both consistent and different from the research results of Wang et al. (2018a) and Wang et al. (2018b) on NPP of vegetation in Anhui province, which might be caused by different climate changes in different time scales and different estimation methods of vegetation NPP under different models. This study only discussed the response of vegetation NPP to the climate change in the same period in Anhui province and did not consider the influence of climate lag effect on vegetation NPP, which will be researched in future studies.

Conclusion

In this paper, the net primary productivity of vegetation in the terrestrial ecosystem was simulated based on the MODIS 13A1-NDVI remote sensing data, meteorological data, land use and land cover data, and CASA model in Anhui province during 2001–2016. On this basis, the temporal variation trend, spatial distribution pattern, and influencing factors of net primary productivity of vegetation and vegetation net primary

productivity of different land use types were further analyzed. The main conclusions were as follows:

1. From 2001 to 2016, the perennial average of total NPP was about 34.62 TgC in Anhui province. In the 16 years, the total NPP of vegetation in more years were lower than the multi-year average. Generally speaking, in terms of time, NPP of vegetation in Anhui province showed a trend of slight decline. In 2016, compared with 2001, the total amount of vegetation NPP decreased by nearly 3.12 TgC. Spatially, the distribution characteristics of NPP were more in the north and south, and less in the middle. During the whole research period, about 66.03% of NPP of the land area was in a decreasing trend in the province. The areas with a slight decreasing trend were widely distributed in the province, and the areas with a significant decreasing trend were mainly distributed in the plain areas along the river. The regions in the increasing trend only accounts for 2.16% of the province's areas, which was mainly distributed in the northern part of Dabie mountain in western Anhui.

2. During 2001–2016, there was a significant difference in the vegetation NPP among different land use types in Anhui province. The vegetation NPP of different land use types was ranked from large to small as follows: woodland, grassland, ecotones of natural vegetation, cultivated land, urban and construction land, wetland, water area, and areas with low vegetation cover. The result was closely related to the vegetation type and covered area.

3. From 2001 to 2016, the monthly mean temperature showed a fluctuating downward trend, while the annual precipitation showed a fluctuating upward trend in Anhui province. Such climatic condition with slightly "cold and wet" characteristics was the important reason for the decrease of vegetation NPP in Anhui province. The correlation between vegetation NPP and temperature was greater than that between vegetation NPP and precipitation. All the 8 types of land use vegetation NPP were positively correlated with monthly mean temperature. In addition to cultivated land, vegetation NPP of the other 7 types of land use was negatively correlated with precipitation. It could be said that the temperature condition had a positive effect on the vegetation NPP in the region, while the precipitation had a negative effect on the vegetation NPP of land use type except cultivated land.

4. In addition to the influence of climate factors on NPP changes, human activities were also a factor that could not be ignored. The most direct impact of human activities on terrestrial ecosystems was the change in land use and land cover. In the past 16 years, the land transfer had been mainly characterized by the decrease of the land area in cultivated land, grassland and ecotones of natural vegetation with high vegetation NPP and the increase of the land area in the water area, town and construction land with low vegetation NPP in Anhui province. This was also the main reason for the decrease of NPP in Anhui province.

Author contributions HFY conceived and designed the experiments. HFY and DDH performed the experiments. HFY, DDH, XNZ, and HX analyzed the data. HFY and DDH wrote the paper.

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