Sains Malaysiana 48(11)(2019): 2317–2324
http://dx.doi.org/10.17576/jsm-2019-4811-03

Spatio-Temporal Changes in Vegetation Net Primary Productivity and Its Responses to Climatic Factors in Jiangsu Province, Eastern China

(Perubahan Ruang-Masa dalam Keberhasilan Primer Bersih Vegetasi dan Responsnya terhadap Faktor Iklim di Wilayah Jiangsu, China Timur)

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ABSTRACT

Vegetation net primary productivity (NPP) is an important indicator in determining the ecological functions and carbon cycle of terrestrial ecosystems. As an important part of Chinese Yangtze River Delta region, Jiangsu is one of main grain producing areas in China. Therefore, understanding of spatio-temporal changes in NPP has a practical significance to ensure ecological sustainability in this region. In this study, we used satellite-based vegetation productivity model, the Carnegie-Ames-Stanford Approach (CASA) to assess spatio-temporal variations in NPP and analyzed the relationships between NPP and climatic factors over Jiangsu. The results showed that annual mean NPP reached up to 745.26 ± 69.21 g C m^{-2} year^{-1}, with high NPP values mainly in the central and southwestern regions. Besides that, annual mean NPP increased from 2000 to 2015, with a rate of 6.54 g C m^{-2} year^{-1}. The increasing trends with higher changing rate were mainly found in the northern regions of Jiangsu, whereas the decreasing trends were mainly found in central and southern Jiangsu. Moreover, the correlation analysis indicated that the mean temperature and total precipitation in spring had a significant relationship with the corresponding NPP in most part of Jiangsu. The findings will have an important significance for improving the ecosystem management in Jiangsu.

Keywords: CASA model; climatic factors; Jiangsu; net primary productivity

ABSTRAK

Produktiviti primer bersih vegetasi (NPP) adalah satu petunjuk penting yang menunjukkan fungsi ekologi dan kitaran karbon dalam ekosistem daratan. Jiangsu merupakan kawasan penting bagi Delta Sungai Yangtze China, iaitu salah satu kawasan penghasil gandum utama di China. Justeru, pemahaman perubahan ruang-masa dalam NPP mempunyai kepentingan praktikal untuk memastikan kelestarian ekologi di kawasan ini. Dalam kajian ini, kami menggunakan model produktiviti vegetasi berasaskan satelit, iaitu Carnegie-Ames-Stanford Approach (CASA) untuk menilai variasi ruang-masa dalam NPP serta menganalisis hubungan antara NPP dengan faktor iklim di Jiangsu. Keputusan kajian menunjukkan purata tahunan NPP mencapai 745.26 ± 69.21 g C m^{-2} tahun^{-1}, dengan nilai NPP yang lebih tinggi didapati di kawasan tengah dan barat daya. Selain itu, nilai purata tahunan NPP meningkat dari tahun 2000 sehingga 2015 pada kadar 6.54 g C m^{-2} tahun^{-1}. Kadar peningkatan yang lebih besar berlaku terutamanya di kawasan utara wilayah Jiangsu, manakala tren penurunan didapati di kawasan tengah dan selatan Jiangsu. Di samping itu, analisis korelasi menunjukkan bahawa purata suhu dan jumlah hujan tahunan mempunyai hubungan positif yang signifikan dengan NPP di sebahagian besar kawasan Jiangsu. Penemuan ini penting untuk meningkatkan pengurusan ekosistem di Jiangsu.

Kata kunci: Faktor iklim; Jiangsu; keberhasilan primer bersih; model CASA

INTRODUCTION

Vegetation Net Primary Productivity (NPP) is defined as the amount of organic dry matter accumulated per unit area and unit time by plant photosynthesis. NPP is an important indicator to determine the ecological functions and carbon cycle in the terrestrial ecosystems. It is also considered as the basis for human survival and sustainable development (Maden & Choy 2017; Piao et al. 2007; Potter et al. 1993). With the development of global change research, more and more scholars have focused on ecological processes in terrestrial ecosystems, e.g., the variability of NPP, to reflect ecosystem conditions and changes at different space and time scales (Kueh et al. 2013; Li & Pan 2018; Wei et al. 2018). Thus, knowing of the spatiotemporal changes in NPP has become a critical issue for assessing the sustainable development of terrestrial ecosystems around the world.

Quantification of the terrestrial NPP is normally use for assessing spatiotemporal changes of NPP. Although the direct harvest method is considered as an effective method to obtain terrestrial NPP, but it is difficult to analyze NPP at a large spatial scale (Chen et al. 2017). In addition to the direct harvest method, the model simulation using the remote sensing have been widely used in recent researches, because it can provide an indispensable tool to monitor, visualize (Rendana et al. 2017), and analyze changes in NPP for better understanding of what has happened in the past. For example, the Carnegie-Ames-Stanford Approach (CASA) model, linking remotely sensed data to the light energy utilization model, makes it possible to obtain real-time observation data at a large scale. Compared with process-based ecosystem models that entail a complex combination of model parameterizations, the CASA model has a higher efficiency and accuracy for estimating NPP at the global, regional and landscape scales (Ruimy et al. 2010; Yu et al. 2009; Zhang et al. 2017).

In China, many researchers investigated the spatiotemporal changes in NPP from different perspectives using the CASA model. Although the data used for assessment existed some differences, the total NPP showed a slightly increasing trend in the whole country (Li & Wang 2018; Wang et al. 2017). As for sub-regions, the NPP in northern China, e.g. the Inner Mongolia steppe, Xinjiang, North China Plain, and Sichuan basin, showed a significant increasing trend, whereas it has an opposite trend occurred in Yangtze River basin, Northeast China, and mid-lower reaches of Pearl River basin. However, comparatively fewer studies have been conducted in eastern China using the CASA model. Additionally, some studies showed that the NPP is affected by different vegetation types and climate factors, showing a larger spatiotemporal heterogeneity. Therefore, the responses of NPP to climatic factors were also detected and further analyzed.

The Jiangsu province is located along the eastern coast of China, which is not only an important part of the Yangtze River Delta region (YRDR) but also one of the main grain producing regions in China. Affected by global change, a series of ecological problems has been occurred in this region, e.g., food security, urban heat island, and water shortage, but only few previous studies have reported on the changes in NPP and its interactions with climatic factors in this region (Xu et al. 2016). Thus, the Jiangsu province was chosen for this study. The major objectives of our study were: to quantify spatiotemporal patterns of NPP using the CASA model; and to detect the relationship between NPP and climatic factors. The relevant findings will provide a useful resource for ecological protection and sustainable development in YRDR.

MATERIALS AND METHODS

STUDY AREA AND DATA COLLECTION

Jiangsu province is located between 30°45′N-35°20′N and 116°18′E-121°57′E (Figure 1(a)). It covers an area of 107,200 km^2, which has a large area of plain as its typical topography, accounting for 68.81% of the total area, and has a dense network of waterways. Regional land use types were shown that cropland was one of important types, accounting for over 69% of the total area, whereas woodland and grassland only accounted for 4.23% of the total area (Figure 1(b)). The province includes 13 prefecture-level cities with a total population of 79.99 million. Situated in a transition belt from a subtropical to temperate zone, it has a typical monsoon climate with moderate rainfall and clear distinction of the four seasons. The annual average temperature is 13-16°C, and annual total precipitation is nearly 1100 mm. Jiangsu is also known as 'a land flowing with milk and honey', which is endowed by an advantaged condition for agricultural production and has various kinds of crops, forests and livestock.

The monthly climate data, e.g., temperature, precipitation, wind speed, sunshine hours, and relative humidity, for 63 stations in Jiangsu during 2000-2015 were collected from the National Climate Center (NCC) of China. The monthly normalized difference vegetation index (NDVI) at 1000 m spatial resolution during 2000-2015 were downloaded from https://modis.gsfc.nasa.gov/. The SRTM 90-m digital elevation data, the 1:1,000,000 soil attribute data, and vegetation type data were all downloaded from http://westdc.westgis.ac.cn/.

The satellite-based vegetation productivity model - Carnegie-Ames-Stanford Approach (CASA) was used to calculate values of NPP in different vegetation types. The calculation formula of CASA model was as follows:

$$NPP(x,t) = APAR(x,t) \times \varepsilon(x,t) \qquad (1)$$

where APAR(x, t) was the absorbed photosynthetically active radiation in a given location and time, and ε(x, t)

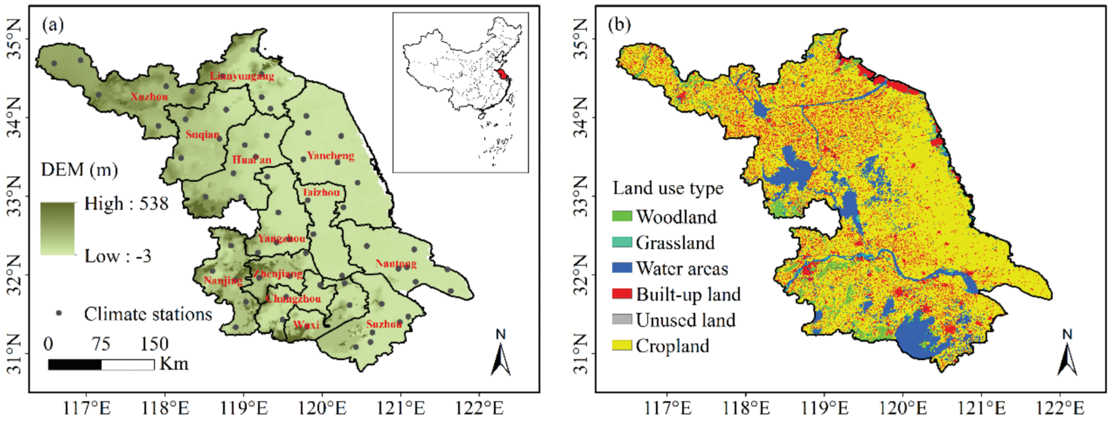

FIGURE 1. The (a) topography and (b) land use maps of Jiangsu

was light use efficiency in a given location and time. The climate data, NDVI, Digital Elevation Model (DEM) and vegetation classification data with a grid resolution of 1000 m were used as the input data to obtain NPP. Detailed calculation steps, e.g. data processing, parameter selection and calibration, were shown in previous work (Li et al. 2018).

METHODS

In this study, a simple linear regression analysis model was used to analyze the NPP trends of each grid using the following equation:

$$\theta_{slope} = \frac{n \times \sum_{i=1}^{n} i \times NPP_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} NPP_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \qquad (2)$$

where θ_{slope} is the changing rate of NPP in the study area; n is the number of studied time intervals (years); NPP_i is the annual NPP for year i. The $\theta_{slope} > 0$ and $\theta_{slope} < 0$ show increasing and decreasing tendencies of NPP, respectively.

The correlation coefficient was selected to describe the correlation between NPP and climatic factors (temperature and precipitation).

$$R_{xy} = \frac{\sum_{i=1}^{n}[(x_i - x_{ave})(y_i - y_{ave})]}{\sqrt{\sum_{i=1}^{n}(x_i - x_{ave})^2 \sum_{i=1}^{n}(y_i - y_{ave})^2}} \qquad (3)$$

where R_{xy} is the correlation coefficient of variables x and y; x_i is the NPP of the i th year; y_i is the temperature or precipitation of the i th year; x_{ave} is the average NPP for all years; y_{ave} is the average temperature or precipitation for all years; and i is the number of years. In this study, the significance level was set at 5%.

RESULTS AND DISCUSSION

VALIDATION OF THE NPP

In this study, we firstly collected 63 samples of aboveground vegetation from the surrounding areas of climate stations according to the vegetation type in different regions of Jiangsu. Then we tested their weight in the laboratory and calculated the NPP value for each sample according to the coefficient of carbon conversion of 0.45 (Tang et al. 2014). A comparison between the CASA-simulated NPP and observed NPP is shown in Figure 2. In general, the CASA model performed fairly well in calculating NPP with a high coefficient of determination value of 0.83 ($p < 0.01$), and a low relative bias value of 4.16% (Figure 2). The statistical results suggested that the simulated NPP using the CASA model were satisfactory compared with the observation, and thus this model had a good ability to estimate NPP in Jiangsu.

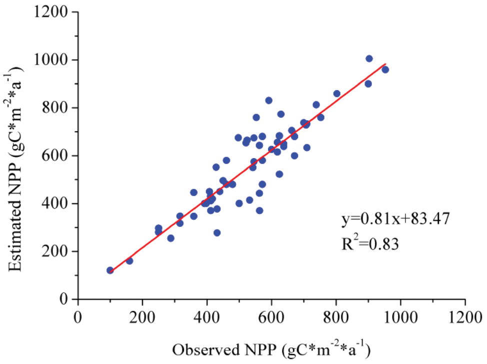

FIGURE 2. Comparison of simulated and observed NPP in Jiangsu

SPATIOTEMPORAL VARIATIONS IN NPP

The annual mean NPP from 2000 to 2015 ranged from 0 to 2200.76 g·m^{-2}·a^{-1}, with an average value of 745.26 ± 69.21 g C m^{-2} year^{-1} (Table 1). Figure 3(a) indicates an obvious spatial pattern of NPP, where higher NPP values were mainly found in the central and southwestern regions of Jiangsu. A possible explanation for this might be due to distribution of high-yield cropland and woodland in these regions (Figure 3 & Figure 1(b)). By contrast, the lower values were located in southern Jiangsu (Figure 3(a)). As for administrative units, the NPP of Taizhou, Huaian, Suqian, Yancheng and Yangzhou reached over 800 g C m^{-2} year^{-1}, whereas the values were less than 600 g C m^{-2} year^{-1} in Wuxi and Suzhou (Table 1).

The changing rate of NPP ranged from -126.46 to 113.74 g C m^{-2} year^{-1}, with an average value of 6.54 g C m^{-2} year^{-1} (Table 1). A larger changing rate of NPP was mainly located in the northern regions of Jiangsu, while a lower changing rate was found in the southern Jiangsu. The changing rate of NPP in Suqian, Huaian, Xuzhou and Lianyungang reached over 14 g C m^{-2} year^{-1}, whereas the values were less than 6.50 g C m^{-2} year^{-1} in Wuxi and Suzhou (Table 1). Previous studies showed the NPP had an insignificant increasing trend in most part of China, which were consistent with our results. Moreover, the changing rate in this study was higher than that of that of MOD17A3 (1.95 g C m^{-2} year^{-1}) in Jiangsu during the same period (Li & Wang 2018).

As shown in Figure 3(c), significant increasing trends of NPP were concentrated in the northern regions of Jiangsu, whereas significant decreasing trends were located in the southern Jiangsu. Particularly, the trend of NPP in Suqian passed the 0.05 significance level with the largest changing rate of 24.27 g C m^{-2} year^{-1} (Table 1). Previous studies indicated that no remarkable changes in NPP of China's terrestrial vegetation accounted for over 79.9% of the total area since the beginning of the 21st century (Li & Wang 2018; Wang et al. 2017), which is consistent with our results.

The regional changing percentage of NPP reached 9.65%. As shown in Figure 3(d), the larger changing percentage were concentrated in the northern regions of Jiangsu, whereas the lower values were located in the

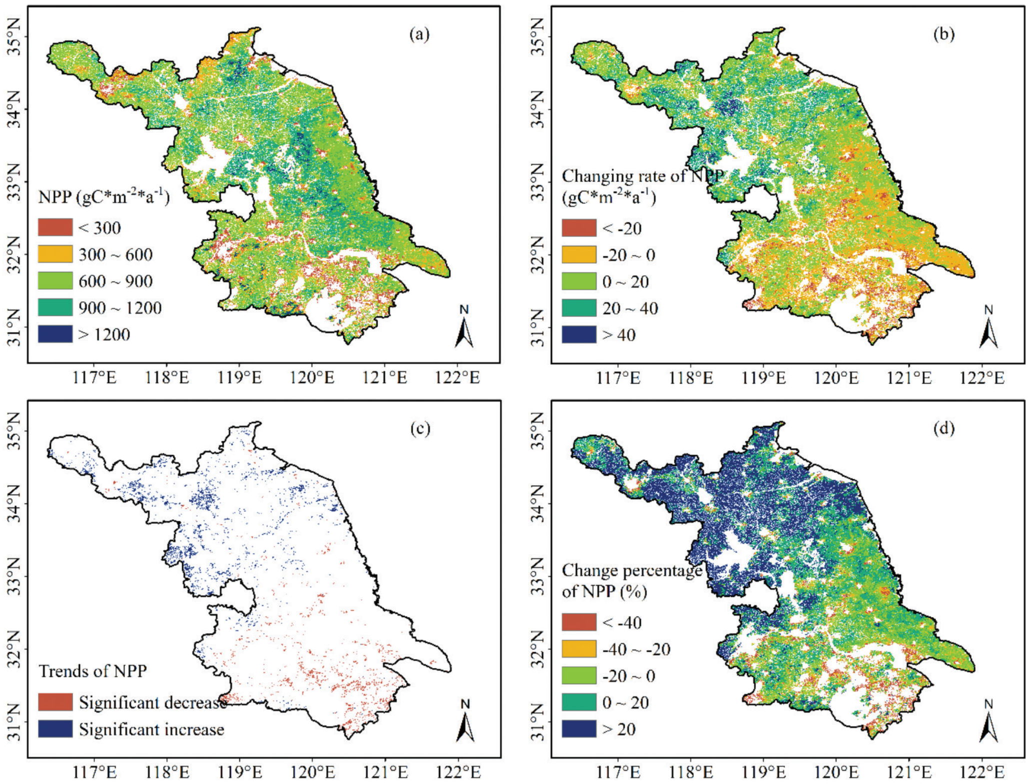

FIGURE 3. The spatial patterns of (a) mean NPP, (b) changing rate of NPP, (c) trends of NPP, (d) changing percentage in Jiangsu

TABLE 1. Changes in annual vegetation NPP in different cities in Jiangsu

	Cities	Average (g C m^{-2} $year^{-1}$)	Changing rate (g C m^{-2} $year^{-1}$)	Changing percentage (%)
Northern regions	Xuzhou	712.84 ± 95.28	16.78	25.89
	Lianyungang	753.29 ± 87.39	14.95	21.83
	Suqian	823.28 ± 120.70	24.27*	32.43
	Huaian	824.49 ± 106.13	19.49	26.01
	Yancheng	819.15 ± 76.97	7.21	9.68
Central regions	Yangzhou	804.27 ± 82.62	7.22	9.87
	Taizhou	848.19 ± 89.23	-0.28	-0.36
	Nantong	759.18 ± 73.02	-4.74	-6.87
Southern regions	Nanjing	635.81 ± 64.12	0.54	0.93
	Zhenjiang	682.24 ± 76.80	-2.31	-3.73
	Changzhou	632.83 ± 62.96	-5.82	-10.12
	Wuxi	590.02 ± 51.62	-6.53	-12.18
	Suzhou	504.42 ± 52.88	-11.32	-24.69
Regional		745.26 ± 69.21	6.54	9.65

*: significant at the 0.05 level

central and southern Jiangsu. The changing percentage of NPP in Suqian, Huaian, Xuzhou and Lianyungang reached over 21%, whereas the values were less than -10% in Changzhou, Wuxi and Suzhou (Table 1).

CHANGES IN TEMPERATURE AND PRECIPITATION

The annual mean temperature reached 16.14 ± 0.35°C and showed a decreasing feature from southern to northern regions in Jiangsu (Table 2). Higher mean temperature values were mainly located in the southern regions of Jiangsu, such as Changzhou, Wuxi and Suzhou, which were higher than 17°C. Meanwhile, lower temperature values were mainly located in the northern regions of Jiangsu, which were lower than 16°C. The annual mean temperature showed an insignificant increasing trend with the changing rate of 0.02°C/year in the whole region. Although an insignificant increasing trend was detected

TABLE 2. Changes in annual mean temperature and total precipitation in different cities of Jiangsu

Cities		Temperature		Precipitation	
		Average (°C)	Changing rate (°C/year)	Average (mm)	Changing rate (mm/year)
Northern regions	Xuzhou	15.30 ± 0.39	0.02	917.18 ± 205.01	-2.53
	Lianyungang	15.09 ± 0.42	0.03	993.85 ± 218.07	-10.04
	Suqian	15.67 ± 0.40	0.02	1017.47 ± 240.02	-5.67
	Huaian	15.91 ± 0.38	0.02	1038.80 ± 227.70	0.77
	Yancheng	15.70 ± 0.38	0.03	1039.14 ± 161.47	2.89
Central regions	Yangzhou	16.31 ± 0.35	0.02	1061.04 ± 173.58	11.87
	Taizhou	16.35 ± 0.34	0.02	1075.22 ± 129.76	10.40
	Nantong	16.56 ± 0.32	0.02	1096.22 ± 95.44	4.96
Southern regions	Nanjing	16.88 ± 0.32	0.01	1127.90 ± 145.59	17.22
	Zhenjiang	16.75 ± 0.32	0.02	1114.59 ± 131.08	14.59
	Changzhou	17.05 ± 0.31	0.02	1161.75 ± 107.84	13.75
	Wuxi	17.06 ± 0.30	0.02	1164.03 ± 105.61	10.51
	Suzhou	17.19 ± 0.30	0.01	1165.14 ± 125.40	7.03
Regional		16.14 ± 0.35	0.02	1058.63 ± 119.75	4.14

in each city, the changing rate of mean temperature was relative lower, which ranged from 0.01 to 0.03°C/year.

The annual total precipitation reached 1058.63 ± 119.75 mm in Jiangsu (Table 2). The more precipitation was mainly located in the southern regions of Jiangsu, such as Changzhou, Wuxi and Suzhou, which were higher than 1160 mm, whereas the lower values were mainly located in the northern regions of Jiangsu, which were lower than 1040 mm. The annual precipitation showed an insignificant increasing trend with the changing rate of 4.14 mm/year in the whole region. Although a decreasing trend was detected in Xuzhou, Lianyungang and Suqian, the changing rate of annual precipitation showed a positive value in the remaining regions, which ranged from 0.77 to 17.22 mm/year.

RELATIONSHIPS BETWEEN NPP AND CLIMATIC FACTORS

The relationships between NPP and climatic factors were calculated by using the Pearson correlation analysis. Overall, annual mean temperature had an insignificant positive relationship with NPP in Jiangsu. As shown in Figure 4(a) and Table 3, the positive correlations between temperature and NPP were mainly distributed in the northern regions, whereas the negative correlations were mainly in the central and southern regions of Jiangsu at the annual scale. The area of significant positive correlations accounted for 0.64 % of the total area (Figure 4(b)). As for four seasons, seasonal mean temperature showed the complex relationship with corresponding NPP in Jiangsu. Particularly, mean temperature in spring showed a significant positive relationship with NPP in Suqian, Huaian, Taizhou, Nanjing and Zhenjing (Table 3).

Annual total precipitation had the complex relationship with NPP in Jiangsu. As shown in Figure 4(c) and Table 3, the positive correlations between precipitation and NPP were mainly distributed in the northern and southern regions, whereas the negative correlations were mainly in the central regions of Jiangsu at the annual scale. The area of significant negative (positive) correlations accounted for 1.21% (0.70%) of the total area, respectively, which were mainly distributed in the central (northern) regions (Figure 4(d)). As for four seasons, seasonal total precipitation showed the complex relationship with corresponding NPP in Jiangsu. Particularly, precipitation in spring showed a significant positive relationship with NPP in Xuzhou, Lianyungang and Huaian (Table 3). However, spring precipitation showed the significant negative relationship with NPP in Nantong (Table 3).

The favorable hydrothermal conditions promoted the growth of natural vegetation (Mao et al. 2014). Situated in a transition belt from a subtropical to temperate zone, the complex relationships between NPP and climatic factors were shown in Jiangsu. On the one hand, mean temperature and total precipitation in spring had a significant positive correlation with NPP in most of northern Jiangsu, which is located in the warm temperate continental monsoon climate zone. On the other hand, more precipitation was not conducive to vegetation growth in coastal regions of Jiangsu due to the impact of maritime climate. In addition to hydrothermal conditions, human activities were also an important reason for affecting NPP. Previous studies indicated that NPP in southern Jiangsu was greatly affected by rapid urbanization (Wang et al. 2017).

CONCLUSION

An in-depth analysis of spatiotemporal changes in NPP provided scientific basis for ecological sustainability in Jiangsu province, a main body of the Chinese Yangtze River Delta city cluster. The main findings were as follows:

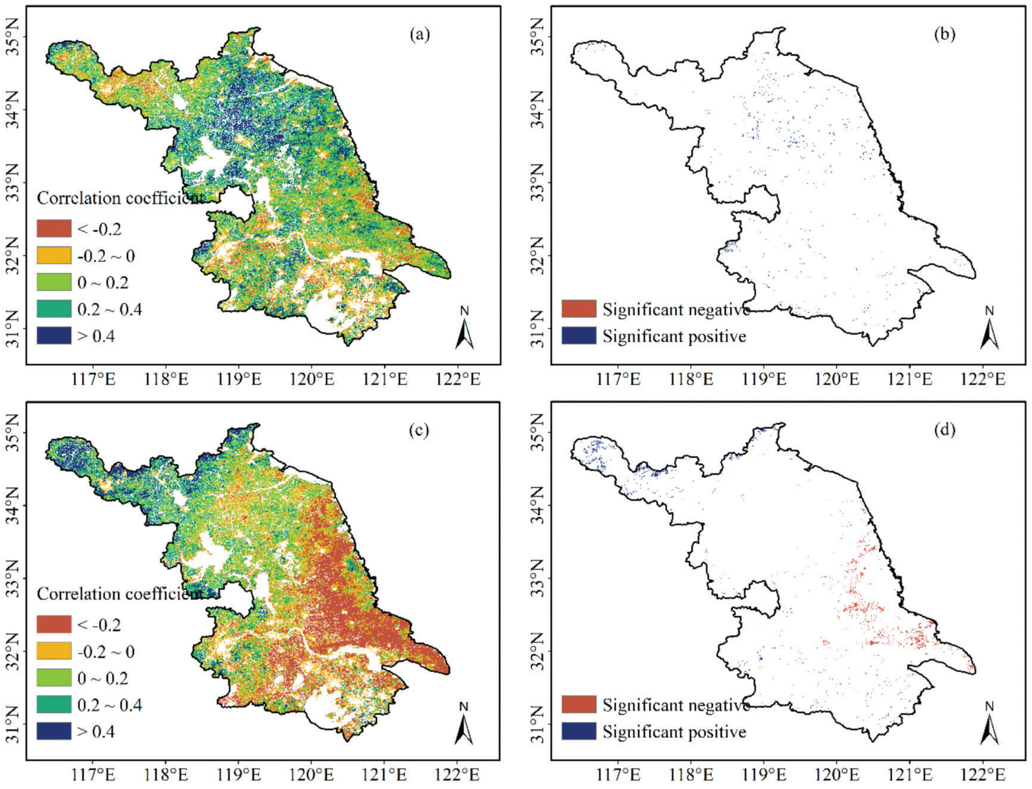

FIGURE 4. The correlations coefficients (a-b) between temperature and NPP, and (c-d) between precipitation and NPP at the annual scale in Jiangsu

TABLE 3. The correlation coefficients between NPP and climatic factors in different cities of Jiangsu

	Cities	Temperature					Precipitation				
		ANNU	DJF	MAM	JJA	SON	ANNU	DJF	MAM	JJA	SON
Northern regions	Xuzhou	0.04	-0.04	0.22	0.34	0.20	0.43	-0.38	0.63*	-0.21	0.44
	Lianyungang	0.12	-0.20	0.05	0.33	0.26	0.35	-0.10	0.69*	0.24	0.27
	Suqian	0.39	-0.11	0.52*	0.32	0.22	-0.12	-0.06	0.45	-0.05	-0.23
	Huaian	0.07	-0.06	0.54*	0.12	0.07	0.31	-0.45	0.51*	-0.16	0.48
	Yancheng	-0.21	-0.30	0.04	0.32	-0.03	-0.16	-0.13	0.28	-0.31	-0.17
Central regions	Yangzhou	-0.25	-0.16	0.49	0.10	-0.48	-0.13	-0.34	-0.02	-0.22	0.01
	Taizhou	-0.14	-0.12	0.52*	0.04	-0.27	-0.41	-0.16	-0.36	-0.44	-0.37
	Nantong	-0.12	-0.24	0.23	-0.33	-0.17	-0.28	-0.31	-0.51*	-0.18	-0.42
Southern regions	Nanjing	0.20	0.29	0.52*	-0.01	-0.08	-0.07	-0.36	-0.01	-0.22	-0.17
	Zhenjiang	-0.28	0.08	0.56*	-0.21	0.01	0.13	-0.43	-0.25	0.11	-0.12
	Changzhou	-0.02	0.06	0.31	-0.28	0.53*	0.09	-0.25	-0.22	0.22	-0.05
	Wuxi	-0.41	0.09	0.44	-0.41	0.26	0.15	-0.24	-0.17	0.32	-0.39
	Suzhou	-0.13	0.09	0.38	-0.23	0.06	0.05	-0.28	-0.16	0.11	-0.12
Regional		0.05	-0.10	0.44	0.01	0.03	-0.22	-0.37	-0.07	-0.29	-0.21

*: significant at the 0.05 level. ANNU, DJF, MAM, JJA and SON indicates annual, winter, spring, summer and autumn, respectively

The CASA model performed well in Jiangsu. The validation results showed that the coefficient of determination (R^2) value was 0.83 (p<0.01) between the simulated and the observed NPP. Moreover, the simulated NPP was generally within the limits of the observations. The annual mean NPP ranged from 0 to 2200.76 g C m^{-2} year^{-1}, with an average value of 745.26 ± 69.21 g C m^{-2} year^{-1}. Higher NPP values were mainly located in the central and southwestern regions of Jiangsu. The annual mean NPP showed a slight increasing trend with the changing rate of 6.54 g C m^{-2} year^{-1}. Significant increasing NPP trends were mainly located in the northern regions of Jiangsu, whereas significant decreasing trends were found in the southern Jiangsu. Moreover, the changing percentage of NPP also showed an obvious spatial difference between the southern and northern regions in Jiangsu. Both annual mean temperature and annual total precipitation showed a slight increasing trend at the regional scale. Correlation analysis indicated that temperature and precipitation showed the complex relationships with NPP at the annual and seasonal scales in Jiangsu. Overall, the mean temperature and total precipitation in spring had a significant relationship with the corresponding NPP in most part of Jiangsu.

In this work, we preliminarily analyzed spatiotemporal changes in NPP and explored the relationships between NPP and climatic factors in Jiangsu due to data availability. In the future, more detailed data will be collected to better calculate the long-term changes of NPP on multiple spatiotemporal scales in Jiangsu using multi-models (Tan et al. 2019), which can be used as valuable references for decision-makers in the ecological protection and sustainable development.

ACKNOWLEDGEMENTS

This work was funded by National Natural Science Foundation of China (41801013), Natural Science Foundation of Jiangsu Province (BK20180939), Strategic Priority Program of the Chinese Academy of Sciences (XDA20030101-02), Jiangsu Key Laboratory Program of Aro-meteorology of NUIST (JKLAM1802), the Open Program of Institute of Chinese Grand Canal of Yangzhou University, the Talent Project of"Lvyangjinfeng"of Yangzhou City, the Startup Foundation for introducing Talent of Yangzhou University (137011343) and the Ministry of Education, Malaysia under the Newton-NERC grant (IMpacts of PRecipitation from Extreme StormS – Malaysia (IMPRESS-MALAYSIA), 203. PHUMANITI.6780001).

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Received: 31 March 2019
Accepted: 15 August 2019