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Analysis of Temporal and Spatial Changes of Carbon Sources/ Sinks in Yangtze River Delta Region (China) from 2000 to 2019

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Abstract: The Yangtze River Delta (China) is an urban agglomeration with the strongest comprehensive strength in China, actively responds to the opening of the national carbon emission trading market and promote its sustainable development, accurate estimation and analysis of the evolution of carbon source/ sink temporal and spatial pattern and its response to climate in the region in recent 20 years, provides decision-making basis for emission reduction policy-making. Through soil respiration model and CASA model, MODIS net primary productivity product and land cover product, monthly mean temperature, and rainfall data from 63 meteorological stations were used to estimate the net ecosystem productivity (NEP) of vegetation in the Yangtze River Delta Region from 2000 to 2019, and analyze the interannual spatial dynamic change of vegetation NEP and its correlations with meteorological factors (temperature and rainfall). The results showed that: (1) From 2000 to 2019, the carbon sink area in the Yangtze River Delta was much larger than the carbon source area, the mean NEP of the vegetation ecosystem in the past 20 years was 253.2g $C \cdot m^{-2} \cdot a^{-1}$, and the spatial distribution presented a trend of higher in the south and lower in the north, higher in the east and lower in the west, and gradually increasing from northwest to southeast, and the NEP of mountain areas is generally higher than that of river courses and urban surroundings. The interannual fluctuation of NEP value was small, but presenting a slightly increasing trend, and the interannual variation of NEP value was significantly correlated with the maximum value of NEP in this region; (2) The carbon sink capacity of different vegetation cover types is (from strong to weak): forestlands > grasslands > wetlands ≈ Croplands; (3) The area with the NEP change rate (θ_{slope}) > 0 accounted for 69.0%, but there was certain spatial difference, the proportions of the areas with θ_{slope} < 0 were (from large to small) were 14.50% (Zhejiang Province, China), 9.10% (Anhui Province, China), 6.65% (Jiangsu Province, China) and 0.79% (Shanghai, China) respectively, but in terms of the own changes of these provinces and municipalities: Shanghai > Zhejiang Province > Jiangsu Province ≈ Anhui Province; (4) There was correlation between NEP and the annual mean temperature and annual precipitation in some regions. Its value was not only related to the plants' own characteristics and the external environment, but also greatly affected by human activities.

Keywords: net ecosystem productivity; remote sensing; Yangtze River Delta Region

Citation: Zou, C.; Chen, D.; Li, H.; Fan, J.; Liu, Z.; Xu, X.; Li, J. Analysis of Temporal and Spatial Changes of Carbon Sources/ Sinks in Yangtze River Delta Region (China) from 2000 to 2019 . *Sustainability* **2022**, *14*, x. https://doi.org/10.3390/xxxxx

Academic Editor: Firstname Lastname

Received: date
Accepted: date
Published: date

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1. Introduction

China is the global largest developing country and the largest carbon emission country. The State President Xi Jinping made a solemn commitment of "peak carbon dioxide emissions and carbon neutrality" to the international community at the General

Debate of the 75th United Nations General Assembly in 2020, and the Fifth Plenary Session of the 19th CPC Central Committee and the Central Economic Working Conference also arranged for the related tasks [1–3]. The establishment of China Carbon Emission Trade Exchange has become a prerequisite and an important measure for our country to realize the commitment of "peak carbon dioxide emissions and carbon neutrality" on schedule, which will lead to the evolution of "carbon emission permit" into a commodity that can be traded on the market [4]. The Yangtze River Delta Region (hereinafter referred to as the Yangtze River Delta) is the urban agglomeration area with the strongest comprehensive strength in China [5], and promoting the integrated development of the Yangtze River Delta has become a national strategy. In order to improve the economic agglomeration, regional connectivity, and policy collaborative efficiency in the Yangtze River Delta Region, and actively respond to the opening of the China Carbon Emission Trade Exchange, building a modern economic system is a severe challenge [6]. Therefore, it is very necessary to accurately measure and analyze the evolution of the temporal and spatial patterns of carbon sources and sinks in this region in recent years and their influencing factors, thus providing strong support for the adjustment of the regional economic structure, industrial structure, and energy structure.

Since 1980s, extensive researches have been conducted on regional carbon sources and carbon sinks at home and abroad, and the research contents mainly focus on the following three aspects: firstly, the metrical research on carbon sources and carbon sinks, including the metrical research on gross primary productivity (GPP) [7–9], net primary productivity (NPP) [10–12], and net ecosystem productivity (NEP) of vegetation [13–15]. Secondly, the analysis of the main influencing factors that cause changes in carbon sources and carbon sinks in the region or the responses of various factors to their changes: such as climate change [16,17], human activities [18,19] and natural environment, etc. [20,21] Thirdly, establish a model and select parameters to predict the future form: combine machine learning technology with remote sensing technology to establish a data set, then use random forest as the estimation model, and adjust the model parameters according to the data characteristics after modeling [22]; analyze the long-term emission characteristics of a certain industry with larger carbon emissions in a specific area and the macro-control effect of its development strategy to predict the future change scenario of carbon emissions in this area [23]; some researches also conducted empirical analysis to the regional characteristics of carbon emissions, as well as scenario simulation, influencing factors analysis and grey correlation degree calculation, and proposed the main paths and specific plans to achieve the low-carbon goals according to the development goals of the regional low-carbon economy in the next few decades [24]. The above researches have laid a theoretical foundation for the research on regional carbon sources and carbon sinks, but these researches all have their shortcomings, such as a wide variety of data types, high precision requirement, complicated calculation, and great human intervention on model parameters. In particular, there are relatively few researches on the temporal changes in the spatial distribution pattern of regional carbon sources and carbon sinks; the analysis and research on the changes in carbon sources and carbon sinks caused by conversion of land types under different land cover types (e.g., woodland, grassland, construction land, etc.) caused by rapid social and economic development, and their spatial pattern changes are much less. According to the new national development strategy, aiming at the challenge of the opening of China Carbon Emission Trade Exchange that will be actively faced by the integrated development of the Yangtze River Delta, this paper analyzes the temporal changes and spatial distribution patterns of carbon sources and carbon sinks in this region from 2000 to 2019, explores the opportunities and challenges behind the rapid social and economic development of the integration of the Yangtze River Delta, so as to understand the history, current status and influencing mechanisms of carbon sources and carbon sinks in this region from multiple aspects, better revise and improve the opening policy of China Carbon Emission Trade Exchange, and provide a good decision-making basis for emission reduction policies.

2. Materials and Methods

2.1. Overview of research area

According to the Outline of the Integrated Development Plan for Yangtze River Delta Region issued by the State Council, the planning scope of the Yangtze River Delta includes: Shanghai, Jiangsu Province, Zhejiang Province, and Anhui Province of China (area: 358,000 km²). Yangtze River Delta Urban Agglomerations are established with 27 cities as the central area (225,000 km²), including Shanghai Municipality, Nanjing, Wuxi, Changzhou, Suzhou, Nantong, Yangzhou, Zhenjiang, Yancheng and Taizhou in Jiangsu Province of China, Hangzhou, Ningbo, Wenzhou, Huzhou, Jiaxing, Shaoxing, Jinhua, Zhoushan and Taizhou in Zhejiang Province of China, Hefei, Wuhu, Ma'anshan, Tongling, Anqing, Chuzhou, Chizhou and Xuancheng in Anhui Province of China, so as to radiate and drive the high-quality development of the Yangtze River Delta Region. Qingpu District (Shanghai), Wujiang District (Jiangsu), and Jiashan County (Zhejiang, China) are taken as the Ecological and Green Integrated Development Demonstration Zone of Yangtze River Delta (area: about 2,300 km²) to the demonstrate and lead the higher-quality integrated development of the Yangtze River Delta Region. Shanghai Lingang and other areas are taken as the new areas of the China (Shanghai) Pilot Free Trade Zone to create special economic function zones that are in line with international general practices and have greater influence and competitiveness in the international market. The Yangtze River Delta Region is in the lower reaches of the Yangtze River in China, and is close to the Yellow Sea and the East China Sea. It is located at the intersection of the river and the sea with many ports. It is an alluvial plain formed before the Yangtze River enters the sea, and has a vast water surface, significant tidal action, and a lot of sediment deposits. It is mainly dominated by subtropical monsoon climate. Since 2000, the annual mean temperature, the annual mean maximum and minimum temperatures have increased significantly, and the temperature increasing rate is higher in winter and spring, and lowest in summer. The Yangtze River Delta is the region with the highest drainage density in China, with a mean length of 4.8–6.7 kilometers per square kilometer. There are more than 200 lakes on the plain, with abundant water resources and good natural water environment. There are complex types of ecosystems and diverse surface coverages. There are mainly six land use types, namely grasslands, croplands, forestlands, wetland, built-up Lands, and unused lands. The Yangtze River Delta spans the north and middle subtropics, and consists of three types of forest tree communities, namely deciduous broad-leaved forest containing evergreen broad-leaved tree species, deciduous and evergreen broad-leaved mixed forest, and evergreen broad-leaved forest.

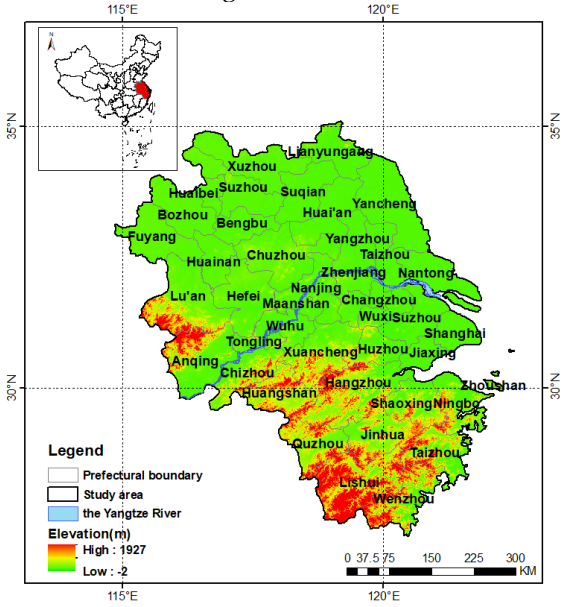


Figure 1. Schematic diagram of research area.

2.2. Data sources

Remote sensing data: EOS/MODIS 500m resolution net primary productivity product (MOD17A3H) from 2000 to 2019. The data used the BIOME-BGC model and the solar energy utilization efficiency model to calculate the annual net primary productivity (NPP) of the regional terrestrial vegetation ecosystem. The data were downloaded from the MODIS website (https://modis.gsfc.nasa.gov/).

Land cover data: MODIS land cover product MCD12Q1 data, land cover classification scheme 1 was used: IGBP global vegetation classification scheme. The data were used to analyze the carbon sink capacity of different vegetation types, including cultivated land, wetland, grassland, shrub, woodland, construction land and unused land (7 categories, covering 17 subcategories). The data were downloaded from the MODIS website (https://modis.gsfc.nasa.gov/) to analyze the difference in carbon sink capacity under the coverage of different vegetation types.

Meteorological data: the monthly mean temperature and monthly precipitation data of 63 stations in the Yangtze River Delta from 2000 to 2019 were downloaded from the website of China Meteorological Data (http://data.cma.cn/). The data for 2020 were not downloaded due to no authorization resulting from the website revision.

2.3. Data processing

2.3.1. Calculation of NEP

NEP is an important indicator to measure the vegetation carbon source/sink in the region, which represents the carbon exchange rate between the terrestrial vegetation ecosystem and the atmospheric system. Although it is not equal to the carbon sink at the regional scale, it can be regarded as a measure of the size of carbon sink [25]. If the influence of other natural and human conditions is not considered, it can be expressed as the difference between NPP and the carbon emissions from soil microbial respiration (R_H) [26], and the calculation formula is:

$$\mathrm{NEP} = \mathrm{NPP} - \mathrm{R_H} \quad (1)$$

In formula (1), NEP is the net ecosystem productivity of vegetation, NPP is the net primary productivity of vegetation, and $\mathrm{R_H}$ is soil microbial respiration, and the units of these three factors are all g $C \cdot m^{-2} \cdot a^{-1}$. When NEP > 0, it means that the carbon fixed by vegetation is more than the carbon emitted by soil respiration, and the carbon sequestration by vegetation is reflected as carbon sink effect. On the contrary, when NEP < 0, it is reflected as carbon source effect. Therefore, it can be used for quantitative analysis of carbon sequestration status and potential of regional vegetation ecosystem. NPP is the data obtained by using the net primary productivity product MOD17A3 of EOS/MODIS, of which, the annual total value is the total amount of NEP of all pixels in a year, the mean value of the total value in a year is the sum of annual total values of NEP of all pixels divided by the number of pixels, and the maximum and minimum values of the annual total value of NEP are the maximum and minimum values of NEP in all pixels in this region in the current year. R_H is calculated with the regression equation of temperature, precipitation, and carbon emissions [27], and the calculation formula is:

$$\mathrm{R_H} = 0.22 \times [e^{0.0913\mathrm{T}} + \ln(0.3145\mathrm{R} + 1)] \times 30 \times 46.5\% \quad (2)$$

In formula (2), conventional meteorological data are used. T (℃) is the monthly mean temperature, and R(mm) is the monthly precipitation.

Since construction land and unused land are carbon sources, when calculating NPP, the pixel values of such land types are removed in advance.

2.3.2. Analysis of NEP change trend

In order to quantitatively describe the change law of NEP in the Yangtze River Delta Region in the past 20 years, unitary linear regression analysis method was used to analyze the change trend of NEP of each pixel in this region from 2000 to 2010. The trend line of a single pixel is simulated by unitary linear regression from the pixel values of that pixel within 20 years [28]. The calculation formula for the slope of the trend line is:

$$\theta_{\text{slope}} = \frac{n\times\sum_{i=1}^{n} i\times NEP_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} NEP_i}{n\times\sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \quad (3)$$

In formula (3), θ_{slope} is the slope of the trend line; i is the serial number of the year 1–20; NEP_i represents the NEP value of the i year. It reflects the overall change trend of NEP of each pixel during these 20 years. If $\theta_{slope} > 0$, it means that the change trend of NEP is increasing, otherwise it is decreasing.

2.3.3 Evaluation Model

The NEP values of observation stations are converted with the water heat balance vegetation net first productivity model proposed by Zhou Guangsheng [29], and compared and verified to verify the accuracy of MOD17A3-NEP data results. The water heat balance vegetation net primary productivity model uses the precipitation and net radiation data obtained from the land surface to obtain the regional potential vegetation net primary productivity, i.e.:

$$NPP = RDI \cdot \frac{r\cdot Rn\left(r^2+Rn^2+r\cdot Rn\right)}{(r+Rn)\cdot(r^2+Rn^2)} \cdot Exp\left(-\sqrt{9.87+6.25RDI}\right) \quad (4)$$

Where *RDI* is radiation dryness; *RN* is the annual net radiation (mm); *R* is annual precipitation (mm); *NPP* is the net primary productivity of vegetation ($10^2 g\cdot m^{-2}\cdot a^{-1}$).

Formula (4) can be further sorted as follows:

$$NPP = RDI^2 \cdot \frac{r\cdot\left(1+RDI+RDI^2\right)}{(1+RDI)\cdot(1+RDI^2)} \cdot Exp\left(-\sqrt{9.87+6.25RDI}\right) \quad (5)$$

It is not suitable for predicting the net primary productivity of terrestrial ecosystem under the condition of global change due to the calculation of annual radiation obtained from the land surface requires climate variables, such as solar radiation at the top of the atmosphere, possible sunshine hours, actual sunshine hours, reflectivity, air temperature, air humidity, altitude and dimension. It is found that there is a highly significant correlation between possible evapotranspiration rate (per) and annual radiation dryness (*RDI*) through analysis, i.e.:

$$RDI = (0.629 + 0.237PER - 0.00313PER^2)^2 \quad (6)$$

The correlation coefficient is 0.90. Among them, PER is obtained by using the relationship between Holdridge's possible evapotranspiration rate and biological temperature and precipitation:

$$PER = \frac{PET}{r} = BT \cdot \frac{58.93}{r} \quad (7)$$

Where: pet is the possible evapotranspiration (mm), BT is the annual average biological temperature (℃).

$$BT = \sum \frac{t}{365} \text{或} = \sum \frac{T}{12} \quad (8)$$

Where, t is the daily average temperature of < 30℃ and > 0℃, and t is the monthly average temperature of < 30℃ and > 0℃.

The NPP value of the observation station can be obtained from formula (5) – (8), and the NEP value can be converted by combining the R_H value of the observation station.

2.4 Sequence mutation point recognition method

Mann-Kendall test [30] is a nonparametric test method widely used in hydrology, meteorology and other fields. Its advantage is that it does not need samples to follow a certain amount of distribution and is not disturbed by abnormal values. It is suitable for

type variables and sequential variables. It has simple calculation, can clarify the start time of mutation and point out the region of mutation. It is a common mutation detection method. Sample size is n's original time series y, r_i represents the i^{th} sample $y_i > y_j$ (1≤j≤i) cumulative number, whose statistics are:

$$S_k = \sum_{i=1}^{k} r_i \ , (k = 1,2,\cdots,n) \quad (9)$$

S_k average value $E(S_k)$ and variance $Var(S_k)$ are respectively:

$$E(S_k) = k(k-1)/4 \qquad Var(S_k) = k(k-1)(2k+5)/72 \quad (10)$$

Standardize S_k as:

$$UF_k = \frac{S_k - E(S_k)}{\sqrt{Var(S_k)}} \ , (k = 1,2,\cdots,n) \quad (11)$$

UF_k forms a UF curve, and whether there is an significant change trend can be obtained through the reliability test. This method is applied to the inverse sequence to calculate another curve UB, and the intersection of the two curves within the confidence interval is determined as the mutation point. If $UF > 0$, the sequence shows an upward trend, otherwise it shows a downward trend. When UF or UB exceeds the critical value (± 1.96), it indicates a significant upward or downward trend. If has an intersection between the two curves of UF and UB, and the intersection is between the critical values, the time corresponding to the intersection is the start time of mutation.

3. Results

3.1. Evaluation of estimation precision

At present, there are two kinds of accuracy evaluation methods: one is based on field observation data; the other is comparative analysis and evaluation based on the research results recognized by peer experts. It is difficult to verify the field observation data of NPP or NEP with a large range and multiple vegetation types due to the large scope of the study area. The acquisition cycle of field observation data is long, and the acquisition time is difficult to match the model simulation time. The two are not comparable to a certain extent due to the influence of climate change and other factors. The similarities and differences of the three models (Miami model, Thornthwaite model and water heat balance vegetation net first productivity model) are compared and verified with the recommended value of the International Biological Program (IBP) based on the above considerations and the analysis of relevant literature within the study area. Because the NPP simulation value of the vegetation net first productivity model is close to the recommended value of local IBP in Zhejiang [31], the model is based on the regional evapotranspiration model of energy balance equation and water balance equation. It can more truly reflect the characteristics of plant physiology and ecology and the relationship between water and heat balance. Therefore, this study selects the vegetation net primary productivity model with partial overlap and verified accuracy in the study area to evaluate the reliability of MODIS net primary productivity product MOD17A3. It is found that the conversion value of the net productivity of the vegetation to the net productivity of the MOD17A3 model is small compared with the conversion value of the net productivity of the MOD17A3 model. The fitting results are shown in Figure 2. There is a good correlation between the product data value and the model data value, with the determination coefficient $R^2 = 0.8479$ and the fitting curve is significantly correlated ($P < 0.01$), indicating that the NEP data converted by MOD17A3 product is reliable.

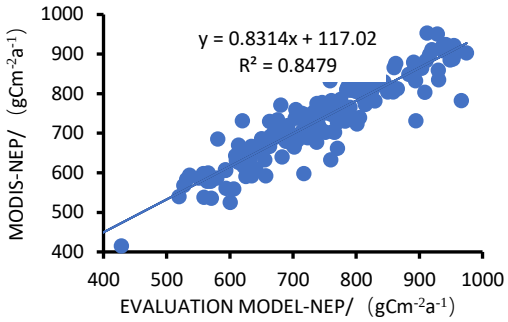


Figure 2. Comparison between MODIS-NEP and vegetation net primary productivity model.

3.2. Spatial distribution characteristics of NEP

NEP represents the net absorption or net storage of carbon in the vegetation ecosystem, which can quantitatively describe the carbon source/sink capacity of the vegetation ecosystem. When NEP > 0, it means that the ecosystem plays the role of carbon sink, otherwise it plays the role of carbon source [17]. Therefore, as a key parameter to characterize vegetation activities, the accurate estimation of NEP not only can measure the health of vegetation ecosystem, but also can quantitatively analyze the carbon sequestration status and potential of regional vegetation ecosystem.

After removing the two land cover types of construction land and unused land in the Yangtze River Delta year by year, the annual mean NEP of each pixel in the remote sensing image of the Yangtze River Delta Region from 2000 to 2019 was calculated, and the spatial distribution map of the annual mean NEP value of this region in 20 years was obtained (Figure 3), which showed that: from 2000 to 2019, the overall spatial distribution pattern of the mean vegetation NEP in the Yangtze River Delta Region presented the trends of higher in the south and lower in the north, higher in the east and lower in the west, and increasing from the northwest to the southeast. Combined with the elevation information in Figure 1, it can be found that the NEP of mountain areas is generally higher than that of the main channels of the Yangtze River and urban surroundings, which is mainly because there are many adult forests in mountain areas, the temperature is low, and the R_H is small. In addition, it can be found that there is a clear boundary in Anhui Province, the NEP of areas south of the Yangtze River is generally higher than that of other areas, the reason is that there is more cultivated land in the north of the Yangtze River and more forests in the south of the Yangtze River. The mean NEP of each pixel in the terrestrial ecosystem in this region is mostly higher than 0 in the past 20 years, so carbon sink is dominant, and the proportion of pixels with NEP > 0 is much larger than that of carbon sources (including construction land and unused land), accounting for more than 85% of the total area of the Yangtze River Delta Region, but the areas with very high NEP value (NEP > 600 g C·m^{-2}·a^{-1}) accounts for less than 1.3%, and the high-value areas are mainly distributed in the Wenzhou, Taizhou, Lishui and Zhoushan (south of Zhejiang Province of China). These areas have high terrain, lush vegetation, and a forest coverage as high as more than 70% [32], and the carbon sequestration amount of vegetation is much higher than the carbon emissions from soil microbial respiration. In addition, the proportion of pixels with a mean NEP < 0 is relatively small, and these pixels are mainly distributed in Shanghai, Suzhou, Hangzhou, and Nanjing of China, etc. These areas have relatively low forest coverage rate, their industrial structures mainly include the industries with high energy consumption and high carbon emissions, such as heavy industry and manufacturing industry, and the construction land expands rapidly [5], so the carbon sink capacity is weak, and the carbon source is dominant. After the statistics of the average annual NEP of the Yangtze River Delta region in recent 20 years, the results show that the average annual NEP of the Yangtze River Delta region is 253.2 g C·m^{-2}·a^{-1}, of which the highest is 355.9 g C·m^{-2}·a^{-1} in

Zhejiang Province of China, then 212.4 g C·m^{-2}·a^{-1} in Jiangsu Province, 208.0 g C·m^{-2}·a^{-1} in Anhui Province of China, and the lowest is 188.5 g C·m^{-2}·a^{-1} in Shanghai of China. The first Zhejiang Province of China is much higher than the last three.

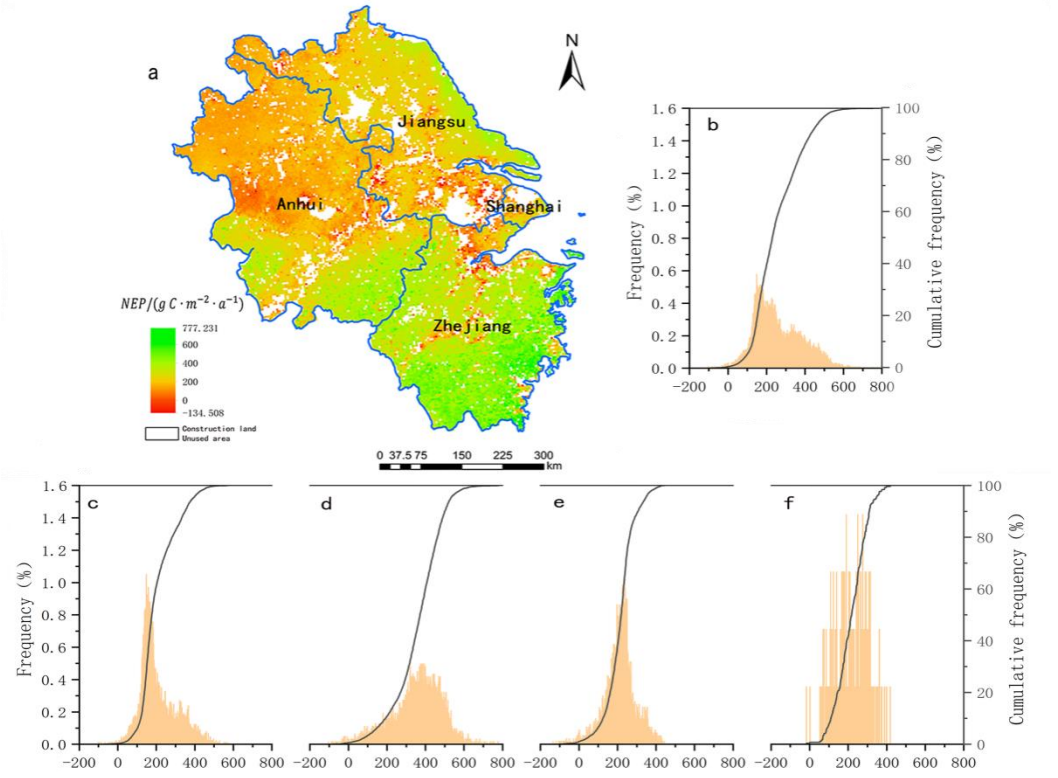


Figure 3. a. Spatial distribution of NEP mean value in Yangtze River Delta from 2000 to 2019. NEP mean distribution frequency: b. Yangtze River Delta region c. Anhui d. Jiangsu e. Zhejiang f. Shanghai

3.3. *Interannual variation characteristics of NEP*

The total NEP value per unit area of the terrestrial vegetation ecosystem in of the Yangtze River Delta Region in each year from 2000 to 2019 was calculated, and the mean NEP value of the Yangtze River Delta Region in each year over the 20 years, the maximum and minimum NEP values in the research area, and the interannual variations of the proportion of pixels with NEP > 0 were obtained (Figure 4a). It can be found that: from 2000 to 2019, the annual mean NEP of vegetation in the Yangtze River Delta Region fluctuated slightly around 253 g C·m^{-2}·a^{-1}, the interannual variations were not large and presented a slightly increasing trend, the slope of the trend line (k) was 2.25, indicating that the health of the vegetation ecosystem in this region was at a high level over the past 20 years; after eliminating the carbon consumption of soil respiration in the system, the vegetation in the entire Yangtze River Delta Region played the role of carbon sink, and the carbon sequestration capacity increased to some extent. The maximum values of NEP under vegetation coverage in this region in these years appeared in southern Zhejiang, and all such NEP values exceeded 750 g C·m^{-2}·a^{-1}, but the interannual fluctuations were large, and the values generally presented a relatively significant upward trend, the slope of the trend line (k) was 3.50, indicating that the maximum carbon sequestration capacity of the vegetation ecosystem in southern Zhejiang increased significantly and was greatly affected by the external environment. During the same period, the location where the minimum NEP occurred in this region was not fixed, and there was no law. The minimum value fluctuated around –233 g C·m^{-2}·a^{-1}, although the interannual variation was small, the values generally presented a downward trend, the slope of the trend line (k) was –3.13, indicating that the carbon emissions from soil microbial respiration in the

vegetation ecosystem in this region increased significantly, and the vegetations in these locations were weakened. Comparing these three NEP values, it can be found that the change and increase in the mean value of NEP in this region were mainly realized by the change of the maximum value of NEP in this region. In addition, it can be found that the proportion of pixels with NEP > 0 fluctuated around 90%, and the interannual change was relatively stable, and the proportion increased slightly irrespective of the value with the trend line slope is closely to zero.

Compared with the interannual variation of the average NEP of three provinces and one city (Fig. 4b), it can be found that the carbon sequestration capacity of Zhejiang Province of China is much higher than that of the other three places. Although there are large fluctuations in each year, there is no significant change trend, and the overall development is relatively stable. The average NEP of Jiangsu Province of China is slightly higher than that of Anhui Province of China, but the increasing trend of Anhui Province of China is higher than that of Jiangsu Province of China. The average value of NEP in Shanghai of China is the smallest and is decreasing year by year.

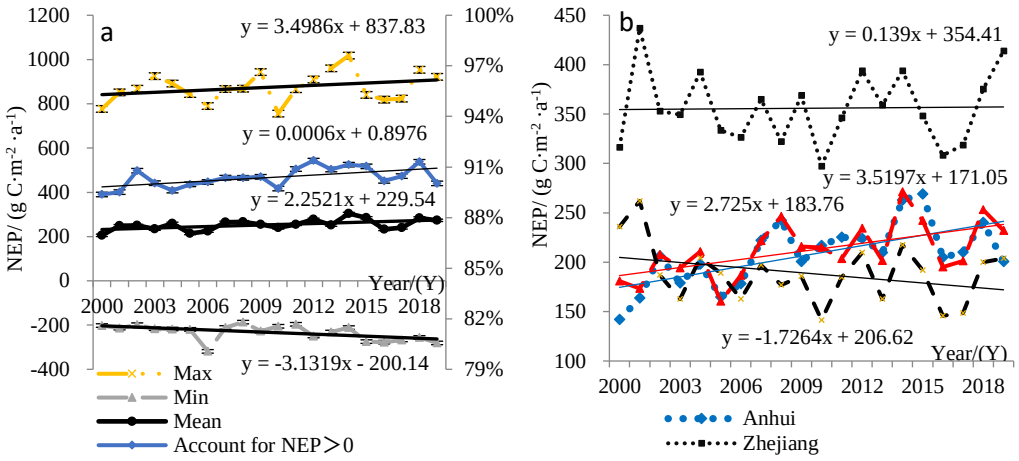


Figure 4. From 2000 to 2019 a. Interannual variation of annual mean, maximum, minimum and NEP > 0 in the Yangtze River Delta b. Interannual variation of mean NEP in Anhui, Jiangsu, Shanghai and Zhejiang.

Through the identification of time series mutation points for the average NEP of each year in the Yangtze River Delta from 2000 to 2019 (as shown in Figure 5), it is found that the UF curve in the Yangtze River Delta has multiple intersections with the critical value after 2011. Therefore, NEP has an upward trend before 2013, but the trend is not significant. NEP has increased significantly from 2013 to 2016, and the upward trend slows down after 2016. UF and UB curves have two intersections in 2004 and 2006. It can be considered that 2006 is the mutation point, and NEP begins to rise. The UF and UB curves of Anhui Province of China have an intersection between the critical values in 2005, and exceeded the critical value after 2008. Therefore, the NEP of Anhui Province increased significantly after 2008 and mutated in 2005. There was an intersection point between UF and UB curves in Jiangsu Province of China in 2006. NEP fluctuated and changed before 2006, and there were several turning points, but it was not significant. NEP increased after 2006 and exceeded the critical value after 2013–2016. Therefore, NEP mutated and tended to rise in 2006. Shanghai UF and UB curves have an intersection between the critical values in 2001 and are within the critical value, so their NEP began to decline after 2001, but the trend is not significant. The UF and UB curves of Zhejiang Province of China are basically within the critical value of significance level a = 0.05. UF and UB have several intersections and fluctuate in the years with intersections, but the change trend is not significant and there is no mutation.

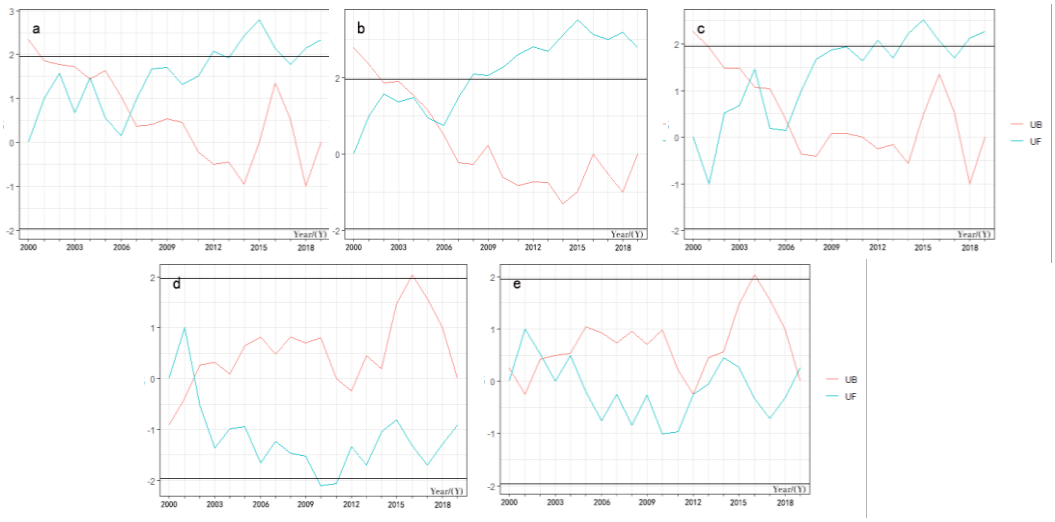


Figure 5. identification of m-k mutation point of NEP value in Yangtze River Delta region (a. Yangtze River Delta region b. Anhui of China c. Jiangsu of China d. Shanghai of China e. Zhejiang of China).

Identify the time series mutation points of the proportion of NEP > 0 in each year of the Yangtze River Delta from 2000 to 2019 (as shown in Figure 6). It is found that the UF and UB curves of NEP > 0 in the Yangtze River Delta have an intersection between the critical value in 2005 and exceeded the critical value after 2009. Therefore, the proportion of NEP > 0 in the Yangtze River Delta increased significantly after 2009 and mutated in 2005. Combined with figure 5, it can be found that the increase of NEP value in the triangle area is mainly caused by the increase of the area of terrestrial ecosystem where the underlying surface plays the role of carbon source. Comparing the respective situations of three provinces and one city in the Yangtze River Delta region, it is found that there is only one intersection point between the critical values of UF and UB curves. Shanghai of China appeared the earliest, and the mutation point appeared in 2001. After 2005, the proportion of NEP > 0 began to decrease significantly; Jiangsu and Zhejiang of China took the second place. The mutation point appeared in 2004, but the proportion of NEP > 0 in Jiangsu began to decrease significantly after 2004, while Zhejiang of China showed a significant decrease from 2007 to 2011 and after 2014; Within the critical range of UF curve in Anhui, the proportion of NEP > 0 has increased, but it is not significant.

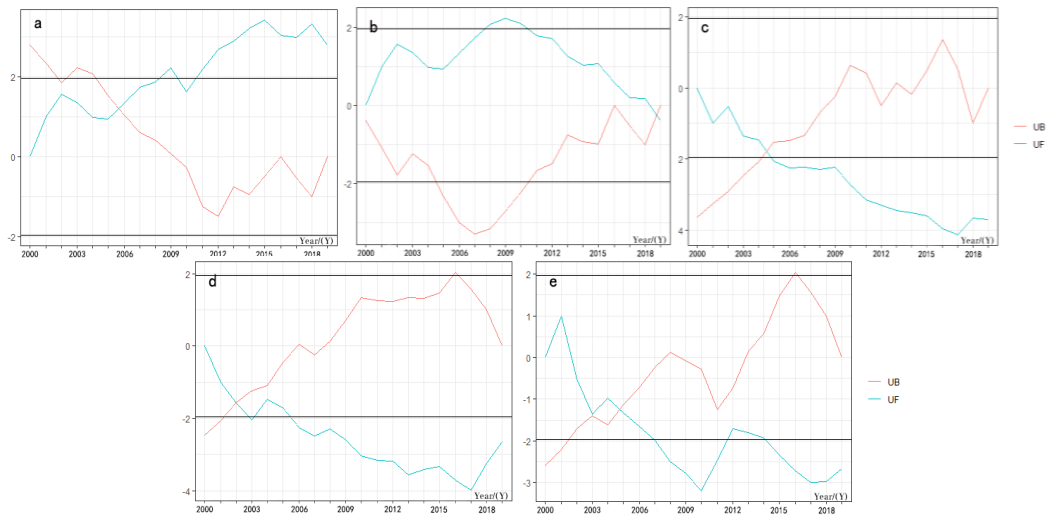


Figure 6. identification of m-k mutation points with NEP > 0 in Yangtze River Delta region (a. Yangtze River Delta region b. Anhui of China c. Jiangsu of China d. Shanghai of China e. Zhejiang of China).

3.4. NEP characteristics of different vegetation cover types

In order to research the distribution of carbon source/sink capacity of terrestrial vegetation ecosystems under different vegetation cover types, the data merger results of land cover types were used, as shown in Figure 7 (taking 2010 as an example). Comparing the land cover type diagram and the NEP distribution diagram, it can be found that there is significant consistency between the two diagrams over the past 20 years, that is, the areas around the construction land and unused land well correspond to the carbon source areas, and the areas of woodland, shrubs and grassland well correspond to the areas with strong carbon sink capacity.

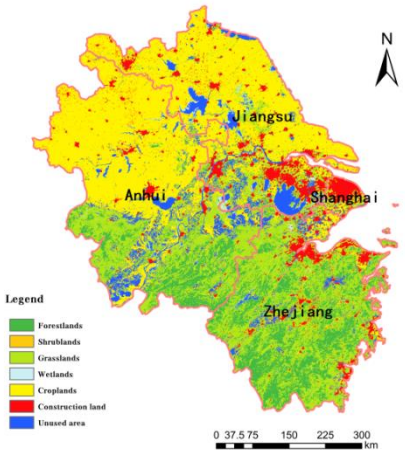


Figure 7. Land cover types in Yangtze River Delta (2010).

In addition, in order to research the changes in the carbon sink capacity of different vegetation cover types and the differences in carbon sink capacity of different land cover types in the past 20 years, the annual changes in NEP (Figure 8) and the mean values of NEP (Table 1) under different vegetation cover types (including grasslands, croplands, forestlands, and wetlands) in the Yangtze River Delta Region were recorded for these 20 years respectively. It can be seen from Table 1 that the carbon sink capacities of terrestrial vegetation ecosystems under different land cover types were different. Among them, woodland had the highest NEP and the best carbon sink capacity, the mean NEP over the 20 years was 378.37 g $C \cdot m^{-2} \cdot a^{-1}$; followed by the grassland, 304.55 g $C \cdot m^{-2} \cdot a^{-1}$; the land cover types with lower carbon sequestration capacity were cultivated land and wetland, with NEP values of 192.17 g $C \cdot m^{-2} \cdot a^{-1}$ and 185.80 g $C \cdot m^{-2} \cdot a^{-1}$ respectively, the construction land and the unused land were carbon sources.

Table 1. Average NEP values of different land cover types.

Vegetation Cover Type	Mean NEP ($gC \cdot m^{-2} \cdot a^{-1}$)	Carbon Source/Sink	Standard Deviation
Forestlands	378.37	Carbon Sink	31.51
Grasslands	304.55	Carbon Sink	25.96
Wetlands	185.80	Carbon Sink	23.79
Croplands	192.17	Carbon Sink	34.77
Built-up Lands	\	Carbon Source	\
Unused lands	\	Carbon Source	\

It can be seen from Figure 6 that the annual mean NEP values under different vegetation coverage types fluctuated to varying degrees from 2000 to 2019, but the interannual fluctuations of woodland, grassland and wetland had a good consistency, while cultivated land was less consistent with the interannual variation fluctuations of the

above three types of vegetations. This may be due to woodland, grassland and wetland are less affected by human activities and are mainly affected by the external natural environmental factors, but cultivated land is affected by the external natural environment and human activities, which cause slight differences. Through linear trend analysis, under the four vegetation cover types, NEP all presented an upward trend, but the annual mean NEP value of woodland had a small increase trend over the years, and the slope was only 0.1, while the slope of grassland and wetland was 1.5, and the slope of cultivated land reached up to 2.35. This may be due to climate warming and the doubling of CO2 concentration have better growth promotion and yield increase effects on rice, wheat, corn and other C3 crops [33], resulting in larger upward trend of NEP of the cultivated lands in Anhui and Jiangsu provinces, where rice and wheat are the main crops and the proportion of cultivated land is very large. In addition, it can also be seen that the carbon sequestration capacity of different land cover types in this region can be divided into three levels: woodland has better carbon sequestration capacity in each year; followed by grassland; wetland and cultivated land have relatively lower capacity.

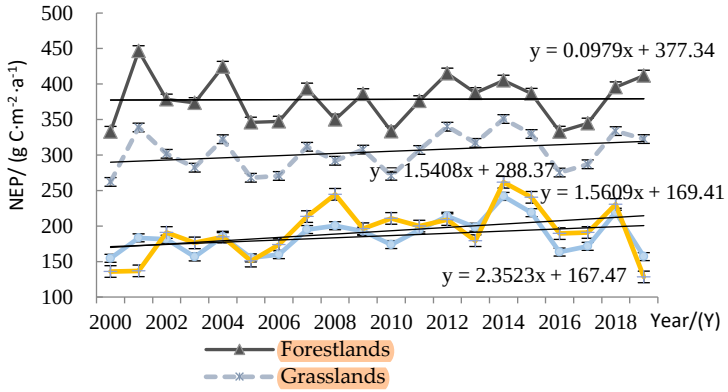
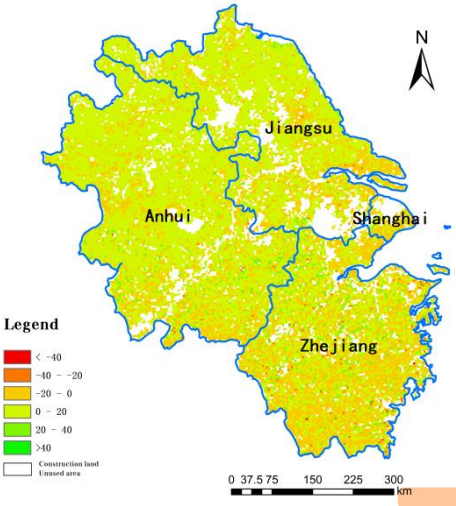


Figure 8. interannual changes of NEP of different land cover types in the Yangtze River Delta from 2000 to 2019**.**

3.5. Analysis of NEP change trend

In order to describe the spatial distribution characteristics of the NEP change trend in the Yangtze River Delta Region over the past 20 years, the unitary linear regression analysis method was used to analyze the NEP change trend of each pixel from 2000 to 2019, and the annual mean NEP variation slope was calculated pixel by pixel (Figure 9).



Delta (2000–2019).

It can be seen from Figure 9 that the change rate of the NEP value in the Yangtze River Delta Region from 2000 to 2019 was not consistent (with increase and decrease),

but increase was the dominant trend of the entire region, and the proportion of pixels with $\theta_{slope} > 0$ reached 69.0 %, that is, the carbon sink capacity increased and the carbon source capacity decreased. However, there were certain spatial differences in the entire region. The proportions of pixels in provinces and municipalities with $\theta_{slope} < 0$ in this region were 14.50% (Zhejiang Province), 9.10% (Anhui Province), 6.65% (Jiangsu Province), and 0.79% (Shanghai). In terms of the changes of pixels with $\theta_{slope} < 0$ in each province and municipality, the pixels with $\theta_{slope} < 0$ in Shanghai account for the largest proportion (62.7%), followed by Zhejiang Province (48.9%), Jiangsu Province (24.64%) and Anhui Province (21.59%). This data indirectly showed that in the past 20 years, the Yangtze River Delta Region did not stop the ecological construction at the same time of stable urban development and expansion, but the urban development and construction of Shanghai were slightly faster than the other three provinces.

3.6 Analysis of NEP and temperature and precipitation

The carbon sink capacity of natural terrestrial vegetation ecosystems in this region is not only related to the autotrophic respiration and heterotrophic respiration of terrestrial plants, but also affected by the external environments, such as climate, soil, seaside, and other conditions [34]. In addition, it is also affected by human activities. The overall annual mean NEP in the Yangtze River Delta Region from 2000 to 2019 was recorded, and the interannual variation curves between NEP and the annual mean temperature and annual precipitation were drawn (Figure 10) to analyze the relations between NEP and the annual mean temperature and annual precipitation. It is found that there is no significant correlation between the NEP and the annual mean temperature and annual precipitation factors in this region. This is due to the terrestrial vegetation ecosystem in the Yangtze River Delta Region is seriously affected by the external environment and human activities. In addition, the region has a wide range, large area, complex and diverse underlying surface, and the meteorological stations are relatively sparse. The meteorological data of all stations are simple and average throughout the year, which cannot represent the actual situation. Therefore, according to subregional statistics, it is found that the NEP values of Shanghai and Zhejiang have a negative correlation with the annual average temperature (r =–0.43), and Anhui has a positive correlation with the annual rainfall (r = 0.36).

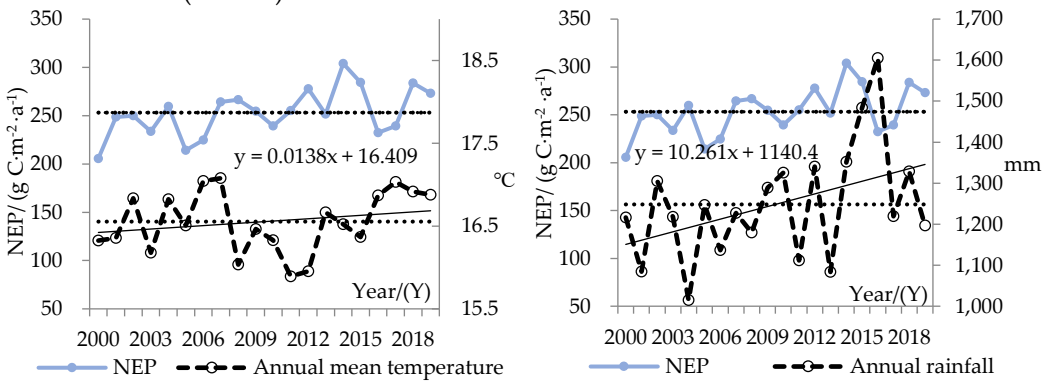


Figure 9. interannual variation of NEP, annual average temperature and annual rainfall in the Yangtze River Delta.

However, it can be seen from Figure 10 that the temperature increases in the Yangtze River Delta Region from 2000 to 2019 was very small, with a slope of only 0.04, but the precipitation increased significantly, with a slope of 11.0. The climate in the entire region is dominated by humidification. Through the identification of mutation points, it is further confirmed that there is no mutation point in the annual average temperature of the five regions, and the change trend is not obvious. Only the Yangtze River Delta and Shanghai have abrupt changes in annual precipitation, but the increase is not significant.

4. Discussion

There are certain uncertainties in the NEP results estimated in this paper, which are mainly due to the small resolution (only 500 m) of the net primary productivity product and land cover product of MODIS, the uneven distribution of the meteorological data stations used, small number of the stations (only 63), and slightly poor representativeness, resulting in the uncertainty of soil respiration estimation. The soil respiration model itself is a complex process, most of the data are on a monthly scale, and there are certain errors in the research, causing a certain uncertainty in the estimation results of NEP. In addition, there are many influencing factors of NEP, which are not only affected by the external natural environment, but also affected by human factors, especially in the economically developed area of the Yangtze River Delta. This paper takes the entire region as a whole to research the relations between NEP and annual mean temperature and annual precipitation, which is not precise enough. Therefore, after further subdivision, correlation is found in some regions. Therefore, the spatial distribution of NEP is also consistent with the research results of Jie Li et al. [35] and Rui Pang et al. [36] in terms of annual average temperature. This paper indirectly shows that the Yangtze River Delta has not stopped ecological construction while the city has developed steadily in the past 20 years.

5. Conclusions

Based on the data of MODIS net primary productivity product MOD17A3H and land cover product MCD12Q1, combined with monthly mean temperature and precipitation data, this paper calculated the NEP values in the Yangtze River Delta Region from 2000 to 2019, obtained its spatial distribution information and change characteristics, and analyzed its correlation with the annual mean temperature and annual precipitation data of the Yangtze River Delta Region. The main conclusions are as follows:

(1) From 2000 to 2019, the carbon sink area in the Yangtze River Delta was much larger than the carbon source area, the mean NEP of the vegetation ecosystem in the past 20 years was 253.2g C·m-2·a-1, and the spatial distribution presented a trend of higher in the south and lower in the north, higher in the east and lower in the west, and gradually increasing from northwest to southeast, and the NEP of mountain areas is generally higher than that of river courses and urban surroundings.From 2000 to 2019, the NEP value of the vegetation ecosystem in the Yangtze River Delta Region had small interannual fluctuations, but the changes in various years were not large and presented a slightly increasing trend, and the interannual variation of NEP was significantly correlated with the maximum NEP in this region.

(2) The carbon sink capacities of different vegetation cover types and terrestrial vegetation ecosystems were different. The carbon sink capacity can be divided into three levels: the carbon sink capacity of woodland is better than that of grassland, and the carbon sink capacity of grassland is better than that of wetland and cultivated land.

(3) From 2000 to 2019, the area of the Yangtze River Delta Region with a change rate of NEP value greater than 0 accounted for 69.0%, but there were certain spatial differences. The proportions of provinces and municipalities with $\theta_slope < 0$ in this region are 14.50% (Zhejiang Province), 9.10% (Anhui Province), 6.65% (Jiangsu Province), and 0.79% (Shanghai), but in terms of the changes of each province and municipality, Shanghai of China accounted for the largest proportion, followed by Zhejiang Province of China, the proportions of Jiangsu Province of China and Anhui Province of China were smaller.

(4) The carbon sink of the terrestrial vegetation ecosystem in the Yangtze River Delta Region is a complex process, and there is no significant correlation between its NEP and the annual mean temperature and annual precipitation factors, indicating that the capacity is not only related to the plants' own characteristics and external environment, but also is affected by human activities.

Author Contributions: Chen Zou: Investigation, Methodology, Software, Validation, Formal analysis, Visualization, Writing - original draft. Hu Li: Funding acquisition, Project administration, Resources. Donghua Chen: Investigation, Methodology. Jingwei Fan, Zhihong Liu: Software,Cartography.Xuelian Xu, Wenlue Fang:Remote sensing image processing. Jiani Li:Evaluation. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Anhui Science and Technology Major Program [grant number 202003a06020002],Anhui Province key research and development plan[grant number2021003, 202104A07020002],Anhui Province Fifth Special Support Program, Anhui University Collaborative Innovation Project [grant number GXXT-2021-048].

Acknowledgments: We would like to thank the forestry administration of ChuZhou City, Anhui Province.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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