STUDY ON THE DEVELOPMENT OF CARBON SINKS IN TERRESTRIAL ECOSYSTEMS: THE YANGTZE RIVER DELTA REGION AS AN EXAMPLE

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Abstract. Given the context of global warming, it is particularly important to study the carbon sinks of terrestrial ecosystems and the extent of their contribution to carbon neutralization. This paper uses ArcGIS to derive carbon sinks in the Yangtze River Delta (YRD) region through Gross Primary Production (GPP) data and further explores the degree of carbon neutrality in the Yangtze River Delta region through the carbon source-to-sink ratio. The results show that the carbon sinks in the Yangtze River Delta region are 0.0586 PgC, 0.0505 PgC, and 0.0679 PgC from 2019 to 2021. The ratios of carbon sinks and sources are 0.1286, 0.1142 and 0.1463, respectively. Terrestrial ecosystems are important carbon sinks and play a significant role in contributing to carbon neutrality. The accessibility and ease of measuring carbon sinks with GPP data and the discussion of the ratio of carbon sources to carbon sinks also allows for the timely tracking of the carbon-neutral process so that green development strategies can be appropriately adjusted to cope with the impacts of climate change on human beings.
Keywords: *carbon sink, carbon source, GPP. Yangtze River Delta region, carbon neutrality*

Introduction

At present, global warming has seriously threatened the development of society and the survival of human beings, and it is a great and arduous task to find a solution (Akram et al., 2022; Shahzad et al., 2022; Wang, 2022). The Paris Climate Agreement sets the goal of “limiting the increase in global average temperature to 2°C” and “working towards 1.5°C” (Redlin and Gries, 2021; Sun et al., 2022). Chinese President Xi Jinping has stated that China will reach peak carbon emissions by 2030 and aim to be carbon neutral by 2060. The Economic Conference of the Central Committee of the Communist Party of China (CPC) included “achieving carbon peaks and carbon neutrality” as one of the annual key tasks, demonstrating the global determination and confidence to achieve carbon peaks and carbon neutrality (LingHu et al., 2022; Xu et al., 2022; Zhou et al., 2023). Carbon sinks play an extremely important role in carbon neutrality (IPCC, 2013). In ecosystems, carbon sinks mainly include terrestrial ecosystem carbon sinks, or “green carbon”, and marine ecosystem carbon sinks, or “blue carbon” (Friedlingstein et al., 2020; Piao et al., 2022). The average rate of atmospheric CO_2 uptake by terrestrial ecosystems is 2.35 $PgCyr^{-1}$, 0.60 $PgCyr^{-1}$ greater than the rate of absorption of CO_2 by the ocean, another important carbon sink in the atmosphere. The rate of increase of terrestrial carbon sinks (0.0415 $PgCyr^{-1}$) was significantly higher than that of marine carbon sinks (0.0299 $PgCyr^{-1}$). Among them, the interannual variation of terrestrial carbon sinks is significantly larger than that of marine carbon sinks (Friedlingstein et al., 2022, 2020; He et al., 2022). Terrestrial ecosystems provide a wide range of functions that are critical to the planet, such as fixing carbon dioxide, purifying air, maintaining water, preserving soil, and maintaining biodiversity,

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It is important in the context of global climate change and carbon neutrality (Heimann and Reichstein, 2008; Houghton et al., 1998; Le Quere et al., 2014; Xu et al., 2018; Yang et al., 2022). Forest ecosystems, as a major component of the terrestrial biosphere, not only does it play a key role in energy balance and water circulation, and it also plays a key role in regulating the climate, carbon cycle and mitigating climate warming (Chu et al., 2019; Pan et al., 2011; Wang et al., 2020).

Measurements of terrestrial carbon sinks can be broadly categorized into two types: bottom-up and top-down. Commonly used “bottom-up” methods include inventory methods, eddy correlation methods, and ecosystem process model simulations. The “top-down” estimation method mainly refers to the atmospheric inversion method based on atmospheric CO_2 concentration inversion of carbon sinks in terrestrial ecosystems. There is no specific standard for ecosystem carbon sink measurement methods (Piao et al., 2022). Dai et al. (2020) used remote sensing techniques combined with field observation data, The average value of vegetation carbon sink in the Poyang Lake wetland was monitored as 401 gCm^{-2} $year^{-1}$, it was argued that as the quality of satellite images continues to improve, the vegetation index (VI) had great potential for carbon sink assessment. Chu et al. (2019) used the InVEST model to assess the level of forest carbon sink in three northern protected forests, The results of the study showed that the forests in the Three Northern Protected Forests area had a strong carbon sequestration capacity. Total carbon sequestration fluctuates, with an overall decreasing trend and a decrease rate of 1.92% from 1990 to 2015. Wang et al. (2020) measured the degree of change in the total carbon sink of terrestrial ecosystems in China more accurately by measuring the atmospheric molar fraction and using remote sensing techniques. Based on these data, it was estimated that for the period 2010 to 2016, China’s terrestrial biosphere absorbed an average of - 1.11 ± 0.38 billion tons of carbon per year, equivalent to about 45% of China’s annual anthropogenic emissions during the same period. Piao et al. (2005) proposed a satellite-based method for estimating forest biomass carbon pools in China based on forest inventory data from 1984 to 1993 and 1994 to 1998, combined with NDVI information, the changes in forest carbon storage over the past 20 years were analyzed, and the results showed that the average total biomass carbon pool in Chinese forests during this period was 5.79 PgC, and the average biomass carbon density was 45.31 MgC/ha. Wei et al. (2022) examined the relationship between regional carbon sinks and net primary productivity (NPP) by accounting for NPP in Shaanxi Province, providing a new perspective on the relationship between NPP and carbon sink capacity. The limitation is that soil respiration has a large uncertainty in the measurement process, which reduces the accuracy of the measurement.

The previous literature has done a lot of research on the measurement of carbon sinks. However, existing literature rarely used GPP data directly to measure carbon sinks, and integrate carbon sinks with carbon sources, and analyze their development status. This paper used GPP to measure the regional carbon sink and provides a new perspective on carbon sink measurement. The Yangtze River Delta region is high in the south and low in the north, the north is mostly plain, the west and south are mainly mountainous hills, the natural vegetation is mostly arable land in the north, the west and south are mainly woodlands, the ecosystem is complex and diverse. Since the reform and opening up, the region has experienced rapid economic development and comprehensive urbanization, and changes in land use types in the region have led to significant changes in regional soil organic carbon storage.

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In summary, this paper evaluated the carbon sinks of terrestrial ecosystems in the Yangtze River Delta from 2019 to 2021 based on GPP data of land use in the region from 2019 to 2021. The specific objectives were: (1) to measure the carbon sinks of terrestrial ecosystems in the Yangtze River Delta; (2) to build the relationship between carbon sources and sinks in the region; (3) to explore the regional carbon neutrality processes.

Materials and methods

Study area

In this paper, the carbon sink measurement target was selected from the Yangtze River Delta region (*Fig. 1*), with latitude N31°and longitude E121°. It is located in the eastern coastal region of China, close to the Yellow Sea and the East China Sea, and has many coastal ports. The Yangtze River Delta city cluster includes Shanghai, Anhui Province (16 prefecture-level cities), Jiangsu Province (13 prefecture-level cities), and Zhejiang Province (11 prefecture-level cities), for a total of 41 cities (Deng et al., 2022). The total area is 211,700 km2, accounting for 2.20% of the total area of the country. The population in 2021 will be 165 million, accounting for 12.43% of the total population of the country. The region’s GDP reaches 20.51 trillion yuan, accounting for 20.93% of the country’s GDP. The northern part of the country is dominated by plains and the southwestern part by hills (Wang et al., 2019).

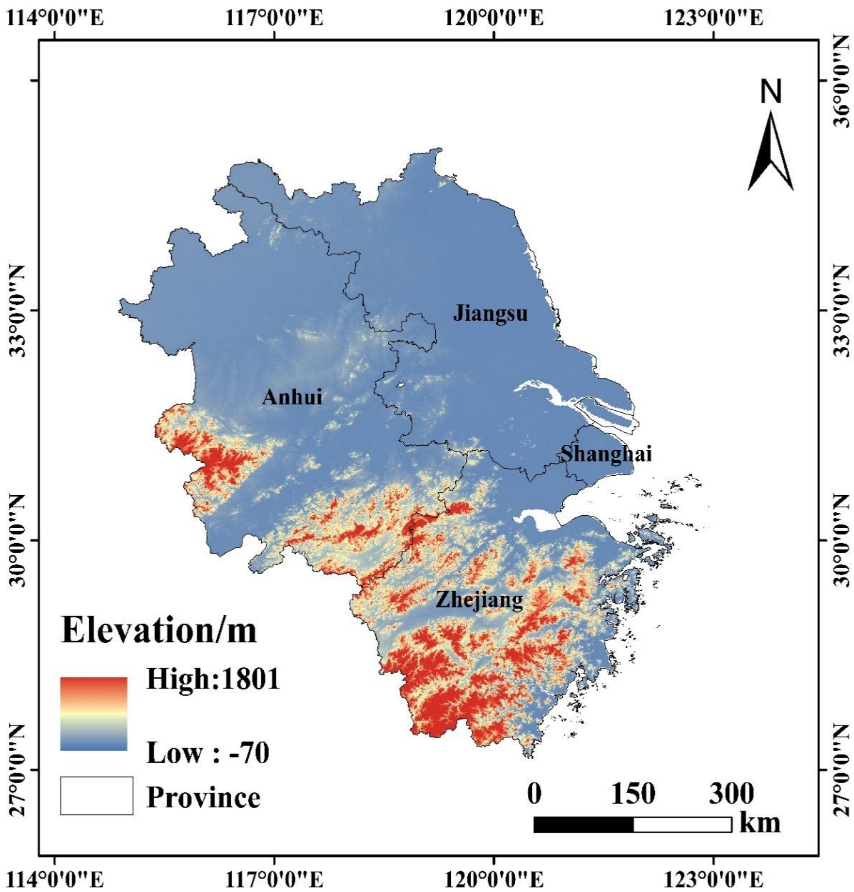

Figure 1. *Study area*

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Data sources

The Terra/MODIS Gross Primary Productivity product (MOD17A2H) is a cumulative composite of GPP values based on the concept of radiation use efficiency and can be used as an input to data models to calculate terrestrial energy, carbon, and water cycle processes and vegetation biogeochemistry. MOD17A2H is an 8-day composite material with a spatial resolution of 1 km, delivered as a gridded Level 4 product in sinusoidal projection (https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD17A2H). This paper selected the GPP data of 2019, 2020, and 2021 in the Yangtze River Delta region.

Data processing

In this study, ArcGIS was used to preprocess the MODIS GPP annual value data set, such as projection conversion, resampling, data format conversion, image cropping and splicing. Carbon sinks can be obtained from regional GPP values minus terrestrial ecosystem respiration (Zhang et al., 2015). Due to the rapid development of remote sensing and geoinformation technology, studies on the terrestrial ecological carbon cycle have emerged, but for ecosystem respiration, there are still uncertainties in the relevant models (Barba et al., 2018; Migliavacca et al., 2011; Speckman et al., 2015). Therefore, in this paper, the respiration of terrestrial ecosystems is converted from the global average annual respiration of terrestrial ecosystems using the results of existing studies (Ai et al., 2018; Chen et al., 2019; Li, 2022). However, due to the uncertainty of ecosystem respiration measurement and the lack of direct use of terrestrial ecosystem respiration in the study area, which was converted, there is bound to be some bias in the accuracy.

Results

Remote sensing satellites (Remote sensing refers to the technology of detecting the radiation, reflection, or scattering characteristics of electromagnetic waves (including light waves) from ground objects by means of sensors mounted on remote sensing platforms, such as artificial satellites or airplanes, without direct contact with the target object or even far away from the object, so as to perceive a certain characteristic of the target and to analyze it, and it has been widely used in ecological protection.) Frohn (1998) could not observe carbon sinks such as lakes, this observation was slightly smaller than the actual value, and the carbon sinks of terrestrial ecosystems in the Yangtze River Delta region for three years 2019, 2020, and 2021 are shown in *Table 1*.

Table 1. *Carbon sinks in the Yangtze River Delta*

Year	Carbon sink (PgC)
2019	0.0586
2020	0.0505
2021	0.0679

According to *Figure 2* and *Table 1*, it could be observed that the carbon sink in the Yangtze River Delta region gradually decreases from south to north, and the overall trend of the total carbon sink was increasing. The total terrestrial ecosystem carbon sink

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in the Yangtze River Delta region in 2021 was 0.0679 PgC, an increase of 15.87% from 0.0586 PgC in 2019 and 34.46% from 0.0505 PgC in 2020. In terms of contribution, terrestrial ecosystem carbon aggregation in the Yangtze River Delta region was concentrated in Zhejiang Province, while Anhui Province had fewer terrestrial ecosystem carbon sinks compared to other regions and had more room for development.

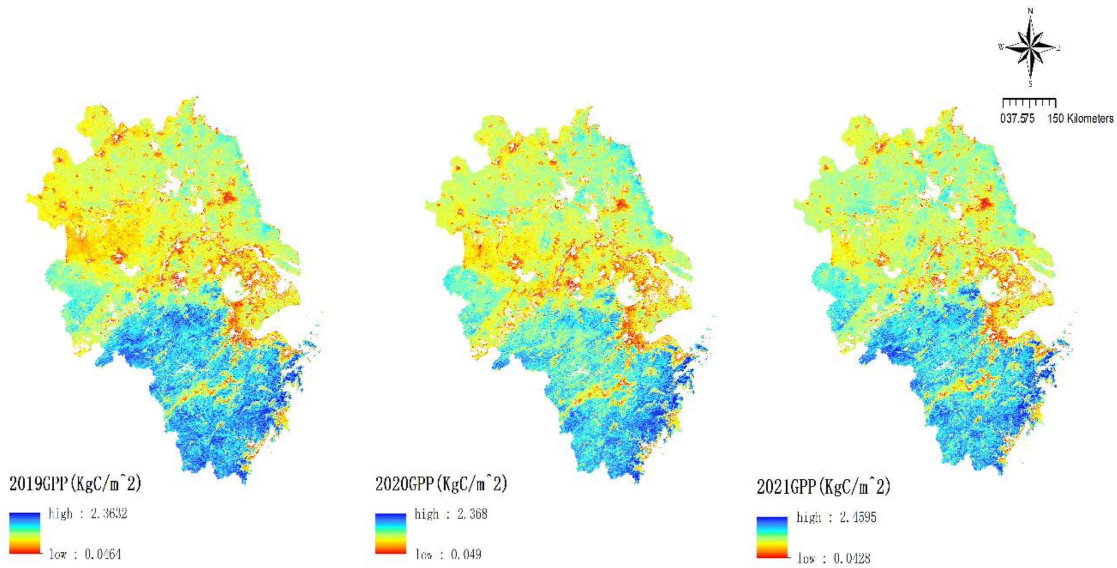

Figure 2. *GPP in the Yangtze River Delta*

The carbon sinks in the Yangtze River Delta were mainly concentrated in the southern part of the region, cultivated land in these areas played a major role in carbon sinks, and the share of carbon sink capacity was the largest in Zhejiang and Anhui, followed by Jiangsu and Shanghai. The distribution of carbon sinks from 2019 to 2021 and the trend of change in this paper were also consistent with Zhou’s study (Zou et al., 2022). Ma et al. (2023) validated the land layout of the Yangtze River Delta region using a land transfer matrix and concluded that urbanization was the main reason for the weakening of carbon sequestration capacity from 2000 to 2020, which fit with the decline in carbon sinks from 2019 to 2020 in this paper. Combined with previous studies, the use of GPP to measure carbon sinks had a certain degree of accuracy. Compared with other top-down and bottom-up carbon sink measurements, the GPP methodology for examining carbon sinks in the YRD region had the advantage of being quick and easy to obtain GPP data and was relatively accurate, but the limitations were also quite obvious. Vegetation respiration data were more difficult to obtain and measure and added uncertainty to the accuracy of GPP measurements of carbon sinks.

Discussion

The connotation of carbon sink to carbon source ratio

The connotation of the carbon sink to carbon source ratio is that the carbon sink to carbon source ratio is infinitely close to 1. In the denominator part, according to the double carbon target planning, the carbon emission curve should be a concave function

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that increases first and then decreases. The carbon sink curve should be a general curve with a gentle upward trend. Considering only the ecological carbon sink, the two will not intersect at the current level of development, and the carbon sink will not exceed the carbon emissions, thus forming a certain carbon sink gap, and this carbon sink gap should be made up using artificial technologies such as CCUS, making the carbon sink to carbon source ratio infinitely close to 1 so as to achieve a balanced development of carbon sink.

The reason why we examined its carbon sink to carbon source ratio instead of directly observing the net carbon sink, is mainly based on the fact that the ratio will stabilize at a value of 1 under the carbon neutrality target. When the ratio is less than 1, it means that the carbon source is larger than the carbon sink, and the amount of carbon sink is not enough to neutralize the greenhouse gases, so we need to increase the sink and reduce the source to make the ratio converge to 1. The method is carbon sink side, increasing environmental protection and strengthening ecological civilization. carbon source side, adjusting the industrial structure, and increasing the use of clean energy. But these adjustments take longer, and the relatively quicker way is still to increase the amount of carbon sequestered by CCUS. Therefore, in the long term, when the ratio is less than 1, it will be constantly converged to 1 by adjusting the ecological carbon sink and the industrial structure of carbon source measurement, and in the short term, it will be constantly converged to 1 by adjusting the amount of carbon sequestered by CCUS.

When the ratio is greater than 1, this is a more extreme situation, which may occur due to the completion of the restructuring of the carbon source measurement industry, or the amount of carbon sequestered by CCUS is not optimal. In this case, cost savings and energy efficiency can be achieved by reducing the use of CCUS or by increasing the use of efficient energy sources such as coal in the carbon source measurement.

In summary, whether the carbon sink to carbon source ratio is greater than 1 or less than 1, the value converges to 1 in a carbon-neutral context. When it is less than 1, adjust the industrial structure, increase the use of clean energy, and increase the amount of carbon sequestered by CCUS. When it is greater than 1, it reduces CCUS use, saves costs, increases efficient energy use, and improves efficiency.

So based on the carbon neutral condition that the ratio of carbon sink to carbon source tends to be 1, it is easier to observe the carbon neutral process clearly.

Ratio analysis

Carbon dioxide emission data of the Yangtze River Delta region is presented in *Table 2*.

Table 2. *CO_2 emissions by provinces in the Yangtze River Delta, 2019-2021*

	2019 (Mt)	**2020 (Mt)**	**2021 (Mt)**
Shanghai	17031.0	15882.1	16744.2
Zhejiang	38118.1	36883.4	38797.5
Jiangsu	72403.0	70186.4	73356.1
Anhui	39072.5	38553.7	40711.1
Total	166624.6	161505.6	169638.9

Data source: MEICModel

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As shown in *Figure 3*, the overall trend of carbon emissions in the Yangtze River Delta region kept increasing, decreasing slightly in 2020, yet increasing sharply in 2021.

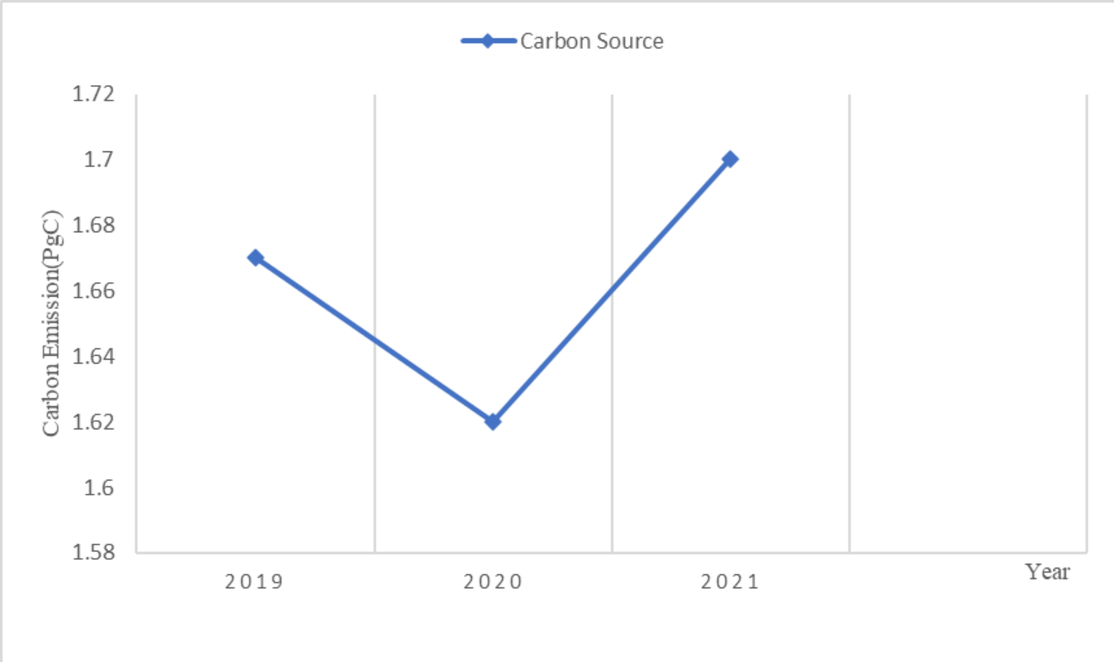

Figure 3. *Carbon source trends in the Yangtze River Delta from 2019 to 2021*

According to *Figure 4*, the trend of carbon sinks in the Yangtze River Delta region was the same as that of carbon sources, which also declined and then increased in the last three years, so there may be a certain pattern that makes carbon sinks and sources have the same changes.

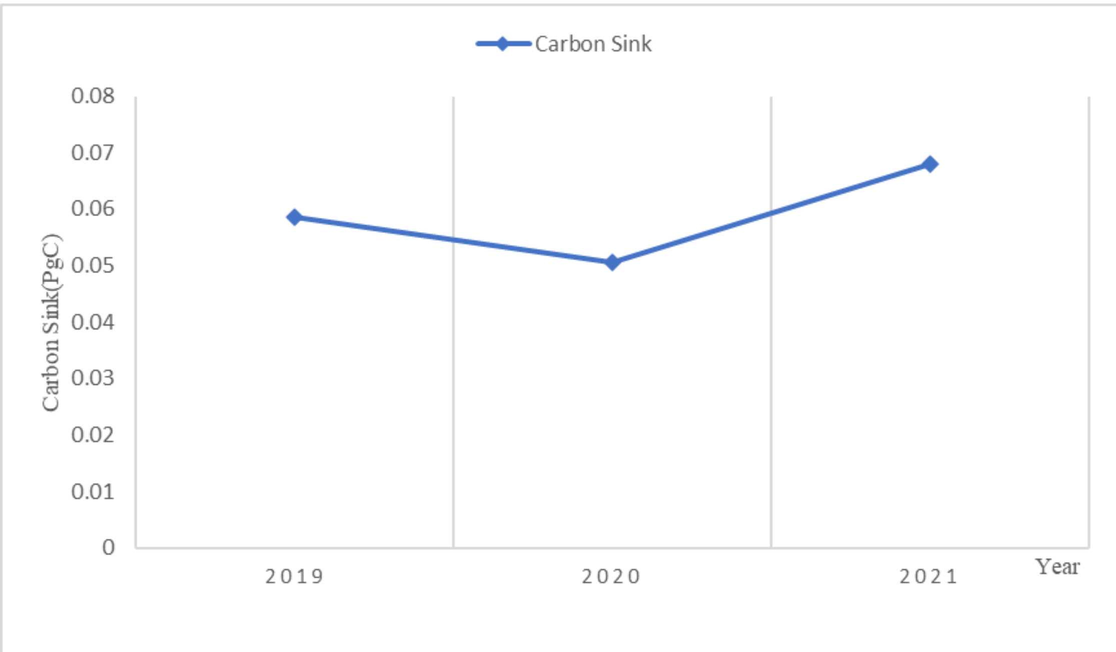

Figure 4. *Carbon sink trends in the Yangtze River Delta from 2019 to 2021*

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Considering the different units of carbon sink and carbon source, and therefore converting all quantities are presented in units of gigatons of carbon (GtC, 10^{15} gC), which is the same as petagrams of carbon (PgC). Units of gigatons of CO_2 (or billion tons of CO_2) used in policy are equal to 3.664 multiplied by the value in units of GtC (Friedlingstein et al., 2022, 2020).

Figure 5 showed the carbon sink gap between the carbon source and carbon sink after unit transformation and thus carbon source and carbon sink comparison, that is, when the carbon sink to carbon source ratio is less than 1, there must be a carbon sink gap.

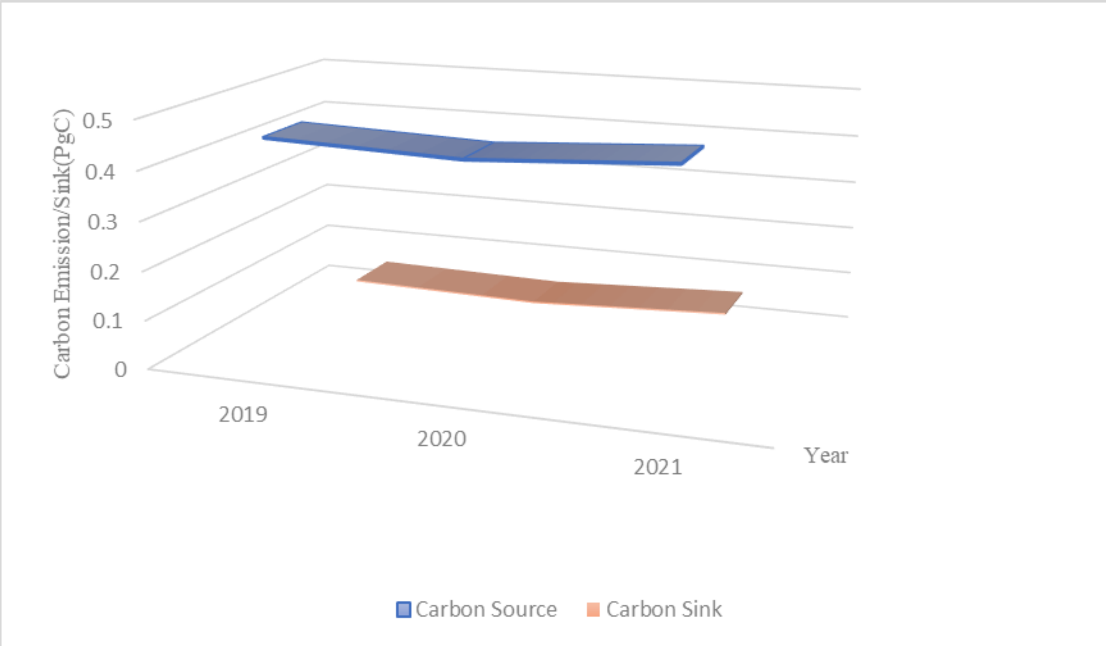

Figure 5. *Carbon sink gap in the Yangtze River Delta from 2019 to 2021*

According to *Table 3,* the terrestrial ecosystem in the Yangtze River Delta region absorbed 12.86% of the CO_2 in 2019, 11.42% of the CO_2 in 2020 and 14.63% of the CO_2 in 2021. This result was the same as the conclusion drawn by Guo et al. (2024) and Han et al. (2017) that carbon absorption in the Yangtze River Delta region was difficult to offset carbon emissions. However, only from the perspective of carbon neutral process, it is more simple and effective to directly compare the ratio of carbon sink and carbon source. From the conclusion of the ratio, it could be seen that there was still a lot of room for development in increasing the carbon sink of terrestrial ecosystems and reducing carbon emissions. The use of other carbon sequestration technologies is also urgent. Carbon capture and storage (CCS) has been considered a key technology for climate change mitigation (Jiang and Ashworth, 2021; Reiner, 2016), and it is expected to reduce greenhouse gas emissions by 32% by 2050 (IEA, 2017). As China's 30 and 60 targets were set, more emphasis was placed on the importance of "turning waste into energy", hence the term "carbon capture, utilization, and storage" (CCUS) was coined and is increasingly used in China. While CCUS has many disadvantages compared to renewable energy, the advantage is that its deployment can avoid the immediate stranding of fossil fuel assets and immediately reduce emissions from existing sources

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(Fuhrman et al., 2020; Xu and Dai, 2021). Although CCUS can be of great help, there is still a long way to go before carbon neutrality is achieved, and sustainable restoration of terrestrial ecosystems and reduction of fossil fuel emissions remain priorities. In this paper, regional carbon sinks are measured using GPP. However, some limitations need to be addressed. On the one hand, terrestrial ecosystem respiration was difficult to obtain and hard to update in time. On the other hand, CCUS is currently in the development stage and data is relatively scarce. After the data is completed in the future, the research on carbon sink measurement can be more accurate.

Table 3. *The ratio of carbon source and sink in the Yangtze River Delta region*

	2019	**2020**	**2021**
Ratio	0.1286	0.1142	0.1463

Conclusion

In this paper, GPP data was used to measure the carbon sink in the Yangtze River Delta region, and the ratio of carbon sink to carbon source was carried out. Through the calculation of the carbon sink in the Yangtze River Delta, it was found that the terrestrial ecological carbon sink could effectively absorb CO_2. In the process of achieving carbon neutrality, in addition to increasing the carbon sink of terrestrial ecosystems and reducing carbon emissions, the application of CCUS technology was also crucial. This study provided a simple and fast method for measuring regional carbon sinks, and at the same time, it simply and clearly showed the process of carbon neutrality. Policymakers can observe the degree of carbon neutrality in a timely manner according to the actual situation, and achieve carbon neutrality by increasing sinks, reducing emissions, and flexibly adjusting CCUS strategies. Overall, this paper’s helps to observe the carbon neutral process and adjust the carbon neutral strategy.

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