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Original Research

Spatial-Temporal Evolutionary Characteristics of Shellfish and Algae Carbon Sinks in China: Analysis Based on Geographic Information System (GIS)

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Abstract

The shellfish and algae carbon sinks as an important part of the fishery carbon sinks. It is of great significance to evaluate the current development status of shellfish and algae carbon sinks for the development of fishery carbon sinks and realization of carbon neutrality. There are a lot of studies on the quantitative relationship of shellfish and algae carbon sinks, but few researches on its spatial relationship. This study used the Natural Breaks and Standard Deviation Ellipse (SDE) in Geographic Information System (GIS) to analyze the spatial evolutionary characteristics of China's shellfish and algae carbon sinks from 1992 to 2021. The results show that spatial distribution of carbon sinks varied widely in different regions, the overall spatial layout was stable and gradually formed a pattern of integrated and coordinated development of key regions and general regions. The structure of the shellfish and algae carbon sinks was unbalanced in China, in which algae carbon sinks had great potential for development. China's shellfish and algae carbon sinks had strong resilience after natural disasters. Based on the above findings, this study suggests that all regions should increase the total output of shellfish and algae, expand the scale of algae, and achieve a balanced development of the shellfish and algae industry. Local governments should introduce marine environmental governance policies according to local conditions to achieve precise intervention in key carbon sink areas and overall governance in general carbon sink areas. The government should actively promote the expansion of shellfish and algae mariculture scale. This study will provide reference for the future development of China's fishery carbon sinks.

Keywords: fishery carbon sinks, spatial-temporal characteristic, Geographic Information System (GIS), China

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Introduction

Climate change has serious impacts on natural ecosystems and socio-economic systems. The change is widely attributed to the increase in carbon emissions, which refer to the emissions of greenhouse gases. At present, China has become the largest carbon emitter, accounting for one-third of the total carbon emissions in the world [1, 2]. Without mitigation measures, China's carbon emissions will increase by more than 50% in the next 15 years [3]. To avoid this situation, the Chinese government announced its efforts to achieve carbon neutrality by 2060 at the 75th session of the United Nations General Assembly [4]. Carbon neutrality means balancing between emitting carbon and absorbing carbon from the atmosphere in carbon sinks [5]. In addition to reducing carbon emissions from energy consumption, the development of the carbon sink function of the ecosystem is also of great significance to the realization of carbon neutrality.

Carbon sinks in ecosystems include forests, oceans, grasslands, wetlands, soils, permafrost, and karst habitats [6, 7]. Compared with other sources, oceans fix 55% of global carbon and absorb about 20%-35% of carbon emissions from human activities every year, which can be stored for hundreds or even thousands of years [8, 9]. Furthermore, marine carbon sinks are composed of a variety of biological carbon sinks such as coral reefs, phytoplankton, kelp forests, and marine fauna [10]. On this basis, Tang put forward the concept of fishery carbon sinks, which refers to the process and mechanism of promoting aquatic organisms to absorb carbon emission in water through fishery production activities and removing the carbon from water through harvesting aquatic biological products [11]. However, carbon sinks generated by shellfish and algae, account for a large proportion of fishery carbon sinks [12, 13]. At the same time, shellfish and algae do not need artificial feeding, relying on natural resources to survive. Therefore, shellfish and algae are promising ways of carbon sinks.

In order to continuously improve the shellfish and algae carbon sinks in China, it is necessary to have a clearer understanding of the carbon sinks status of shellfish and algae in various regions. However, the natural conditions in China are complex and the fishery resources in different provinces vary greatly [14]. It is particularly necessary to assess carbon sinks of shellfish and algae in the subregion and provide information for improving the carbon sinks capacity of shellfish and algae in different regions. The current research on the carbon sink of shellfish mostly focuses on the quantitative relationship. However, there are few studies on the spatial evolutionary process and characteristics of carbon sinks from the perspective of geography. Therefore, the main contributions of this study are as follows. First, shellfish and algae carbon sinks were calculated, and their time evolutionary characteristics were revealed. Second, the spatial evolutionary characteristics of shellfish and algae carbon sinks were revealed. Third, relevant suggestions on how to increase the shellfish and algae carbon sinks were provided.

The rest of the paper is organized as follows. Section 2 reviews past research. Section 3 introduces the materials and methods. Section 4 presents the measured results and related analysis, and the relevant discussion is presented in Section 5. Section 6 presents the conclusion of the study, recommendations, and shortcomings of this study.

Literature Review

This study will sort out the research on the spatial relationship of shellfish and algae carbon sinks from the following two aspects. First, the calculation of carbon sinks in shellfish and algae. Second, quantitative relationship of carbon sinks in mariculture shellfish and algae.

Calculating carbon sinks has always been one of the most basic problems in studying shellfish and algae carbon sinks. The current study on the method of calculating the carbon sinks of shellfish and algae is still in the fumbling stage, and there is no mature calculation standard [15]. The accounting methods of shellfish and algae can be divided into three types. Type I: Scholars mainly calculate the carbon sinks fixed by shellfish and algae themselves, which can be called removable carbon sinks [16-18]. Specifically, shellfish can absorb bicarbonate roots (HCO_3^-) from seawater to form the shell of calcium carbonate ($CaCO_3$). Details as follows: $Ca^{2+} + 2HCO_3^- = CaCO_3 + H_2O + CO_2$. Meanwhile, shellfish can filter and assimilate phytoplankton and particulate organic debris in seawater to form the soft tissue of individual [19]. As for the carbon sinks that can be removed by algae, it is mainly biomass carbon formed by photosynthetic carbon fixation growth. Type II: In addition to the mobile carbon sinks, shellfish and algae carbon sinks also include organic carbon stored in seawater. Some scholars include this part of the carbon sinks into the total carbon sinks. Specifically, dissolved organic carbon (DOC) and particulate organic carbon (POC) are the main forms of organic carbon present in seawater [20]. Macroalgae can effectively absorb CO_2 from seawater through photosynthesis, synthesize their own substances, and release a large amount of DOC during growth. Through the output of DOC, they store carbon below the mixed layer (the annual carbon storage is 117 Tg Ca^{-1}). Furthermore, algae also bury and export part of the carbon in the form of POC through sedimentation and floating (annual carbon storage is 49Tg Ca^{-1}) [21]. Meanwhile, shellfish removed part of POC in seawater through feeding activities, further transferring and transforming carbon in the food chain. Moreover, shellfish discharge a large number of feces, which not only accumulate in large quantities at the bottom of the culture area but also release DOC into the water body [22]. Type III: Microbial carbon storage mechanisms related to shellfish and algae were gaining attention in other scientific fields. About 90% of the DOC in the ocean is RDOC which cannot be used by living organisms, and microorganisms are the main contributors to RDOC [23]. Specifically, microorganisms produce and release refractory dissolved organic carbon (RDOC) through the microbial carbon pump (MCP) mechanism during growth metabolism, and thus sequestered some of the carbon in the ocean for thousands of years [24-26].

The quantitative relationship between carbon sinks of mariculture shellfish and algae is mainly divided into three aspects: the comparison of carbon sinks capacity, the influencing factors of carbon sinks, and the assessment of carbon sink potential. First, scholars usually make comparisons of shellfish and algae carbon sinks in a certain region [27-29]. Scholars mostly make vertical comparisons of the carbon sink capacity of a region in a period of time or horizontal comparisons of the carbon sink capacity of different regions in the same period of time [30-32]. Meanwhile, some scholars have studied the quantitative relationship of shellfish and algae carbon sinks in different regions based on spatial econometrics. For example, Xu et al found that there is a positive spatial correlation between the net carbon sinks efficiency of mariculture in the region and the aggregation effect is significant [33]. Xu et al. found that the spatial spillover relationship of fishery carbon sinks is not stable, and showed a “V” shaped fluctuation characteristic [34]. Second, the formation of shellfish and algae carbon sinks is the result of the joint action of many factors, and the impact mechanism is very complex. The researchers suggested that the cost of aquaculture, the way in which it is cultured, the adequacy of nutrients and even human intervention in algae harvesting may be factors that affect the carbon sequestration capacity of shellfish [35, 36]. In addition, Chinese scholars often analyzed the driving factors of shellfish and algae carbon sinks with the help of LMDI, and found that many factors such as economy, technology, aquaculture efficiency and industrial structure are related to shellfish and algae carbon sinks [37, 20]. Third, the assessment of the potential of shellfish and algae carbon sinks has been the focus of academic attention. Some scholars have assessed the potential for the development of seaweed carbon sinks in some regions and have found that algae carbon sinks are key to increasing carbon sink capacity. For example, Luo found that annual average shellfish and algae carbon sinks in China is 1.10 million tons from 2003 to 2019, of which shellfish accounted for 91.63% [38]. The economic potential of shellfish and algae carbon sinks is also the focus of research. Luo found that carbon sequestration benefit of seaweed cultivation is 22,405.67±259.59 million CNY [38]. Lai found that the annual average economic value of China’s shellfish and algae carbon sinks is USD 71,303.56 million, and the product value is the main contributor, accounting for 99.11% [13].

However, few studies have investigated the spatial relationship of shellfish and algae carbon sinks from a geographical perspective. GIS spatial statistical analysis tool can analyze the information about the spatial location, distribution, shape, formation and evolution of geographical objects. Compared with the spatial-temporal data comparison, the spatial statistics analysis tool can show the spatial change process of the research objects more completely. Therefore, the Natural Breaks and SDE in GIS were used to analyze the shellfish and algae carbon sinks in the study.

Materials and Methods

Study Area

China has a long coastline, including 10 provinces (Liaoning, Hebei, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong, Guangxi, Taiwan, and Hainan), 2 municipalities (Shanghai and Tianjin) and 2 special administrative regions (Hong Kong and Macao). To coordinate the natural resource endowment and ecological environmental capacity of different regions and sea areas, China has also divided the coastal provinces into three marine economic circles. These are the northern marine economic circle (Liaoning, Hebei, Tianjin, and Shandong), the eastern marine economic circle (Jiangsu, Shanghai, and Zhejiang), and the southern marine economic circle (Fujian, Guangdong, Guangxi, and Hainan). Meanwhile, mariculture production in Shanghai, Tianjin, Hong Kong and Macau is extremely low, and some data were missing for Taiwan Province. Therefore, the above areas are not included in the study. The study areas are shown in Fig. 1.

Data Source

All the data in this paper are from China Fishery Statistical Yearbook (2020-2021).

Calculation Methods of Shellfish and Algae Carbon Sinks

According to Liu’s calculation method, shellfish and algae carbon sinks were divided into shellfish carbon sinks and algae carbon sinks for calculation [39]. The specific calculation process is as follows:

$$CS_{total} = CS_{shellfish} + CS_{algae} \tag{1}$$

Where, CS_{total} is the shellfish and algae carbon sinks; $CS_{shellfish}$ is the shellfish carbon sinks; CS_{algae} is the algae carbon sinks. At the same time, the shellfish carbon sinks and algae carbon sinks can be divided into long-term carbon sinks and short-term carbon sinks according to their storage cycle period. The specific classifications are shown in Table 1.

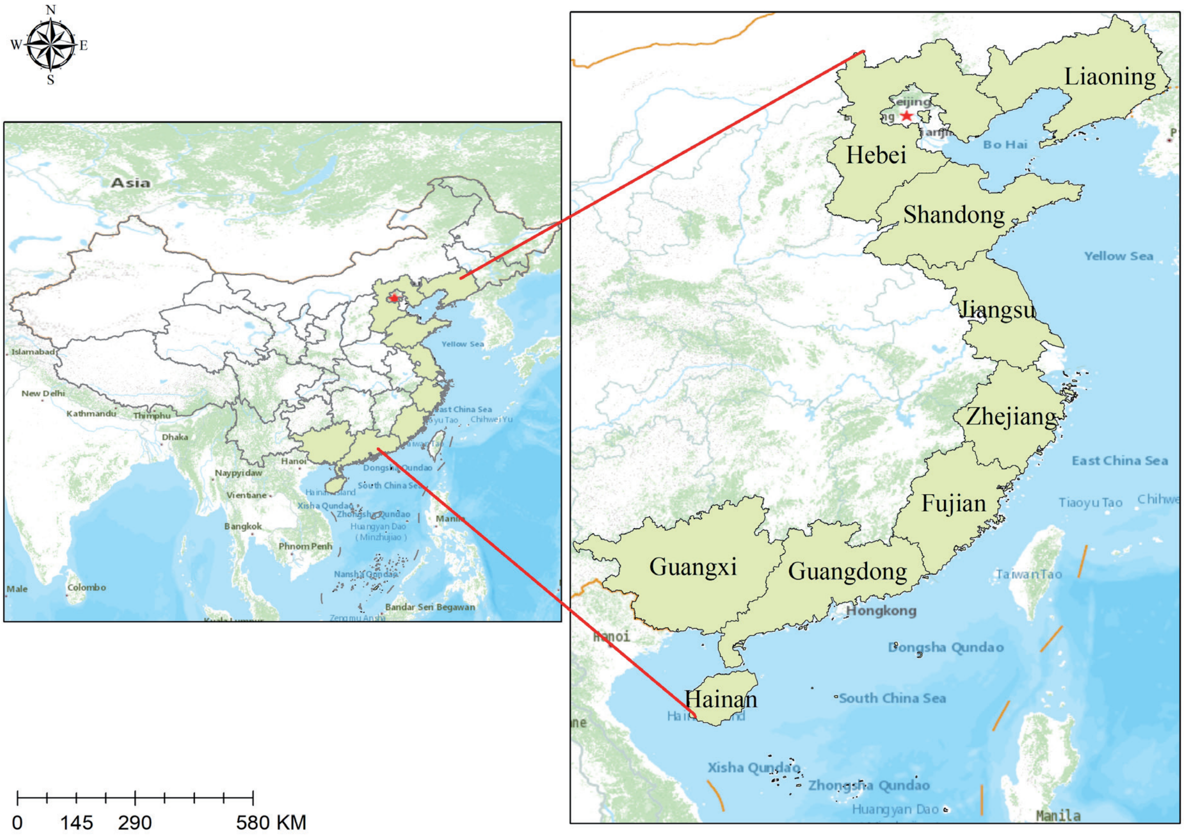

Fig. 1. Spatial distribution of shellfish and algae in China.

Table 1. Classification of shellfish and algae carbon sinks by time.

Category	Long-term carbon sinks	Short-term carbon sinks
Algae	—	Biomass
	RDOC	—
	POC	—
Shellfish	—	Biomass
	POC	—

Calculation of Shellfish Carbon Sinks

Shellfish carbon sinks can be divided into long-term carbon sinks and short-term carbon sinks. The calculation process is as follows:

$$CS_{shellfish} = CS_{short1} + CS_{long1} = CS_{biomass1} + CS_{POC1} \tag{2}$$

Where, $CS_{biomass1}$ belongs to short-term carbon sinks and CS_{POC1} belongs to long-term carbon sinks. Specifically, $CS_{biomass1}$ is the carbon sinks of shellfish biomass, determined by the shell and soft tissue carbon of shellfish. CS_{POC1} is the POC carbon sinks generated in the growth of shellfish, determined by the ratio between $CS_{biomass}$ and biological deposit carbon.

$$CS_{biomass1} = CS_{shell} + CS_{soft} \tag{3}$$

Where, CS_{shell} is the carbon sinks of shell, and CS_{soft} is the carbon sinks of soft tissue. They are calculated as follows:

$$CS_{shell} = \sum_{i=1}^{n} P_i \times D_i \times G_{si} \times C_{si} \tag{4}$$

$$CS_{soft} = \sum_{i=1}^{n} P_i \times D_i \times G_{ti} \times C_{ti} \tag{5}$$

Where, P_i is the production of the ith shellfish; D_i is the dry weight ratio of the ith shellfish; G_{si} is the shell's specific gravity of the ith shellfish; C_{si} is the shell's carbon content of the ith shellfish; G_{ti} is the soft tissue's specific gravity of the ith shellfish; C_{ti} is the soft tissue's carbon content of the ith shellfish. This study referred to the setting method of Xiang and set the specific conversion coefficient of carbon sinks [40]. As shown in Table 2.

$$CS_{POC1} = CS_{biomass1} \times \varepsilon_1 \tag{6}$$

CS_{POC1} is the POC carbon sinks in shellfish; ε_1 is the ratio of carbon entering the biological deposit to carbon removed by harvesting. This study set the ε_1 to 1.33 [11].

Table 2. Table of conversion factors for shellfish and algae carbon sinks.

Category	Species	Dry weight ratio (%)	Carbon content (%)		Specific gravity (%)	
			Soft tissue	Shell	Soft tissue	Shell
Shellfish	Mussels	75.28	45.98	12.68	8.47	91.53
	Scallops	63.89	43.89	11.44	14.35	85.65
	Razor clam	70.48	44.99	13.24	3.26	96.74
	Clam	52.55	42.84	13.24	1.98	98.02
	Oysters	65.10	44.90	11.52	6.14	93.86
	Cockle	64.21	45.86	11.51	11.41	88.59
	Abalone	64.21	40.04	12.02	11.41	88.59
	Sea snail	64.21	36.83	11.29	11.41	88.59
	Pen shell	64.21	40.73	13.16	11.41	88.59
Algae	Kelp	—	31.2		—	
	Wakame- vegetable	—	28.81		—	
	Nori	—	41.96		—	
	Gracilaria	—	24.50		—	
	Eucheuma	—	26.37		—	
	Edible seaweed	—	30.36		—	
	Chinese- herbal- seaweed	—	30.36		—	
	Green moss	—	30.36		—	

Calculation of Algae Carbon Sinks

Algae carbon sinks can also be divided into long-term carbon sinks and short-term carbon sinks. The calculation process are as follows.

$$CS_{algae} = CS_{short2} + CS_{long2} = CS_{biomass2} + CS_{RDOC} + CS_{POC2} \tag{7}$$

Where, $CS_{biomass2}$ belongs to short-term carbon sinks, while CS_{RDOC} and CS_{POC2} both belong to long-term carbon sinks. $CS_{biomass2}$ is the carbon sinks of algae biomass; CS_{RDOC} is the RDOC carbon sinks generated in the process of algae growth, determined by the conversion coefficient between $CS_{biomass2}$ and RDOC; CS_{POC2} is the POC carbon sinks generated in the process of algae growth, determined by the particle deposition rate, area, and sediment organic carbon content of algae.

$$CS_{biomass2} = \sum_{i=1}^{n} P_{ai} \times C_{ai} \tag{8}$$

P_{ai} is the production (dry weight) of the ith algae; C_{ai} is the carbon content of the ith algae. The specific coefficients are shown in Table 2.

$$CS_{RDOC} = CS_{biomass2} \times \varepsilon_2 \times \varepsilon_3 \times \varepsilon_4 \tag{9}$$

ε_2 is the conversion coefficient between NPP and GPP; ε_3 is the conversion coefficient between GPP and DOC; ε_4 is the conversion coefficient between DOC and RDOC. After referring to the setting method of scholars, this study set ε_2, ε_3, ε_4 as 1.92,0.245 and 0.855 respectively [23, 41-43].

$$CS_{POC2} = \sum_{i=1}^{n} V_i \times 365 \times S_i \times M_i \tag{10}$$

V_i is the average particle deposition rate in the ith algae growth region; 365 is the number of days in a year; S_i is the area of the ith algae growth; M_i is the percentage of sediment organic carbon content of the ith algae growth region. Meanwhile, V_i and M_i are set to 162.34 g/m^2 /day and 0.52% [23, 44, 45].

Natural Breaks

The Natural Breaks is a classification method based on numerical statistical distribution law proposed by George F. Jenks. Specifically, any statistical sequence has some natural turning points, feature points, that can be used to divide objects into groups with similar qualities. The advantage of the model is to maximize the differences between turning points or feature points [46]. The data of shellfish and algae carbon sinks in each province were classified according to the natural breakpoint model to find the best classification of carbon sinks. The specific process are as follows.

First, given the sample set $R = \{R_1, R_2, ..., R_9\}$. Where R_i is the shellfish and algae carbon sinks in each province. Then calculate the sum of deviation squares and the sample mean of carbon sinks in each province. The specific calculation steps are as follows:

$$SDAM = \sum_{i=1}^{9}(R_i - \bar{R})^2 \tag{11}$$

$$\bar{R} = \frac{1}{9}\sum_{i=1}^{9} R_i \tag{12}$$

Where, *SDAM* is the sum of the deviation squares of the carbon sinks; $\bar{R}$ is the sample mean of the carbon sinks; R_i is the carbon sinks in the *i*th province (there are 9 provinces).

Second, it is assumed that the *R* is divided into 5 class clusters, which are C_1, C_2, ..., C_5. Then the corresponding sum of deviation squares are calculated, which are $SDAM_{C1}$, $SDAM_{C2}$, ..., $SDAM_{C5}$. Then, sum the sum of the deviation squares. The calculation process is as follows:

$$SDAM_t = \sum_{j=1}^{5} SDAM_{Cj}, t = 1,2,\cdots,C_9^5 \tag{13}$$

Where, $SDAM_t$ represents the sum of the total deviation squares of all the class clusters corresponding to the *j*th divide method that divides the sample set into 5 class clusters. The smallest value in $SDAM_1$, $SDAM_2$, ..., $SDAM_{C_9^5}$ is selected as the result $SDAM_{mni}$, and the corresponding classification range of this value is the best classification.

Standard Deviation Ellipse (SDE)

Standard deviation ellipse (SDE) was first proposed by Lefever. This method is one of the most important methods used to analyze the spatial differences and distribution characteristics of regional geographic elements [47]. Specifically, this method mainly describes the spatial characteristics of the tested elements from three aspects: the mean center position, the ellipse direction, and the standard deviation of the axes. The three respectively represent the position of the center of gravity in the spatial distribution of the element, the main and sub-trend directions of the element in the spatial distribution, and the dispersion degree of the element in the corresponding directions. Based on ArcGIS software, this study analyzed the spatial variation of China's shellfish and algae carbon sinks from 1992 to 2021 on a three-year basis. The expression formula of spatial features are as follows.

Mean center position:

$$\overline{X_w} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} \ ; \ \overline{Y_w} = \frac{\sum_{i=1}^{n} w_i y_i}{\sum_{i=1}^{n} w_i} \tag{14}$$

Ellipse direction:

$$tan\theta = \frac{\left(\sum_{i=1}^{n} w_i^2 \tilde{x}_i^2 - \sum_{i=1}^{n} w_i^2 y_i^2\right) + (\sqrt{\left(\sum_{i=1}^{n} w_i^2 \tilde{x}_i^2 - \sum_{i=1}^{n} w_i^2 y_i^2\right)^2 + 4\sum_{i=1}^{n} w_i^2 \tilde{x}_i^2 y_i^2}}{2\sum_{i=1}^{n} w_i^2 \tilde{x}_i y_i} \tag{15}$$

X-axis standard deviation:

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n}(w_i \tilde{x}_i cos\theta - w_i y_i sin\theta)^2}{\sum_{i=1}^{n} w_i^2}} \tag{16}$$

Y-axis standard deviation:

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^{n}(w_i \tilde{x}_i sin\theta - w_i y_i cos\theta)^2}{\sum_{i=1}^{n} w_i^2}} \tag{17}$$

Where, (x_i, y_i) represents the spatial position of the research element. w_i represents weight. $(\bar{X}_w, \bar{Y}_w)$ is a weighted mean of the center. θ is the azimuth angle of the ellipse. x_i, y_i represents the deviation between the coordinates of research elements and the mean center coordinates, respectively. σ_i, σ_i denote the standard deviation along the *X* axes and *Y* axes, respectively.

Results

Temporal Evolutionary Process in Shellfish and Algae Carbon Sinks from Provincial Perspective

From the time dimension, this study visualized of the shellfish and algae carbon sinks in China from 1992 to 2021. The results are shown in Fig. 2.

The shellfish and algae carbon sinks in each province generally showed an increasing trend over time. However, in some special years, the carbon sinks in each province have changed dramatically. For example, in 1997 and 2001, the shellfish and algae carbon sinks of each province suddenly decreased, but the change did not cause a lasting impact on each province. Through the comparative analysis of provinces, it can be found that the carbon sinks of Guangdong, Shandong and Fujian all reached the level of millions of tons. The total carbon sinks in Hainan Province were less than 100 000 tons in the past 30 years, which was the lowest among all provinces. Specifically, shellfish carbon sinks accounted for a large proportion of the shellfish and algae carbon sinks in each province. However, there were some extreme cases, such as Guangxi, Hebei and Guangdong, where shellfish and algae carbon sinks were almost entirely composed of shellfish carbon sinks. However, the proportion of algal carbon sinks was significantly smaller than that of shellfish carbon sinks. Only in Hainan Province, the total carbon sinks were dominated by algal carbon sinks. It is worth noting that the algae carbon sinks in Jiangsu, Liaoning and Fujian Provinces have surpassed or approached the shellfish carbon sinks in the past 30 years. It is undeniable that shellfish and

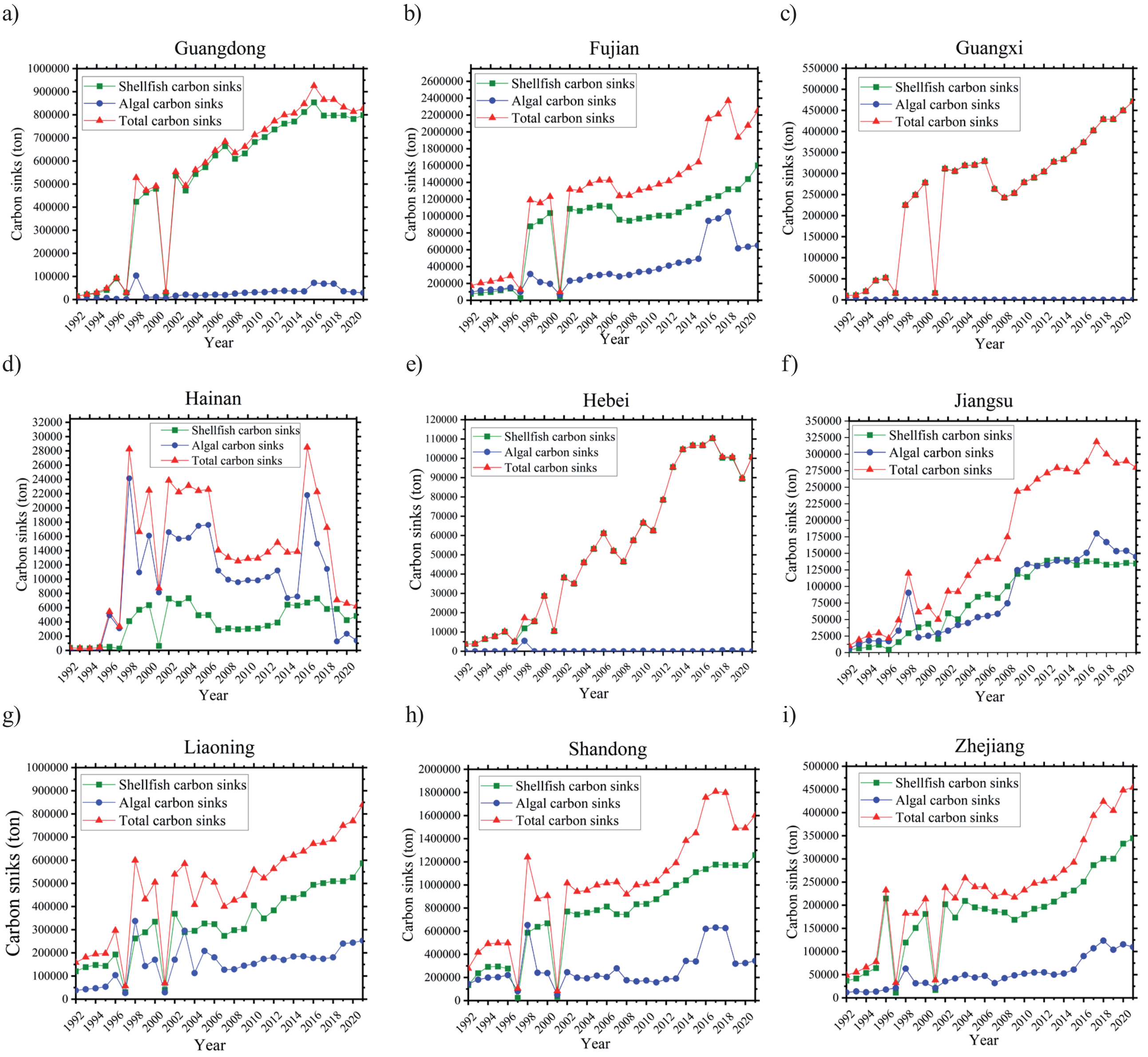

Fig. 2. The temporal change trend of shellfish and algae carbon sinks from provincial perspective.

algae carbon sinks, shellfish carbon sinks, algae carbon sinks have been increasing year by year in the past 30 years from provincial perspective.

Temporal Evolutionary Process in Shellfish and Algae Carbon Sinks from Regional and National Perspective

From the time dimension, this study visualized the shellfish and algae carbon sinks at regional and national from 1992 to 2021. The results are shown in Fig. 3.

On the whole, the total shellfish and algae carbon sinks had steadily increased year by year with a good momentum of growth in the past 30 years. Meanwhile, the growth trends of regional shellfish and algae carbon sinks and national shellfish and algae carbon sinks were basically consistent. In particular, the shellfish carbon sinks were significantly higher than algae carbon sinks, and shellfish carbon sinks were still increasing at a high growth rate over time. Algal carbon sinks were inferior to shellfish carbon sinks in both quantity and growth rate. From a regional perspective, the shellfish and algae carbon sinks in the eastern marine economic circle have achieved reasonable structure and high-quality development. Specifically, the total carbon sinks of the eastern marine economic circle were large and the growth rate was fast. At the same time, the growth rate of algal carbon sinks in this region were significantly higher than that in other regions. The structure of the carbon sinks in southern marine economic circle was not reasonable. Specifically, the total amount and growth rate of algae carbon sinks were significantly lower than that of shellfish carbon sinks. In addition, affected by natural disasters in 1997 and 2001, the shellfish and algae carbon sinks suddenly decreased in all regions. However, shellfish and algae carbon sinks recovered

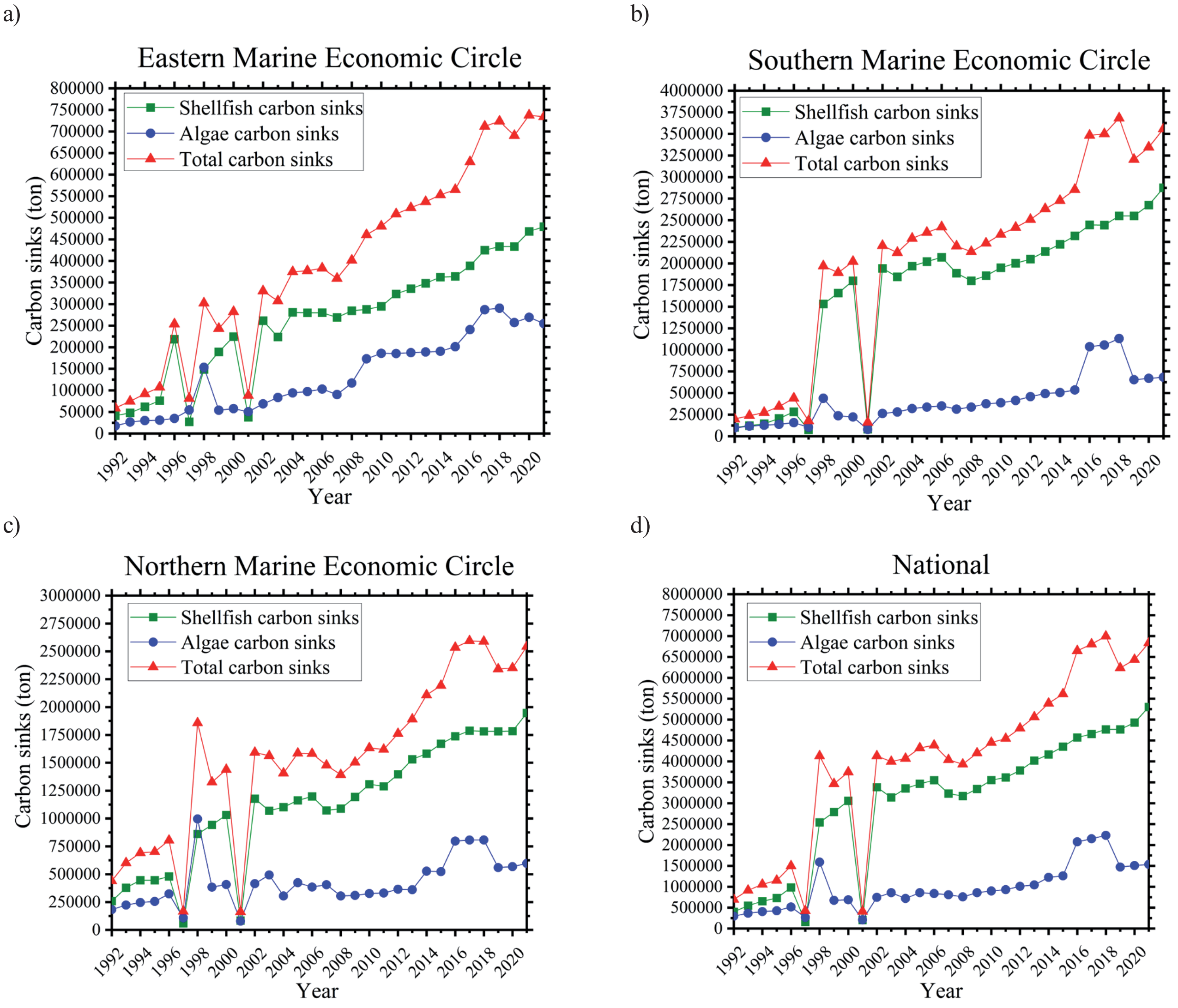

Fig. 3. The temporal change trend of shellfish and algae carbon sinks from regional and national perspective.

to the original level in a short time without lasting impact.

Spatial Evolutionary Process in Shellfish and Algae Carbon Sinks from Provincial Perspective

In this study, the Natural Breaks was used to classify the shellfish and algae carbon sinks in each province from 1992 to 2021. The specific results are shown in Fig. 4.

The shellfish and algae carbon sinks of Hebei and Hainan had been stable in low carbon sink areas for a long time. This situation may be closely related to the reduction of mariculture area in the two places. Specifically, due to the development of freshwater pond aquaculture, the area of marine aquaculture in Hainan has gradually decreased [48]. The urgent pursuit of economic benefits in Hebei has led to a series of marine environmental problems, which have led to the restriction of the mariculture industry [49]. Shandong, Fujian, Liaoning, and Guangdong were stable in high or medium and high carbon sinks areas. This has benefited from the local emphasis on marine environmental issues and policy support. For example, the Ministry of Finance allocated subsidy funds to Shandong at the end of 2013; Liaoning issued ten policies and measures to promote the healthy development of marine fisheries in 2009; Guangdong implemented the Marine Economic Comprehensive Pilot zone in 2012, and received funding from the Ministry of Finance in 2013. These policies have stimulated the development of local marine fisheries and laid a solid foundation for the development of the aquaculture industry everywhere [50-52]. The classification of shellfish and algae carbon sinks in Jiangsu, Zhejiang, and Guangxi fluctuated frequently and were generally in medium or medium, and low carbon sinks areas. The unreasonable structure of shellfish and algae carbon sinks may be the reason for this situation. Specifically, Jiangsu was actively adjusting the structure of the shellfish and algae carbon sinks, which was currently in a transition period. It also

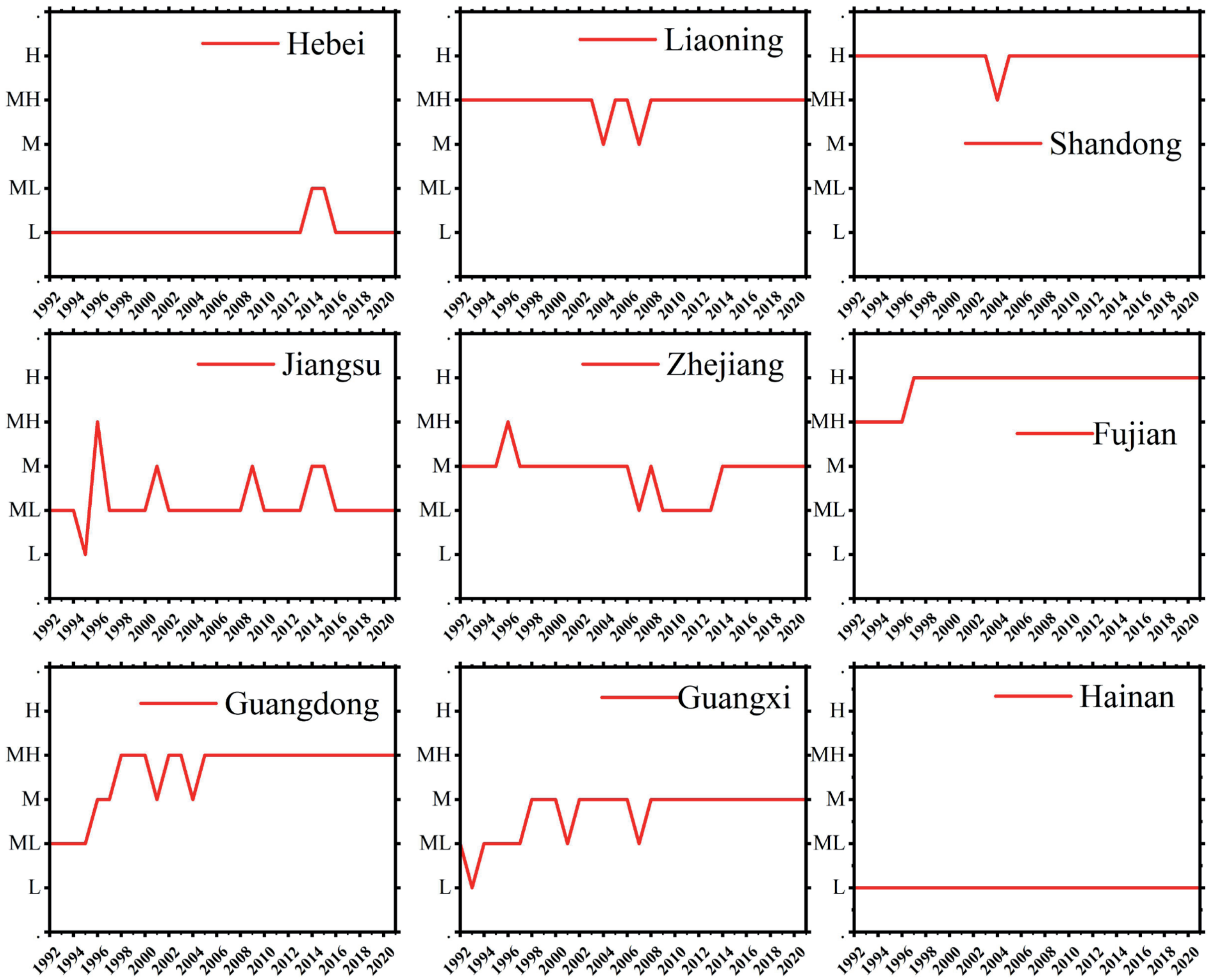

Fig. 4. Classification of the total shellfish and algae carbon sinks by province.
(Note: H: high carbon sink area; MH: medium and high carbon sink area; M: medium carbon sink area; ML: medium and low carbon sink area; L: low carbon sink area).

temporarily restricts the development of shellfish and algae carbon sinks [53]. To meet the needs of economic development, Guangxi and Zhejiang have been vigorously developing shellfish farming. In general, the shellfish and algae carbon sinks in each province were quite different but with clear stratification.

Spatial Evolutionary Process in Shellfish and Algae Carbon Sinks from Regional and National Perspective

In this study, the SDE was used to analyze the spatial changes of shellfish and algae carbon sinks in China over the past 30 years from regional and national perspectives. The specific results are shown in Fig. 5.

The central location of shellfish and algae carbon sinks in the northern marine economic circle mainly moved in the northeast-southwest direction. Specifically, the central location transfer distance of shellfish and algae carbon sinks gradually increased from 1992 to 2021. If five years were taken as a unit, it can be found that the transfer distances of the central location are 13.24KM, 4.07KM, 48.17KM, 36.94KM, 43.62KM and 50.69KM, respectively. The head and tail transfer distance reached 21.37KM, and the overall transfer distance is 196.75KM. The location of the shellfish and algae carbon sinks center in the eastern marine economic circle moved along the northwest-southeast direction, and the transfer distance of the carbon sinks center decreased obviously. Taking five years as a unit of observation, the transfer distances from 1992 to 2021 are 181.29 KM, 136.95 KM, 47.85 KM, 53.62 KM, 30.38 KM, and 28.27KM, respectively. The head and tail transfer distance reached 87.16KM, and the overall transfer distance is 478.39KM. The central location of the shellfish and algae carbon sinks in the southern marine economic circle moved along the northeast-southwest direction, and the central transfer distance fluctuated greatly. From 1992 to 2021, the transfer distance of the central locations is 115.54 KM, 91.82 KM, 10.47 KM, 1.25 KM, 41.59 KM, and 7.81KM, respectively. The head and tail transfer distance reached 176.72KM, and the total transfer distance is 268.51KM. In summary, the spatial distribution of shellfish and algae carbon sinks in the northern marine

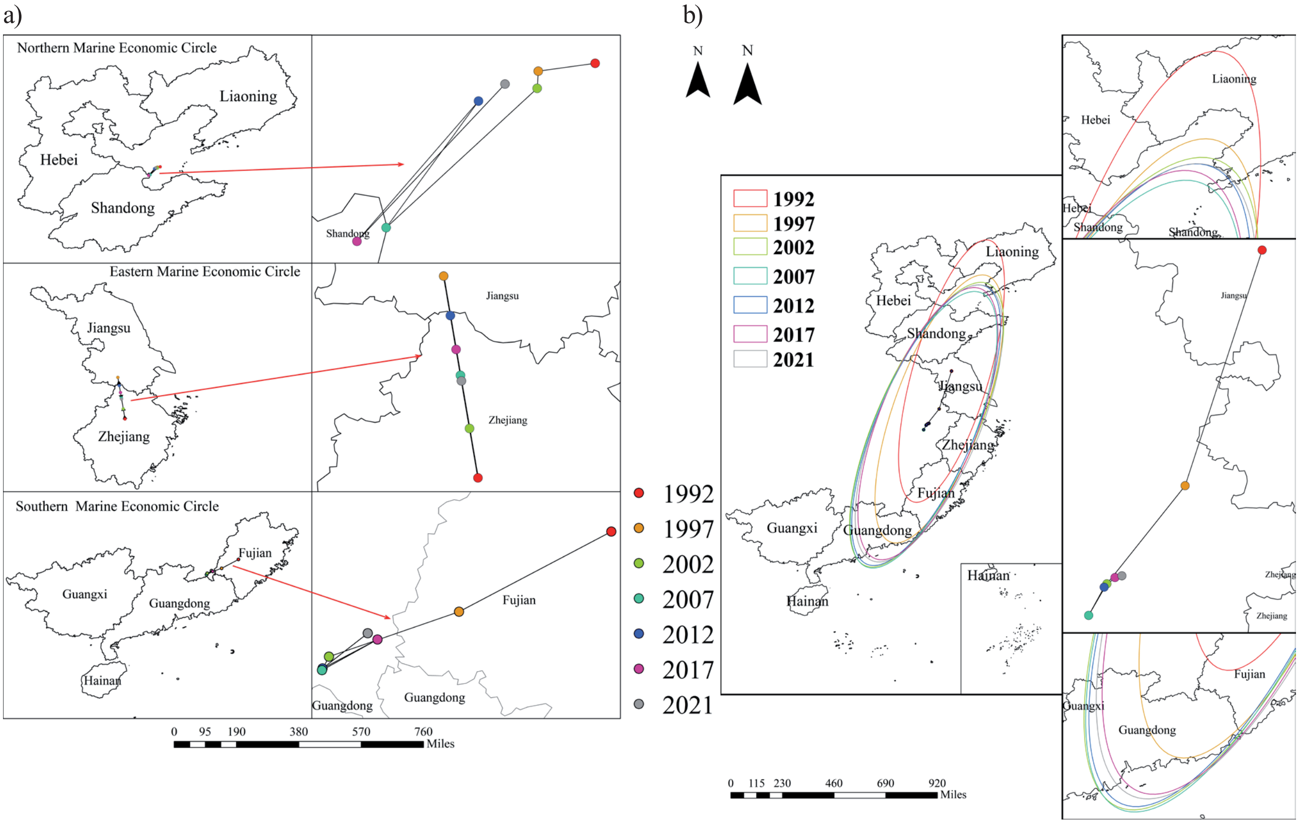

Fig. 5. Spatial variation of shellfish and algae carbon sinks in China from regional and national perspectives.
(Note: The colored dots in figures a and b represent the central locations of shellfish and algae carbon sinks in different years. The lines in figures a and b reflect the changes in the location of the shellfish and algae carbon sinks centers. The colored ellipses in figure b represent the standard distribution ellipses of China's shellfish and algae carbon sinks in different years, which is an abstract expression of the distribution of China's shellfish and algae carbon sinks.)
a) Regional spatial evolutionary trend of shellfish and algae carbon sinks.
b) National spatial evolutionary trend of shellfish and algae carbon sinks.

economic circle was in the early stage of change, and the shellfish and algae carbon sinks center might still be greatly shifted in the future. The spatial distribution of shellfish and algae carbon sinks in the eastern marine economic circle was gradually stable, while the overall spatial distribution of shellfish and algae carbon sinks was in the late stage of change. The spatial distribution of the southern marine economic circle was temporarily unstable, and the overall distribution of shellfish and algae carbon sinks might still change greatly.

Taking five years as an observation unit, it can be found that the central location transfer distance of China's shellfish and algae carbon sinks from 1992 to 2021 decreases accordingly. Specifically, the central location transfer distances are 281.14KM, 143.71KM, 43.09KM, 37.75KM, 16.27KM and 7.70KM, respectively. This means that the spatial distribution of China's shellfish and algae carbon sinks has been relatively stable, and the range of change has gradually decreased. Meanwhile, the distribution of shellfish and algae carbon sinks in China showed a northeastern-southwest direction, and the significance of this feature was gradually improving. Specifically, the deviation angle of the standard ellipse of China's shellfish and algae carbon sinks increased from 5.36° to 11.87° during 1992-2021. The X-axis length of the standard ellipse of China's shellfish and algae carbon sinks increased from 235.71KM to 344.00KM, and the Y-axis length increased from 982.53KM to 1055.57KM. Through the above analysis, it can be found that the direction of the spatial distribution of China's shellfish and algae carbon sinks has gradually cleared, the dispersion has been strengthened, and the stability has gradually increased. This shown that the basic framework of the spatial distribution of China's shellfish and algae carbon sinks has been formed, and a coordinated development model of key carbon sinks regions and general carbon sinks regions has been formed, which has been relatively stable. Meanwhile, China has also been expanding the area of mariculture shellfish and algae and developing new shellfish and algae carbon sinks areas.

Discussion

This study analyzed the temporal and spatial distribution characteristics of China's shellfish and algae carbon sinks from the perspectives of provincial, regional and national. Furthermore, this study will compare the analysis results with the existing relevant research from the following three aspects to ensure the rationality of the conclusions.

It Is Necessary to Comprehensively Understand the Spatial Evolution Process of Shellfish and Algae Carbon Sinks

The temporal and spatial differences of China's shellfish and algae carbon sinks have been widely concerned. For example, Xiang et al found that the carbon sinks of mariculture in Liaoning, Shandong, Fujian and Guangdong are relatively large [39]. Yang et al. found that there are significant differences in the capacity of shellfish and algae carbon sinks among different regions in China, with Shandong, Liaoning and Fujian having larger annual carbon sinks [54]. The conclusions of different scholars are slightly different, which may be caused by the difference in calculation methods. However, the large difference in carbon sinks between regions has become the basic consensus of academia [13, 51]. In addition, this study also found that the total carbon sinks of shellfish and algae have been increasing over time in China. According to the data from the Food and Agriculture Organization (FAO) of the United Nations, Since 1985, mariculture industry of China has achieved considerable development, and the aquaculture area and output are among the top in the world [55]. Meanwhile, China has continuously introduced policies to stimulate the development of marine aquaculture industry, which has also made great contributions to the prosperity of shellfish and algae carbon sinks [56, 57]. It can be seen that the positive change in the national spatial pattern of shellfish and algae carbon sinks is not accidental, but the result of efforts in marine environmental protection over the years.

It is Indispensable to Scientific Analysis the Internal Structure of Shellfish and Algae Carbon Sinks

Shellfish carbon sinks have an absolute advantage over the carbon sinks of shellfish and algae at both national and regional levels [58]. Cao et al found that the carbon sinks formed by marine shellfish farming in China is 1.5 times that of seaweed farming [59]. The yield and culture structure of shellfish and algae are considered to be the main reasons for this phenomenon [54, 60]. Specifically, different regional market has different emphasis on breeding species. For example, the yield of algae cultivation in Liaoning Province is much higher than that of shellfish cultivation [61]. Meanwhile, Quan et al found that algae culture structure has obvious differences in different provinces, and the difference are related to carbon sinks [62]. The difference of carbon sinks conversion efficiency is also an important reason for the different carbon sinks capacity [63]. For example, the rebound conversion efficiency of shellfish in Changdao sea area of Shandong Province is about 10%, while the conversion efficiency of algal carbon sinks is about 6% [64]. But the situation has changed in some areas. Jiangsu Province has recognized that algal carbon sinks have great potential for development, and has gradually increased efforts to develop algal carbon sinks [65].

It is Essential to Accurately Identify the Special Properties of Shellfish and Algae Carbon Sinks

According to the Bulletin of China Marine Disaster, China suffered severe marine disasters in 1997 and 2001. Among them, the coastal provinces suffered many storm surges in 1997 and caused severe economic damage [66, 67]. The two years of disaster had a serious impact on the shellfish and algae carbon sinks in that year, but the impact did not last long. shellfish and algae carbon sinks quickly recovered to pre-disaster levels the following year, demonstrating an alarming disaster resilience. From the macro perspective, the phenomenon is inseparable from the continuous improvement of China's marine mariculture insurance policy. In recent years, mariculture policy has changed from single to diversified, and normative policy has been emphasized in China. At the same time, the frequency of policy issuance and cooperation between different sectors has been enhanced [68, 69]. At the micro level, governments are also committed to reducing the vulnerability of mariculture [70]. For example, the vulnerability of marine aquaculture is reduced by increasing investment in fisheries technology, improving governance, promoting public education, reducing poverty, and improving the health of fishers. These measures provide the basis for the rapid recovery of shellfish and algae carbon sinks following natural disasters.

Conclusions

In order to contribute to the development of marine carbon sinks, provide reference for the future development of China's fishery carbon sinks. This study firstly analyzed the temporal evolutionary trend of the shellfish and algae carbon sinks from the perspectives of provincial, regional, and national, and the structure of the shellfish and algae carbon sinks was found to be unbalanced in China. Specifically, the development of shellfish and algae carbon sinks was too dependent on shellfish carbon sinks, while algal carbon sinks still have great development potential. However, in some areas such as Jiangsu, Fujian, and Liaoning, the phenomenon was gradually changing. At the same time, severe marine natural disasters occurred in 1997 and 2001, which had a huge impact on the total shellfish and algae carbon sinks in that year, but the total carbon sinks in the next year recovered rapidly. This indicates that shellfish and algae carbon sinks had strong resilience after natural disasters. Secondly, this study analyzed the spatial trend of shellfish and algae carbon sinks in China and found that there were great differences in carbon sinks in different regions from the perspective of provincial. In particular, Shandong, Fujian, Liaoning, and Guangdong belong to high or medium-high carbon sink areas. Zhejiang and Guangxi were basically in the middle, low carbon sink area. From the national and regional perspective, the direction of the spatial distribution of carbon sinks was gradually clear, the dispersion was increasing, and the overall distribution characteristics were gradually clear. Specifically, the carbon sinks distribution in the Eastern Marine Economic Circle was gradually stable, while the change of the carbon sinks distribution in the northern and Southern Marine Economic Circles was still large. It can be found that the spatial distribution of carbon sinks varies widely in different regions, the overall spatial layout was stable and gradually forms a pattern of integrated and coordinated development of key regions and general regions.

Based on the above findings, this study forms the following suggestions. First, all regions should increase the total output of shellfish and algae, expand the scale of algae mariculture, and achieve balanced development of the shellfish and algae industry. Specifically, local governments should introduce relevant measures to stimulate the increase of algae cultivation scale. Meanwhile, the government should speed up the distribution of the upstream and downstream industries of algae mariculture to promote the development of algae mariculture industry with market demand. Second, local governments should introduce marine environmental governance policies according to local conditions to achieve precise intervention in key carbon sink areas and overall governance in general carbon sink areas. Specifically, the local government should take measures according to local conditions, combine local natural conditions, economic conditions, development goals and other factors, and formulate a carbon sink growth strategy in line with local characteristics. Third, the government should actively promote the expansion of shellfish and algae mariculture scale. Shellfish and algae mariculture have good risk resistance ability and stable economic benefit. Furthermore, shellfish cultivation will also make an important contribution to the enhancement of marine carbon sink.

The study only can reveal the overall spatial and temporal characteristics of shellfish and algae carbon sinks, but cannot make a deeper analysis of the formation mechanism of the spatial and temporal distribution. In the future, on the basis of shellfish carbon sinks and algal carbon sinks, as well as long-term carbon sinks and short-term carbon sinks, we will make a more specific study on the formation mechanism of the spatial-temporal distribution characteristics of shellfish and algae carbon sinks by means of pairwise combination research.

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Conflict of Interest

The authors declare no conflict of interest.

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