*Pol. J. Environ. Stud. Vol. 33, No. X (2024), 1-10*
DOI: *10.15244/pjoes/187122* ONLINE PUBLICATION DATE:

*Original Research*

# Assessment of Carbon Sink Capacity and Economic Value of Maricultured Shellfish and Algae in China

**Haodong Tian*, Shengjie Sun, Weibo Li, Zhiyi Qiao****

College of Aquatic,Tianjin Agricultural University, Tianjin 300384, China

*Received: 3 January 2024*
*Accepted: 13 April 2024*

## Abstract

Low carbon is an important way to realize a circular economy in the ocean, and achieving carbon balance in marine fisheries is an important development method for the transformation of the traditional economy of the ocean. In this study, the carbon sinks of mariculture shellfish in China and nine provinces (regions) along the Chinese coast were measured from 2013 to 2022. The results show that the carbon sinks of marine aquaculture shellfish in China from 2013 to 2022 show a slowly rising trend, with a cumulative carbon sink of $1954.32\times10^4$ t and an annual average of $195.43\times10^4$ t, which is equivalent to an annual emission reduction of $717.24\times10^4$ t and an average annual saving of CNY487 million yuan in emission reduction costs. In order to further enhance the quality of carbon sinks and their economic value for mariculture shellfish, in-depth research on carbon sink measurement methods, optimization of mariculture structure, acceleration of the promotion of fishery carbon trading and the promotion of the paid ecological services of carbon sinks in aquaculture fisheries, and other countermeasures and suggestions are proposed in light of the actual situation with a view to realizing the maximum ecological, economic, and social benefits of mariculture shellfish in the future.

**Keywords:** Fisheries carbon sinks, mariculture, algae, shellfish, carbon sink value

## Introduction

In recent years, the world has been increasingly affected by climate change, and global warming has led to frequent natural disasters. In September 2020, China proposed to "strive to reach the carbon peak by 2030 and achieve carbon neutrality by 2060". The development of low-carbon economic industries and the effective reduction of atmospheric emissions of carbon dioxide and other greenhouse gases have become important ways for the world to combat climate change and achieve sustainable development. However, it is difficult to achieve the purpose of controlling carbon dioxide if only relying on emission reduction, so carbon sequestration and sink enhancement are the necessary ways for China to achieve carbon neutrality [1].

Carbon sink refers to the process, activity, and mechanism of removing gases such as carbon dioxide, methane, and other gases that cause the greenhouse effect from the atmosphere with aerosol or initial formation [2]. Tang et al. [3] proposed the definition of fishery carbon sink by combining the concept of carbon sink, i.e., the process and mechanism of removing carbon fixed in aquatic organisms' products out of the water body through fishery production and harvesting activities. Marine shellfish aquaculture is an important component

*e-mail: 15519074492@163.com
**e-mail: zhiyiqiao@tjau.edu.cn

and the main carrier of marine fisheries carbon sink, with efficient carbon sequestration function and carbon sink potential [4]. Filter-feeding shellfish capture a large amount of particulate organic carbon in seawater through feeding activities and convert it into biomass tissues, as well as fix inorganic carbon in seawater by biomineralization to form calcium carbonate shells and remove a large amount of biogenic carbon from seawater by harvesting cultured shellfish, which positively affects carbon cycling in cultured seawater and its adjacent seaward areas [5]; macroalgae can convert dissolved inorganic carbon (DIC) into organic carbon in seawater through photosynthesis, and then convert DIC into organic carbon through photosynthesis, and then convert DIC into organic carbon, through photosynthesis, and along with the harvesting of cultured algae, a large amount of carbon is directly removed from seawater; at the same time, due to the absorption of nutrient salts in seawater by their growth process, the alkalinity and pH of surface seawater are increased, the $pCO_2$ of the water body is reduced, and the diffusion of atmospheric $CO_2$ into seawater is promoted, which effectively increases the sequestration capacity of the offshore waters [6].

At present, there are more studies on the carbon sink capacity of shellfish aquaculture in China. Yan Liwen et al. [7] estimated the carbon sink of algae in China in 2009 by using the data of the Food and Agriculture Organization of the United Nations, and the results showed that the carbon sink of algae in China in 2009 was 78.38×10$^4$ t, which accounted for half of the world's carbon sink. There are also some experts and scholars who have measured the carbon sink capacity of shellfish and algae aquaculture in coastal provinces and cities. Qi Zhanhui et al. [5] estimated that shellfish and algae in Guangdong Province absorbed a total of 11×10$^4$ t of carbon sources in 2009, and the total value of the carbon sinks ranged from 5,940×10$^4$ to 23,800×10$^4$ USD. Li Ang [8] calculated that the carbon sink of marine shellfish aquaculture in Hebei Province in 2010 was about 2.75×10$^4$ t. Ji Jianyue et al. [9] calculated that the carbon sink of Chinese marine shellfish in 2012 was 97×10$^4$ t. Yu Zuo'an et al. [10] calculated that the average annual total carbon sink of marine aquaculture of shellfish in Liaoning Province in 2015-2017 was 27.7×10$^4$ t. Hejabe et al. [11] estimated that the total 10-year carbon sink of marine aquaculture shellfish in Yantai City, Shandong Province, from 2010 to 2019 amounted to 116.36×10$^4$ t, which is equivalent to a reduction of 426.65×10$^4$ t of carbon dioxide, with a value of about CNY267 million yuan.

In summary, there are few comprehensive studies on the carbon sinks and value of shellfish aquaculture in China and coastal provinces. This paper provides a comprehensive assessment of the carbon sink capacity and value of shellfish aquaculture in China and coastal provinces based on data from 2013-2022, with a view to providing a scientific basis for the development of fishery carbon sinks in China and the achievement of the goal of carbon neutrality.

## Materials and Methods

### Data Sources

The data for this study were obtained from the China Fisheries Statistical Yearbook from 2013 to 2022, compiled by the Administration of Fisheries and Fishery Administration of the Ministry of Agriculture and Rural Affairs of China, the General Station of Aquatic Technology Extension of China, and the Chinese Fisheries Society [12]. Hong Kong, Macao, and Taiwan were not included in this study due to data availability and to safeguard the validity of the data. Tianjin and Shanghai were affected by the natural environment of the sea area and other factors, which made it relatively difficult to carry out seawater shellfish aquaculture production [13], and the statistical data in the China Fishery Statistical Yearbook was 0, so they were excluded from this study.

### Methods for Measuring Carbon Sinks in Mariculture Shellfish and Algae

As the world's largest aquaculture production country, China's mariculture production and area are the world's first. The direction of mariculture is to promote the marine "low-carbon transition", one of the important modes of economic development. In 2022, the total output of mariculture was 2,275.70×10$^4$ t, of which shellfish aquaculture volume was 1569.58×10$^4$ t, accounting for 68.97% of the total volume of mariculture; and algae farming volume was 271.39×10$^4$ t, accounting for 11.93% of the total volume of mariculture. 10$^4$ t, accounting for 68.97% of the total mariculture output, and 271.39×10$^4$ t of algae, accounting for 11.93% of the total mariculture output. As an important part of China's marine aquaculture, shellfish and algae account for more than 80 percent of marine aquaculture.

In this study, the measurement of the carbon sink of mariculture shellfish was referred to as the method of direct carbon sink accounting of mariculture shellfish by Yue Dongdong et al. [14] with the following formula:

$$C_S = C_B + C_W \tag{1}$$

$$C_B = \sum\nolimits_1^n C_i \tag{2}$$

$$C_i = C_{is} + C_{ir} \tag{3}$$

$$C_{is} = W_i \times G_i \times M_{is} \times C'_{is} \tag{4}$$

$$C_{ir} = W_i \times G_i \times M_{ir} \times C'_{ir} \tag{5}$$

Where $C_S$ is the total carbon sink of marine aquaculture shellfish, $C_W$ is the total carbon sink of algae, $C_B$ is the total carbon sink of shellfish, and n is the number of species of farmed shellfish, $C_i$ is the carbon

Table 1. Dry and wet conversion coefficients, soft tissue mass ratios, and shell mass ratios. of different shellfish species.

| Shellfish species | Wet and dry conversion factor (%) | Specific gravity of soft tissue mass (%) | Specific gravity of shell mass (%) |
|---|---|---|---|
| *Mactridae* [16] | 52.55 | 1.98 | 98.02 |
| *Mytilus edulis* [16] | 75.28 | 8.47 | 91.53 |
| *Pectinidae* [16] | 63.89 | 14.35 | 85.65 |
| *Ostrea gigas* [16] | 65.10 | 6.14 | 93.86 |
| Other shellfish [16] | 64.21 | 11.41 | 88.59 |

sink of i species of shellfish, $C_{is}$ is the carbon sink of shells of i species of shellfish, $C_{ir}$ is the carbon sink of soft tissues of i species of shellfish, $W_i$ is the production of i species of shellfish, $G_i$ is the coefficient of dry and wet weights of i species of shellfish. $M_{is}$ is the specific gravity of the mass of the shells, $C'_{is}$ is the carbon content of the shells of i species of shellfish; $M_{ir}$ is the specific gravity of the mass of the soft tissues, and $C'_{ir}$ is the carbon content of the soft tissues.

The carbon sink of mariculture algae was measured with reference to the accounting method of Zhang Jihong et al. [15], and since the algal yield data used in this paper is the mass of its dry weight, the conversion of wet and dry does not have to be taken into account in the calculation. The formula is as follows:

$$C_W = \sum\nolimits_1^k C_j \tag{6}$$

$$C_j = Q_j \times C'_j \tag{7}$$

k is the number of species of cultured algae, $C_j$ is the carbon sink of j species of algae, $Q_j$ is the annual production of j species of algae, and $C'_j$ is the carbon content of j species of algae.

According to the (China Fisheries Statistical Yearbook), there are 9 main species of shellfish in China, including *Ostrea gigas*, *Abalone*, *Viviparidae*, *Arcidae*, *Mytilus edulis*, *Atrina pectinate*, *Pectinidae*, *Mactridae,* and *Sinonovacula constricta*, etc., while there are 8 main species of seaweed in China, including *Laminaria japonica*, *Undaria pinnatifida*, *Porphyra*, *Gracilaria*, *Eucheuma muricatum*, *Gelidium amansi*, *Hizikia fusifarme*, and *Enteromorpha*, respectively. At present, some species of shellfish and algae do not have detailed parameters for their carbon content, so this paper measures the carbon sinks of marine aquaculture shellfish and algae with the help of existing research results.

In the above equation, the dry and wet coefficients and carbon contents measured by cultured shellfish refer to the relevant studies of Yue Dongdong et al. [16], Zhou Yi et al. [17], Lin Zhenxian et al. [18], and Ji Jianyue et al. [19]. The specific parameters are shown in Tables 1, 2, and 3.

Table 2. Soft tissue and shell carbon content of different shellfish species.

| Shellfish species | Carbon content of soft tissue (%) | Carbon content of shells (%) |
|---|---|---|
| *Mactridae* [16] | 44.90 | 11.52 |
| *Mytilus edulis* [16] | 44.40 | 11.76 |
| *Pectinidae* [16] | 43.90 | 11.40 |
| *Ostrea gigas* [16] | 45.89 | 12.68 |
| Other shellfish [16] | 43.87 | 11.44 |

Table 3. Carbon content of different algae.

| Algae species | Carbon content (%) |
|---|---|
| *Laminaria japonica* [17] | 31.2 |
| *Gracilaria* [17] | 20.60 |
| *Porphyra* [18] | 38.19 |
| *Undaria pinnatifida* [19] | 26.40 |
| Other algae [19] | 30.36 |

In this paper, Chinese marine shellfish species were classified into five treatments, specifically: *Ostrea gigas*, *Mactridae*, *Pectinidae*, *Mytilus edulis,* and others, where "others" included *Abalone*, *Viviparidae*, *Arcidae*, *Atrina pectinate*, *Sinonovacula constricta,* shellfish production without species-specific statistics, and other carbon sink accounting parameters were determined based on the average values of the four species *Ostrea gigas*, *Mactridae*, *Pectinidae*, and *Mytilus edulis* to approximate the calculation [16].

The carbon content of *Undaria pinnatifida* has not been addressed in the relevant studies, and since wakame belongs to the group of macroalgae along with *Laminaria japonica*, *Porphyra*, and *Gracilaria*, the average carbon content of *Laminaria japonica*, *Porphyra*, and *Gracilaria* was set as the carbon content of *Undaria pinnatifida*. The average carbon content of *Eucheuma muricatum*, *Gelidium amansi*, *Hizikia fusifarme,* and *Enteromorpha* was set as the carbon content of the other classes [19].

### Methods for Assessing the Economic Value of Carbon Sinks

The carbon sink value of mariculture shellfish refers to the economic value generated by the removal of $CO_2$ during the aquaculture process. Therefore, its formula is:

$$V_C = C_T \times C_C \tag{8}$$

$$C_T = C_S \times \beta \tag{9}$$

Where $V_C$ is the value of the carbon sink of marine aquaculture shellfish, $C_T$ is the total carbon sink of marine aquaculture shellfish, $C_C$ is the economic cost per unit of carbon abatement, $C_S$ is the total carbon sink of marine aquaculture shellfish, and β is the carbon dioxide constant of 3.67 based on the mass of carbon contained in a unit of $CO_2$ (27.27%).

According to the series of reports on the achievements of economic and social development since the 18th National Congress of the Communist Party of China issued by the National Bureau of Statistics of China, China's GDP has grown at an average annual rate of 6.6% in the past ten years, so the economic cost of carbon emission reduction of units in each province in the formula is calculated with reference to the actual cost of $CO_2$ emission reduction of the province under the background of the GDP of each province at the growth rate of 6.5%, and the whole country is calculated in accordance with the average cost of emission reduction of the average $CO_2$ [20], the specific parameters are shown in Table 4 below.

## Results and Discussion

### Carbon Sinks from Mariculture Shellfish and Algae

According to the measured parameters and the production of shellfish and algae converted by the formula, as shown in Figs. 1 and 2, the largest contribution to the carbon sink of farmed shellfish in China is oyster, and the largest contributing species of algae is kelp. In 2022, the carbon sink of *Ostrea gigas* reaches 59.40×10$^4$ t, accounting for 27.30% of the total amount of farmed shellfish and algae-farmed carbon sinks, and the *Laminaria japonica* carbon sink reaches 44.63×10$^4$ t, accounting for 20.51% of the total amount of carbon sinks. 20.51% of the total carbon sinks are the two main species of farmed shellfish and algae carbon sinks in China.

According to Table 5, the cumulative carbon sink of marine aquaculture shellfish from 2013 to 2022 is 1954.32×10$^4$ t, with an annual average of 195.43×10$^4$ t. The national trend shows a slow increase, with coastal provinces and regions, such as Fujian, Guangxi Zhuang Autonomous Region, and Zhejiang, showing slow increases, and other provinces and regions showing fluctuations of a certain magnitude. Among the provinces, Shandong, Fujian, and Liaoning ranked the top three in the period of 2013-2022, followed by Guangdong Province, and Hainan Province has always been the province with the lowest amount of carbon sinks. The main reason for this is that China's main shellfish production areas are relatively concentrated, with an orderly regional distribution and obvious characteristics. In terms of regional distribution of production, four provinces, namely Shandong, Fujian,

Table 4. Actual abatement cost of provincial $CO_2$ emission reduction in the context of China's GDP growth rate of 6.5%.

| China | Hebei | Liaoning | Jiangsu | Zhejiang | Fujian | Shandong | Guangdong | Guangxi | Hainan |
|---|---|---|---|---|---|---|---|---|---|
| 67.83 | 67.82 | 67.83 | 67.82 | 67.82 | 67.79 | 67.9 | 67.82 | 67.81 | 67.99 |

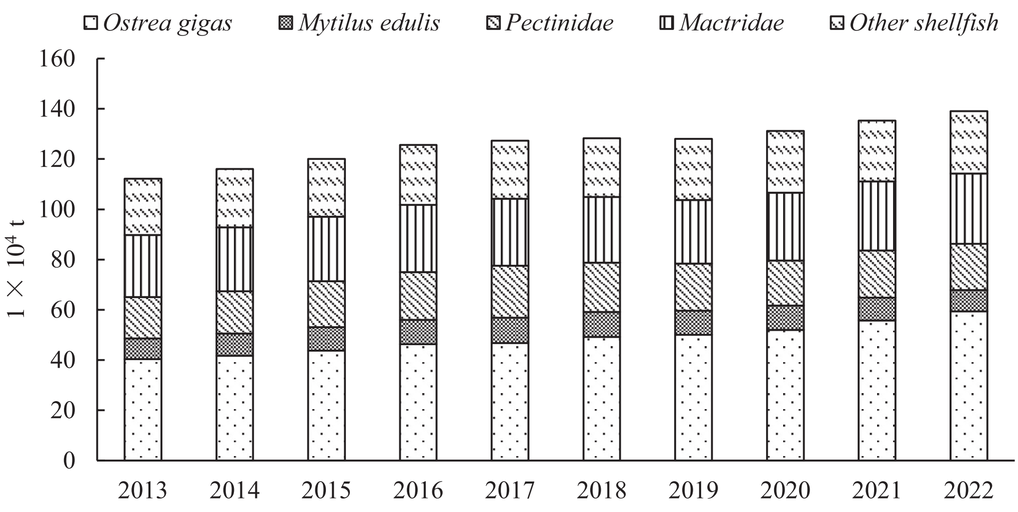


Fig. 1. Mass of carbon sinks removed from seawater by mariculture shellfish, 2013-2022.

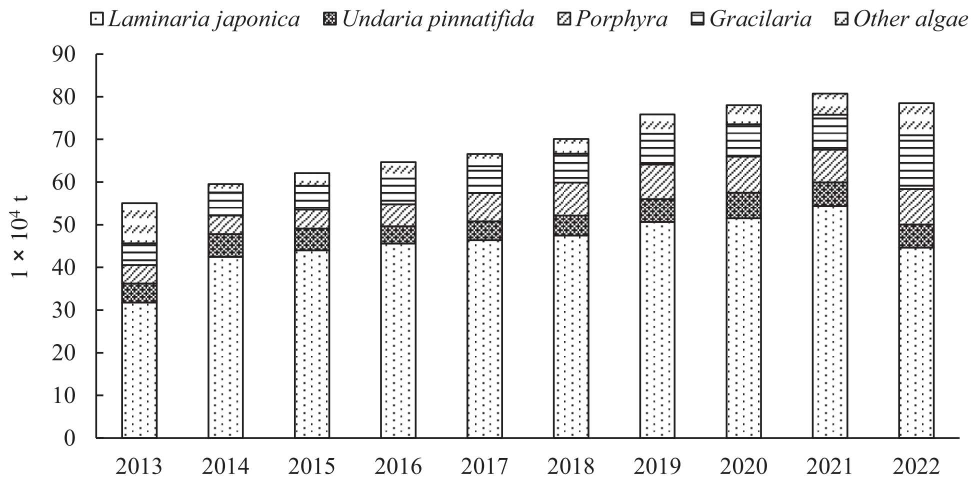


Fig. 2. Mass of carbon sinks removed from seawater by mariculture algae, 2013-2022.

Guangdong, and Liaoning, are in the lead, with Shandong and Fujian always in the top two, and Shandong's marine shellfish aquaculture production accounts for more than a quarter of China's total. Since 2009, Liaoning has continued to expand its scallop aquaculture area, and its output has surpassed that of Guangdong, ranking third. Shandong has actively responded to the national low-carbon development strategy by expanding the scale of cultivation of kelp and other species with high economic value and strong carbon storage capacity, amplifying the function of fishery carbon sinks, and promoting the transformation of blue carbon from a resource to an asset, with outstanding performance in seaweed carbon sinks. As a major seaweed cultivation province, Fujian clearly proposed to increase marine carbon sinks in the national economic and development plan in 2011. In recent years, Fujian has devoted itself to the development of seaweed aquaculture, enhancing the carbon storage capacity of seaweeds and promoting the development of a marine low-carbon economy through a number of measures, such as restoring and rebuilding large-scale seaweed farms, developing carbon sink fisheries based on shellfish aquaculture, setting up a technical system for evaluating the sequestration of seaweeds and increasing sinks, and exploring the mechanism for trading marine carbon sinks. Liaoning seaweed cultivation areas are concentrated in Dalian, Jinzhou, Changhai, Lushunkou, etc. As the conditions of the sea area limit the scale of cultivation, the output of seaweed cultivation in the province is relatively stable. The deployment and construction of the Guangdong Comprehensive Pilot Area of Ocean Economy in 2012 created conditions for the development of carbon sinks for seaweeds. Hainan is located in the tropics, and the climate conditions are not suitable for the growth of temperate seaweeds, which is the mainstream of the current market. Because of the many constraints and high costs of seaweed production, the seaweed cultivation area in Hainan Province is relatively small. Moreover, Hainan has been focusing on coastal tourism as its marine economic development, and with the construction of the Hainan International Tourism

Table 5. Mass of carbon sinks removed from seawater by cultured shellfish (Unit:1×$10^4$ t).

| Year | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|---|---|---|---|---|---|
| China | 167.17 | 175.61 | 182.22 | 190.34 | 193.94 | 198.34 | 203.93 | 209.17 | 216.01 | 217.59 |
| Hebei | 4.05 | 4.44 | 4.56 | 4.55 | 4.72 | 4.34 | 3.56 | 3.79 | 4.19 | 4.29 |
| Liaoning | 27.88 | 28.91 | 29.24 | 30.14 | 29.93 | 28.47 | 31.77 | 32.2 | 34.06 | 34.63 |
| Jiangsu | 6.83 | 6.64 | 6.35 | 6.44 | 7.02 | 6.94 | 6.88 | 7.24 | 7.07 | 7.28 |
| Zhejiang | 8.19 | 8.44 | 8.91 | 9.74 | 11.58 | 12.31 | 13.09 | 14.57 | 14.58 | 16.17 |
| Fujian | 45.02 | 47.43 | 50.67 | 54.63 | 56.53 | 60.9 | 64.74 | 66.55 | 68.98 | 68.12 |
| Shandong | 48.24 | 52.17 | 54.26 | 55.73 | 56.33 | 56.79 | 54.95 | 56.34 | 58.92 | 58.02 |
| Guangdong | 19.4 | 19.63 | 19.88 | 20.25 | 18.87 | 19.4 | 19.68 | 18.93 | 18.28 | 17.47 |
| Guangxi | 6.58 | 6.85 | 7.26 | 7.71 | 8.14 | 8.64 | 8.95 | 9.23 | 9.96 | 10.44 |
| Hainan | 0.79 | 1.06 | 1.03 | 1.07 | 0.75 | 0.55 | 0.32 | 0.33 | 0.29 | 0.21 |

Island, the space available for cultivation in Hainan has been squeezed, and the production of shellfish and algae has declined, leading to an overall downward trend in its carbon sink. In 2022, Fujian province will have the largest shellfish carbon sink of 68.12×10$^4$ t, followed by Shandong province, with a carbon sink of 58.02×10$^4$ t. Hainan is the province with the smallest carbon sink, with only 0.21×10$^4$ t. The average amount of carbon sink in coastal provinces is 195.43×10$^4$ t. The trend shows a slow increase in the country, and other provinces and regions show some fluctuations. Hainan is the smallest province, with a carbon sink of 0.21×10$^4$ t.

## The Value of the Carbon Sink of Mariculture Shellfish and Algae

After calculating the carbon sink of mariculture shellfish in China and nine provinces (regions) along the coast of China, and then based on the mass of carbon per unit of $CO_2$ (27.27%), the carbon sink of mariculture shellfish in China is equivalent to an average annual emission reduction of 717.24×10$^4$ t from 2013 to 2022, as shown in Table 6.

According to Table 7, it can be seen that from 2013 to 2022, the value of carbon sinks of Chinese mariculture shellfish and algae as a whole showed an upward trend, with the value of carbon sinks increasing from CNY416 million yuan in 2013 to CNY542 million yuan in 2022, and the average annual value of carbon sinks was RMB 487 million. The average annual value of carbon sinks will be CNY400 million yuan. Zhejiang and Guangxi are on an upward trend in terms of provinces; Hebei and Hainan fluctuate considerably; Hainan is on a downward trend, and the downward trend is very obvious. Other provinces fluctuate slightly, but are on an overall upward trend.

## Discussion

According to the results of this study, there are two main influencing factors affecting shellfish carbon sinks

Table 6. Carbon sinks for quasi-$CO_2$ emission reductions from mariculture shellfish and algae in China (Unit:1×10$^4$ t).

| Year | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|---|---|---|---|---|---|
| China | 613.51 | 644.49 | 668.75 | 698.55 | 711.76 | 727.91 | 748.42 | 767.65 | 792.76 | 798.56 |
| Hebei | 14.86 | 16.29 | 16.74 | 16.7 | 17.32 | 15.93 | 13.07 | 13.91 | 15.38 | 15.74 |
| Liaoning | 102.32 | 106.1 | 107.31 | 110.61 | 109.84 | 104.48 | 116.6 | 118.17 | 125 | 127.09 |
| Jiangsu | 25.07 | 24.37 | 23.3 | 23.63 | 25.76 | 25.47 | 25.25 | 26.57 | 25.95 | 26.72 |
| Zhejiang | 30.06 | 30.97 | 32.7 | 35.75 | 42.5 | 45.18 | 48.04 | 53.47 | 53.51 | 59.34 |
| Fujian | 165.22 | 174.07 | 185.96 | 200.49 | 207.47 | 223.5 | 237.6 | 244.24 | 253.16 | 250 |
| Shandong | 177.04 | 191.46 | 199.13 | 204.53 | 206.73 | 208.42 | 201.67 | 206.77 | 216.24 | 212.93 |
| Guangdong | 71.2 | 72.04 | 72.96 | 74.32 | 69.25 | 71.2 | 72.23 | 69.47 | 67.09 | 64.11 |
| Guangxi | 24.15 | 25.14 | 26.64 | 28.3 | 29.87 | 31.71 | 32.85 | 33.87 | 36.55 | 38.31 |
| Hainan | 2.9 | 3.89 | 3.78 | 3.93 | 2.75 | 2.02 | 1.17 | 1.21 | 1.06 | 0.77 |

Table 7. Carbon Sink Value of Mariculture Shellfish and Algae in China (Unit:CNY 1×10$^8$ yuan).

| Year | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|---|---|---|---|---|---|
| China | 4.161 | 4.372 | 4.536 | 4.738 | 4.828 | 4.937 | 5.077 | 5.207 | 5.377 | 5.417 |
| Hebei | 0.101 | 0.111 | 0.113 | 0.113 | 0.117 | 0.108 | 0.089 | 0.094 | 0.104 | 0.107 |
| Liaoning | 0.694 | 0.720 | 0.728 | 0.750 | 0.745 | 0.709 | 0.791 | 0.802 | 0.848 | 0.862 |
| Jiangsu | 0.170 | 0.165 | 0.158 | 0.160 | 0.175 | 0.173 | 0.171 | 0.180 | 0.176 | 0.181 |
| Zhejiang | 0.204 | 0.210 | 0.222 | 0.242 | 0.288 | 0.306 | 0.326 | 0.363 | 0.363 | 0.402 |
| Fujian | 1.120 | 1.180 | 1.261 | 1.359 | 1.406 | 1.515 | 1.611 | 1.656 | 1.716 | 1.695 |
| Shandong | 1.202 | 1.300 | 1.352 | 1.389 | 1.404 | 1.415 | 1.369 | 1.404 | 1.468 | 1.446 |
| Guangdong | 0.483 | 0.489 | 0.495 | 0.504 | 0.470 | 0.483 | 0.490 | 0.471 | 0.455 | 0.435 |
| Guangxi | 0.164 | 0.170 | 0.181 | 0.192 | 0.203 | 0.215 | 0.223 | 0.230 | 0.248 | 0.260 |
| Hainan | 0.020 | 0.026 | 0.026 | 0.027 | 0.019 | 0.014 | 0.008 | 0.008 | 0.007 | 0.005 |

in China: one is shellfish aquaculture yield, and the other is shellfish aquaculture species. The culture yield plays a dominant role in the carbon sinks of Chinese marine aquaculture shellfish [21], and the culture yield is the basis for the calculation of the quality of carbon sinks; that is to say, the larger the culture yield, the higher the quality of carbon sinks. Some studies have shown that the contribution of the yield factor to the change of carbon sinks of Chinese mariculture shellfish can reach more than 83%, and the contribution of the algal yield factor to the change of algal carbon sinks can reach more than 58% [22]. Different farming species also affect the quality of carbon sinks; shellfish have higher carbon sink coefficients compared to algae; in shellfish products, shellfish is a higher quality carbon sink farming species; scallops and mussels have higher carbon sink coefficients; and in algae products, kelp has a higher carbon sink coefficient [22].

For the carbon sinks of marine aquaculture shellfish and algae, this study mainly refers to a large number of studies by other experts and scholars using the production of farmed shellfish and algae, but marine aquaculture shellfish and algae, in addition to harvesting the carbon removed, also include the carbon used in the process of their growth. For example, the detrital organic carbon produced during the growth of algae, part of which will become a food source for other organisms and part of which will eventually be deposited and buried on the seabed through direct sedimentation. In addition, Dissolved Organic Carbon (DOC) and Particulate Organic Carbon (POC), which are released by macroalgae during their growth can enter the food web or form Recalcitrant Dissolved Organic Carbon (RDOC) under the action of microfood loops and remain in seawater for a long time [23, 24]. Considering these factors, the total carbon sink of algae, if accounted for on the basis of net carbon sink (carbon removed from storage)/0.75 [25], the total amount of carbon absorbed by mariculture algae in China in 2022 would be about $104.68\times10^4$ t of carbon.

In this paper, the carbon sink of marine shellfish aquaculture was measured by dry weight ratio and carbon content, including carbon fixed in the shells of shellfish and carbon in two parts of the soft tissue. However, the shellfish carbon sink needs to be considered more, using the shellfish energy balance allocation model [26], i.e.,

$$C = F + U + R + P \tag{10}$$

In the formula, C is the total energy in the food ingested by the shellfish, F is the energy in the food ingested by the shellfish that is not utilized and excreted with the feces (i.e., fecal energy), U is the energy consumed by excretion (i.e., fecal energy), R is the energy consumed by respiratory metabolism, and P is the energy consumed by the shellfish for growth. The energy balance equation can not only clearly express the flow of energy in the culture activities of individual shellfish, but also demonstrate the basic processes, mechanisms, and quantities of carbon uptake, removal, storage, or release [25]. In the formula, C is approximated as the organic carbon taken up by shellfish from food and water, i.e., the particulate organic carbon actually utilized by aquaculture, and P is approximated as the growth energy in the original model, i.e., the yield of shellfish. The weighted average of C/P is about 25% under aquaculture conditions [15, 25], from which a total of about $392.40\times10^4$ t of carbon was projected to have been taken up by marine-farmed shellfish nationwide in 2022.

In addition to this, shellfish and algal aquaculture activities have introduced a large number of aquaculture facilities into the sea area, such as floating rafts, cables, and net cages, as well as shells, which provide a large number of attachment bases for attached organisms, resulting in a significant increase in the number of calcium-rich attached organisms, such as sea squirts and sponges, in the aquaculture area. Attached organisms also have a strong filter-feeding capacity for suspended particulate organic matter in the water column [5] and can be removed in large numbers, e.g., through cage changes, or dislodged from the culture equipment and deposited to the seabed on their own when the water temperature decreases. Due to their large numbers, their biological deposition can even exceed that of cultured species [27]. However, its biomass is difficult to count, so the carbon sink effect of attached organisms was not considered in this study for the time being. However, such a limitation reduces a part of the important content, which will have a certain impact on the conclusion of the measurement of the carbon sink of shellfish and algae in mariculture. In order to accurately and comprehensively measure the carbon sinks of marine aquaculture shellfish, the carbon used in the whole growth process of shellfish should be studied first, and the income and expenditure model of its carbon source and sink should be established, so as to reduce the uncertainty of the calculation of carbon sinks.

As there is no accurate accounting system for the economic value of shellfish carbon sinks, this paper calculates the economic value of marine aquaculture shellfish carbon sinks based on the existing research with reference to the actual provincial $CO_2$ emission reduction costs against the background of the provincial GDP growth rate of 6.5%. In practice, there are many factors affecting the abatement cost. Firstly, the level of R&D and application of abatement technology directly affects the abatement cost; secondly, the larger the $CO_2$ emissions, the more abatement technology and capital investment may be required, which increases the abatement cost; finally, the government's abatement policies and regulations also have a significant impact on the abatement cost, such as the government's abatement requirements for certain industries or regions may be higher, which results in the relevant enterprises and regions needing to invest more funds and technology to meet the emission reduction targets. In addition, the impact of energy structure on emission reduction costs is mainly reflected in the carbon emission intensity and price of different energy sources, for example, the use of low-carbon energy sources (e.g., wind energy, solar energy) to replace high-carbon energy sources (e.g., coal) can reduce carbon emissions, but it may require higher investment costs; the improvement of energy use efficiency can reduce the energy consumption and carbon emissions per unit of output, thus reducing the cost of emission reduction; the level of urbanisation and population density have a significant impact on the cost of emission reduction, mainly due to the need to invest more funds and technologies to meet the emission reduction targets. Population density and the abatement cost are mainly reflected in energy consumption and transport carbon emissions. With the advancement of urbanization and the increase in population density, energy consumption, and transport carbon emissions may increase, thus raising the abatement cost. In the follow-up study, it should be noted that there are many factors influencing the abatement cost, and there may be interactions and influences between different factors. Therefore, when actually analyzing and assessing the abatement cost, it is necessary to consider various factors in a comprehensive manner and adopt appropriate methods for calculation and assessment. Only on this basis can the value of shellfish carbon sinks be assessed more accurately.

As China builds a moderately prosperous society, the proportion of high-quality protein required in the dietary structure of the population is increasing. Ruminants, a common source of high-quality protein, have high carbon emissions due to their need for feed feeding, occupation of arable land, and greenhouse gas production from intestinal digestion. In contrast, shellfish are a much lower-carbon pathway to a high-quality food protein supply. Studies have confirmed that all 11 commonly farmed shellfish species are high protein foods, with the protein content of shellfish ranging from 47.65% to 62.72% of the dry weight of soft tissue [27]. Bivalve shellfish farming does not require feed, and its carbon footprint is much smaller than that of livestock. The greenhouse gas emissions of long oysters farmed in China were only 2.27 kg$CO_2$-eq when 1 kg of protein was supplied [28], which was significantly lower than that of beef ((103.05±42.14) kg$CO_2$-eq), milk ((39.72±13.20) kg$CO_2$-eq), pork ((39.72±13.20) kg$CO_2$-eq), and milk ((39.72±13.20) kg$CO_2$-eq). Pork ((32.09±8.14) kg$CO_2$-eq) and egg ((19.37±7.15) kg$CO_2$-eq) carbon footprints [29]. Shellfish aquaculture in China can save more carbon emissions compared to other livestock and poultry species when providing an equivalent amount of high-quality protein, which is of great significance for China to achieve its carbon neutrality goal.

## Conclusions and Recommendations

### Conclusions

This study measured the carbon sinks of mariculture shellfish in China and nine provinces (regions) along the coast of China from 2013 to 2022, and based on this, assessed the value of the carbon sinks of China's mariculture shellfish using existing research on the actual cost of provincial $CO^2$ emission reductions under the background of China's GDP growth rate of 6.5%. Finally, the following conclusions were drawn:

From the perspective of China as a whole, the carbon sink of mariculture shellfish increases steadily. From 2013 to 2022, the carbon sink of China's mariculture shellfish increased year after year, from 167.17×$10^4$ t at the beginning of the period to 217.59×$10^4$ t at the end of the period, with an increase of 30.16% in the carbon sink during the period of the study. In terms of regional structure, Shandong, Fujian, and Liaoning ranked in the top three. Among them, the carbon sink of marine aquaculture shellfish in Shandong has been larger, increasing from 48.24×$10^4$ t in 2013 to 58.02×$10^4$ t in 2022, followed by Fujian, with a carbon sink of 45.02×$10^4$ t in 2013 and 68.12×$10^4$ t in 2022. In the period of 2013-2017, Fujian ranked second in terms of carbon sinks after Shandong, and after 2018, it surpassed Shandong as the top three. In 2018, it overtook Shandong to become the province with the largest carbon sink from mariculture shellfish in China. Liaoning Province increased from 27.88×$10^4$ t in 2013 to 34.63×$10^4$ t in 2022, with a growth rate of 24.21%. The lowest was in Hainan Province, where the carbon sink decreased by 0.58×$10^4$ t in 2022 compared with 2013, a decrease of 73.42%. This is basically consistent with the difference in regional distribution of China's mariculture shellfish production, i.e., Shandong, Fujian, and Liaoning are the top three provinces in China in terms of shellfish and algae production, and at the same time, their fishable waters are also more prone to *Ostrea gigas*, *Mactridae*, *Pectinidae*, *Laminaria japonica*, and other species with greater carbon sink capacity. From the point of view of the proportion of carbon sinks of different shellfish species, it is similar to the structure of China's marine aquaculture shellfish production, which is mainly dominated by *Ostrea gigas* and *Mactridae*. Firstly, the carbon sink of *Ostrea gigas* increased from 40.42×$10^4$ t in 2013 to 59.4×$10^4$ t in 2022, which tends to stabilize in the last five years. Consistent with accounting for the largest share of China's marine aquaculture shellfish production, *Ostrea gigas* has always accounted for the largest share of carbon sinks. This is followed by the carbon sinks of *Mactridae*, and finally the carbon sinks of other shellfish, *Pectinidae* and *Mytilus edulis*. It can be seen that the structure of the carbon sink of marine aquaculture shellfish in China is relatively stable and has been dominated by *Ostrea gigas* and *Mactridae* without major changes. The main reason for this is twofold: firstly, the endowment of fishery resources in China is determined by the difference in fishery resources suitable for each species of shellfish, among which *Ostrea gigas* and *Mactridae* have more suitable waters for aquaculture; secondly, the rate of technological progress of each species of shellfish in mariculture is not very different, especially *Pectinidae* and *Mytilus edulis,* which account for a relatively small proportion of the total number of shellfish in China, and no subversive technology, which makes the rapid increase in their production and thus carbon sinks exceeded by the phenomenon, has not happened. According to the algae carbon sinks, to see the main carbon sink species for *Laminaria japonica*, *Laminaria japonica* carbon sinks accounted for the main part of the *Laminaria japonica* carbon sinks in 2013-2021 *Laminaria japonica* carbon sinks show a steady increase in 2022; the decline is more serious. The main reason for this is that from November 2021 to April 2022, one of the main producing areas of *Laminaria japonica*, Rongcheng, Shandong Province, had a *Laminaria japonica* ulcer disaster, which affected an area of more than 9300 $hm^2$, with a direct economic loss of CNY2 billion yuan. The results of the assessment of the value of carbon sinks of marine aquaculture shellfish and algae show that the value of carbon sinks from 2013 to 2022 shows an upward trend, totaling CNY4.865 billion yuan, which shows that the economic benefits of the carbon sinks of marine aquaculture shellfish and algae in China are remarkable and that they can play an important role in the marine circular economy.

## Recommendations

China has the world's largest-scale mariculture industry and is also one of the countries with the largest greenhouse gas emissions, accounting for about 30% of global carbon emissions. Combining mariculture carbon sinks with the construction of a blue grain silo is a win-win strategy that is a scientific way of developing to cope with the current situation and the new challenges of the world's economic development. In this regard, the present study proposes the following countermeasures and recommendations based on the results of the above research and the shortcomings of the research on fishery carbon sinks.

(1) At present, the development of mariculture carbon sinks in China is still in the primary stage, and there are still many deficiencies in basic theoretical research. Literature and practical research have found that the accounting methods of mariculture carbon sinks are not uniform, relevant data is missing, and there is no standard calculation method to evaluate some carbon components such as DOC, POC, RDOC, and buried carbon. Therefore, the investment in carbon sink research should be increased, in-depth research on carbon sink measurement methodology should be carried out, and relevant data should be continuously expanded. Only by establishing a set of scientific and feasible measurement methodologies and a rich database can we understand the specific situation of China's mariculture carbon sinks, so that we can put forward more targeted policy recommendations for the development of China's and even the world's mariculture carbon sinks.

(2) This study found that culture yield and different culture species affect the quality of carbon sinks, and that seawater culture shellfish and algae are an important part of the formation of fishery carbon sinks, so increasing the yield of seawater culture shellfish and algae, either directly or indirectly, is an increase in the carbon sinks of marine fisheries. Expand the area of aquaculture in the relevant sea areas suitable for the growth of macroalgae and increase the scale of aquaculture of kelp, nori, and other species with higher carbon content. For shellfish, we can increase the production of shellfish farming as a whole, and each species can only be increased but not decreased, and increase the production of oysters, mussels, and scallops, which are high in carbon content, by adjusting the aquaculture structure. It is also possible to innovate the mode of aquaculture and carry out multi-level aquaculture technology to realize the mixed culture of shellfish and algae, so as to increase the yield. Continuous research on shellfish aquaculture can be adapted to various sea areas in China to increase the production of shellfish and algae. Finally, it can also extend the industrial chain through the shellfish's own characteristics to extend the industrial chain, improve market demand, and increase the production of its culture. At the same time, the construction of fishery co-operative organizations plays an active role in production, disease prevention, and circulation, which can effectively reduce the impact of disasters and epidemics on the production of shellfish, increase the scale of production, and also effectively increase the market premium capacity of producers, improve the disadvantaged position of producers in the market, and promote the increase of shellfish aquaculture production.

(3) The amount of carbon sink value accounted for in this study shows that the economic benefits of fishery carbon sinks are significant.2021 On 6 July 2021, the national carbon market was officially launched, and China built the largest carbon market in the world. In recent years, fishery carbon sinks have gradually entered the carbon trading market. On 19 May 2022, the first bivalve shellfish carbon trading project in the country was completed in Xiuyu District, Putian City, relying on the Straits Resources and Environment Trading Centre and the seller, Forest Oyster (Fujian) Aquatic Co. Accelerating the promotion of fishery carbon trading will not only enable aquaculture enterprises or fishermen to increase additional income, but also improve their enthusiasm for shellfish aquaculture, thereby increasing the production of shellfish and carbon sinks and contributing to China's goal of achieving "carbon neutrality". The ocean power will continue to contribute to China's goal of "carbon neutrality". In addition, it is necessary to continuously improve the management methods and rules of the carbon trading market, promote the paid ecological services of carbon

sinks in aquaculture fisheries, and promote international blue carbon cooperation and trade in marine fisheries, so as to facilitate the creation of a greater carbon sink value from shellfish aquaculture.

## Acknowledgments

This study was funded by the Tianjin Municipal Science and Technology Commission's Major Project on Science and Technology for Ecological and Environmental Governance (18ZXSZSF00080).

## Conflict of Interest

The authors declare no conflict of interest.

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