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[1]Shengnan Chen

Analysis of Green Total Factor Productivity Measurement of China's Marine Carbon Sink Fisheries Based on EBM-GML Model

Abstract: - As a green, low-carbon and sustainable ecological fishery, marine carbon sink fisheries can significantly increase the total amount of carbon sequestered by marine carbon sinks while saving the social cost of fishery production and improving the quality and production efficiency of fishery products, which is of great significance in promoting high-quality economic development and achieving the goal of "dual carbon". Based on panel data of nine key coastal provinces in China, this paper constructs an input-output analysis framework, measures the green total factor productivity of China's marine carbon sink fisheries using the super-efficient EBM model and GML index, and explores its regional differences and convergence characteristics using the Theil index and convergence model. The results show that: 1) Green total factor productivity in marine carbon sink fisheries is growing at the national, regional and provincial levels, with growth mainly due to green technological progress, but there are differences in the level of growth. 2) There are large regional differences in the development of marine carbon sink fisheries in various regions, and intra-regional differences are the main source of the overall differences in the development of marine carbon sink fisheries. 3) There is absolute β-convergence and conditional β-convergence in China and the Bohai Rim, Yangtze River Delta and Pearl River Delta regions.

Keywords: marine carbon sink fisheries; green total factor productivity; regional differences; convergence

Introduction

As a result of the evolution of the natural environment and human activities, the concentration of greenhouse gases, mainly carbon dioxide (CO2), has increased dramatically, and the resulting global climate change has been of widespread concern to all countries. As a responsible big country, China has long included emission reduction targets in its 12th Five-Year Plan, and President Xi Jinping has proposed a "dual carbon" goal of peaking carbon dioxide emissions by 2030 and achieving carbon neutrality by 2060. At present, there are two types of measures to address the greenhouse effect: one is to reduce "carbon sources" and the other is to increase "carbon sinks". As the world's largest carbon reservoir, the ocean stores 93% of the earth's carbon dioxide[1], and annually absorbs 20%-35% of the total carbon dioxide emitted by human activities[2]. The amount of dissolved inorganic carbon stored in the ocean is about 3.8×10^{13}t[1]. As an important component of the modern marine economy, diesel combustion, electricity consumption and irrational aquaculture methods in mariculture fisheries are the main "carbon sources"[3]. Inorganic carbon is absorbed and fixed into particulate organic carbon by marine organisms such as shellfish and algae through photosynthesis and biological deposition, thus completing the process of carbon transfer, which is called "carbon sink"[4]. Since the concept of "carbon sink fisheries" was put forward in

[1] [1] *School of Economics and Management, Shanghai Ocean University, Shanghai, Peoples R China. Email: quinna_chen@163.com

2005, this means of biological carbon sequestration with a high input-output ratio and significant comprehensive benefits has received widespread attention. More and more studies have begun to emphasize the important role of marine aquaculture in the ocean's carbon sinks. From 2009 to 2020, China's mariculture production increased from 1.41×10^7t to 2.14×10^7t. The capacity of mariculture in sequestering carbon continues to increase, and a distribution pattern of mariculture in the Bohai Rim, Yangtse River Delta, and Pearl River Delta economic zones has gradually been formed[5]. Against this background, it is of great significance to comprehensively measure the green total factor productivity(GTFP) of China's marine carbon sink fisheries, and to deeply explore its regional differences and convergence characteristics, in order to guide the high-quality development and green transformation of China's marine fisheries, realize the goal of "dual carbon", and build an environmentally friendly and resource-saving society.

The concept of "carbon sink fisheries" was first proposed by Tang Qisheng in 2005, who believed that any fishery production activity in the ocean that does not require baiting has the function of carbon sink, and may form marine carbon sink, and accordingly can also be called Marine carbon sink fisheries[6]. Currently, research on carbon sink fisheries mainly focuses on three aspects. The first is the research on the assessment of carbon sink capacity or carbon sequestration. Most of the researches start from the perspective of material quality assessment, and utilize the yield and carbon content coefficients to measure the carbon sequestration of marine shellfish aquaculture, and researches show that marine shellfish aquaculture has a significant function as carbon sink[7]. Some studies have also added the perspective of value quantity assessment, and selected the Swedish carbon tax rate and artificial forestation method to evaluate the carbon sink capacity of marine aquaculture in a more comprehensive way[9]. Qi ZH et al. (2012)[9] assessed that in 2009, shellfish and algae harvested in Guangdong Province mariculture could remove about 11×10^4t of carbon from seawater, equivalent to 4×10^5t of carbon dioxide, creating an ecological emission reduction of up to 238 million U.S. dollars in economic value. The second is the research on the evaluation of the green development level of mariculture. One type is the applied evaluation of the green development level of mariculture by constructing an evaluation index system[14]; the other is to measure the green production efficiency of mariculture taking into account the economic and resource inputs as well as the environmental outputs, mainly including green technology efficiency[15], eco-economic efficiency[16], green total factor productivity[17], carbon emission efficiency[18] and so on. The research methods include stochastic production frontier modeling[19], Data Envelopment analysis (DEA), Malmquist index method and so on. DEA mainly includes radial model represented by BCC and CCR model and non-radial model represented by SBM model. Malmquist index is more often used in conjunction with DEA method because it can reflect the growth level of GTFP[20]. In the selection of indicators, workforce, number of fish fry (fish seedlings)[21], aquaculture area[22] and intermediate consumption of mariculture[16] are generally selected as input variables. Desired outputs mainly consider the total production or gross output value of mariculture, and undesired outputs are accounted for from the perspective of discharges[23](output of nitrogen and phosphorus pollution) and economic losses[24]. Thirdly, it is the research on the factors influencing the efficiency of green development of mariculture. It mainly includes industrial structure[25], scale of aquaculture[26], environmental regulation[25], scientific and technological innovation[27] and so on. Zhang XX et al. (2020)[28] found that income level, fishery technology promotion, use of fishery medicines, and carbon sequestration have a direct promotion effect on the green efficiency of marine carbon sink fisheries in this region, while production structure, economic scale, fishery disasters, and sea pollution have a direct inhibitory effect.

In summary, existing studies have made useful explorations on the relevant topics of this paper, which provide insights for this paper. Compared with the existing literature, the possible contributions of this paper are: First, in terms of research content, this paper focuses on marine carbon sink fisheries, constructs a theoretical analytical framework integrating economic growth, resource inputs, and environmental effects from the perspective of GTFP, and analyzes and explores the dynamic evolution, regional differences, and convergence characteristics of the green development of the marine carbon sink fisheries, which not only improves the theoretical analysis of the GTFP of the marine carbon sink fisheries, but also provides empirical support for promoting the green development of the marine carbon sink fisheries. Secondly, in terms of research methodology, radial DEA model requires inputs and outputs to grow in the same proportion, which is contrary to the actual situation; the non-radial SBM model loses the original proportion between the target value and the actual value of inputs and outputs on the effective frontier, which may lead to the problem of biased measurement of efficiency[29]. The EBM model simultaneously takes into account the radial ratio between the target and actual values of inputs and outputs and the non-radial slack variables of each input and output, which can effectively make up for the shortcomings of the above two types of DEA models. Thirdly, in terms of research perspective, this paper selects the three major regions from north to south, namely Bohai Rim, Yangtze River Delta and Pearl River Delta, as the comparative analysis object, to study the regional differences of marine carbon sink fisheries, so as to provide theoretical basis for the joint promotion of the green development of marine carbon sink fisheries in the inter-regional cooperation.

Materials and methods

Construction of measurement index system

In the context of resources and environment increasingly becoming a hard constraint for economic growth, compared with the traditional total factor productivity theoretical framework that only takes into account factors such as improvement of factor allocation efficiency, technological progress, economic scale, etc., GTFP measures the quality of economic development by incorporating factors such as energy consumption and pollution emission into the scope of economic growth, which is in line with requirements of ecological civilization, embodies the concept of green development, and can more scientifically measure and evaluate the quality of an economy's growth. Focusing on marine carbon sink fisheries, this paper constructs a measurement index system for analyzing GTGP of the marine carbon sink fisheries(see Table 1), which is mainly composed of three categories: economic growth, resource input, and environmental effect. Resource input is the input indicator of GTFP of marine carbon sink fisheries; economic growth is the desired output indicator; and the environmental effect consists of both desired and undesired output indicators. The environmental effect consists of desired output and non-desired output. The promotion of economic development and the reduction of environmental pollution have been taken into account while guiding the rational consumption of marine carbon sink fishery resources.

Table 1. Measurement index system of GTFP in marine carbon sink fisheries.

Index	Index category	Variable	Description of variables
Input	Resource input	Aquaculture area	Area of mariculture shellfish and algae

		Workforce	Specialized practitioners in marine carbon sink fisheries
		Fish seedling	Shellfish and algae nursery stock
		Intermediate consumption	Intermediate consumption in fisheries×gross value of marine carbon sink fisheries/total value of fisheries production
		Fixed asset	Year-end ownership of marine motorized production (farmed) fishing vessels
Output	Economic growth	Economic output	Gross economic value of marine carbon sink fisheries
	Environmental effect	Ecological output	Carbon sequestration by marine carbon sink fisheries
		Pollutant	Amount of nitrogen and phosphorus pollution
		Carbon emission	Carbon emission by marine carbon sink fisheries

Indexes of resource input

The most important input variables in the production model are land, workforce and capital[30]. Combining the availability of data and the characteristics of marine carbon sink fisheries, we select aquaculture area, workforce, fish seedling, intermediate consumption and fixed asset as input indicators. Aquaculture area refers to the natural and human-created aquaculture waters, which is reflected by the area of marine aquaculture shellfish and algae. Workforce refers to people directly involved in the production and operation activities of marine carbon sink fisheries, which is characterized through the number of professional practitioners in marine carbon sink fisheries. Fish seedlings are direction markers of aquaculture production. Fishermen independently decide on the types of seedlings based on market conditions, biological characteristics and natural resources. Drawing on the seedling index of Zhang XX et al. (2020)[28], the number of shellfish and algal algae nurseries was used to characterize fish seedlings of marine carbon sink fisheries. Intermediate consumption mainly includes feed, fuel, electricity consumption and office supplies purchase, etc. Drawing on the intermediate consumption index of Xiang A et al. (2022)[31], the intermediate consumption of marine carbon sink fisheries is discounted according to the intermediate consumption of fisheries, and adjusted to the comparable price of 2009 based on the price index of agricultural production materials, so as to eliminate the influence brought by the fluctuation of prices. Fixed assets include farmed fishing vessels used for marine carbon sink fisheries production and infrastructure construction, etc. Due to the lack of data on infrastructure, this paper characterizes the year-end ownership of marine motorized production (farmed) fishing vessels.

Indexes of economic growth

"Economic growth" is the desired output element of GTFP in marine carbon sink fisheries, and is generally measured by production value or yield. Given that the weight of the edible part accounts for a small proportion, and the weight of shellfish products is mainly concentrated in the shell part, the production as the desired output index cannot truly reflect the economic contribution of marine aquaculture[16]. Therefore, this paper selects economic output as an indicator of economic growth, and economic output is characterized by the total economic output value of marine carbon sink fisheries.

Indexes of environmental effect

"Environmental effect" includes the ecological output (positive effect) and non-desired output (negative effect) brought by aquaculture to the environment, and this paper mainly selects three indexes of ecological output, pollutants and carbon emissions. Ecological output is mainly manifested as the carbon sequestration capacity of marine carbon sink fisheries. This paper combines the relevant literature and research results and comprehensively organizes and obtains shell and soft tissue carbon content parameters[11], mass gravity of shells and soft tissues[11] and wet and dry weight conversion coefficients of marine aquaculture[31], and estimated the carbon sequestration capacity of marine carbon sink fisheries through the carbon synthesis coefficient method[32]. Referring to the shell and algae pollution production coefficients of Zong HM et al. (2017)[33], pollutants were calculated to obtain the total amount of nitrogen and phosphorus pollution through the pollution production coefficient method. Carbon emissions from marine carbon sink fisheries mainly come from two aspects. One is direct carbon emissions from energy combustion, which mainly refers to the carbon dioxide discharged through the combustion of diesel fuel consumed by aquaculture fishing boats. The other is indirect carbon emissions from the use of electricity, which mainly refers to carbon dioxide emissions caused by electricity consumption in the production process of electrification and oxygenation of seawater ponds and factory farming[34]. Therefore, this paper draws on the carbon emission estimation formula of Shao GL et al.(2019)[35] to characterize carbon emissions from marine carbon sink fisheries in terms of carbon emissions from diesel fuel and electricity consumption, by means of energy conversion coefficients[34] and carbon emission coefficient[35].

Methods

Super-efficient EBM modeling

Data Envelopment Analysis (DEA) model is a common methodology to measure efficiency in existing studies, such as the traditional radial CCR model and BCC model. However, the radial DEA model requires that inputs and outputs increase or decrease in the same proportion, and it cannot measure the slack variables. The non-radial SBM model, although it can circumvent the premise assumption of increasing or decreasing in the same proportion, cannot deal with the radial problem. The EBM model proposed by Tone and Tsutsui (2010)[36], on the other hand, includes both radial and non-radial distance functions, which can effectively compensate for the shortcomings of the above two types of DEA models. In addition, the EBM model incorporates non-desired outputs, which can effectively deal with the complex relationship between marine carbon sink fisheries resources, economy and environment. At the same time, in order to further distinguish the efficiency of effective decision-making units and solve the problem that the maximum efficiency value of the EBM model is one, it is also necessary to super-efficient the EBM model. In view of the above, this paper adopts the EBM model based on non-directed, super-efficient, non-expected output and variable returns to scale to measure GTFP of marine carbon sink fisheries in China from 2009 to 2020. The specific formula are as follows:

$$r^* = \min \frac{\theta - \varepsilon_x \sum_{i=1}^{m} \frac{w_i^- s_i^-}{x_{ik}}}{\varphi + \varepsilon_y \sum_{r=1}^{s} \frac{w_r^+ s_r^+}{y_{rk}} + \varepsilon_b \sum_{p=1}^{q} \frac{w_p^{b-} s_p^{b-}}{b_{rk}}} \qquad (1)$$

In the formula, r* denotes the GTFP in marine carbon sink fisheries; x, y and b respectively represent the raw data for inputs, desired outputs and non-desired outputs; m, s and q represent the number of indexes for inputs, desired outputs and non-desired outputs respectively; w_i^-、w_r^+、w_p^{b-} and s_i^-、s_r^+、s_p^{b-} represent the weights and slack variables of input i, desired output r and non-desired output p; θ and φ denote the efficiency values of the radial component; ε (0≤ε≤1) denotes the efficiency value of importance level of the non-radial component.

Global Malmquist-Luenberger (GML) index methodology

GML index is constructed on the basis of the common global frontier in each period, which solves the problems of the ML index being unsolvable under the condition of variable returns to scale, and of technological regression due to the shift of the production frontier, which is not cyclical in nature[37]. GML index belongs to a kind of dynamic analysis. It reflects the growth level of GTFP and can simultaneously consider the technical progress of the production frontier and the efficiency change of the production frontier and the decision-making unit. GML index can be further decomposed into green efficiency change(GEC) and green technological change (GTC). The decomposition formula is as follows:

$$\begin{aligned}
&GML_t^{t+1}(x^t, y^t, b^t, x^{t+1}, b^{t+1}) \\
&= \frac{1+D^G(x^t, y^t, b^t)}{1+D^G(x^{t+1}, y^{t+1}, b^{t+1})} \\
&= \frac{1+D^t(x^t, y^t, b^t)}{1+D^t(x^{t+1}, y^{t+1}, b^{t+1})} \times \left[\frac{1+D^G(x^t, y^t, b^t)}{1+D^t(x^t, y^t, b^t)} \times \frac{1+D^t(x^{t+1}, y^{t+1}, b^{t+1})}{1+D^G(x^{t+1}, y^{t+1}, b^{t+1})} \right] \\
&= GEC^{t,t+1} \times GTC^{t,t+1}
\end{aligned} \tag{2}$$

If GML > 1, it indicates that GTFP has increased and level of green development of marine carbon sink fisheries has improved; if GEC > 1, it indicates that green technical efficiency has improved; if GTC > 1, it indicates that there is a green technological change; and vice versa.

Theil index

Theil index can be used to analyze regional differences in China's marine carbon sink fisheries by measuring the contribution of inter-group differences and intra-group differences to total differences through division of samples. The calculation formula is as follows:

$$T = \frac{1}{n} \sum_{i=1}^{n} \frac{GTFP_i}{\overline{\overline{GTFP}}} \log \frac{GTFP_i}{\overline{\overline{GTFP}}} \tag{3}$$

T denotes Theil index of the overall difference in GTFP of marine carbon sink fisheries, ranging from 0 to 1. The larger T is, the greater the difference in GTFP in China. The n denotes total number of provinces; $GTFP_i$ denotes the GTFP of a province i, and $\overline{GTFP}$ denotes the average value of GTFP of marine carbon sink fisheries in all provinces.

Theil index can be further disaggregated to calculate the contribution of inter- and intra-group differences to total differences and to dissect sources of regional differences in marine carbon sink fisheries. In this paper, a sample containing n provinces is categorized into K regions, with each group categorized as g_k (k = 1, 2, ... , K), and the number of provinces in the kth group g_k is n_k; $GTFP_k$ denotes GTFP of region k, and T_b and T_w are Theil indexes of inter-regional and intra-regional differences in GTFP respectively. The decomposition formula is as follows:

$$T = T_b + T_w \tag{4}$$

$$T_b = \sum_{k=1}^{K} GTFP_k \log \frac{GTFP_k}{n_k / n} \tag{5}$$

$$T_w = \sum_{k=1}^{K} GTFP_k \left(\sum_{i \in gk} \frac{GTFP_i}{GTFP_k} \log \frac{GTFP_i / GTFP_k}{1 / n_k}\right) \tag{6}$$

Convergence model

The β-convergence indicates that, as time changes, provinces lagging behind in the development of marine carbon sink fisheries have higher growth rates, and there is a "catching-up effect" on provinces with higher levels of development, so that GTFP of marine carbon sink fisheries eventually converges to the same steady-state equilibrium value. Depending on whether control variables are added or not, β-convergence can be divided into absolute β-convergence and conditional β-convergence. Absolute β-convergence does not include control variables and study whether GTFP of marine carbon sink fisheries will gradually converge, that is to say, verify whether there is a "catching-up effect" of backward provinces on developed provinces. The model of absolute β-convergence is constructed as follows:

$$g_{i,t+1} = \ln GTFP_{i,t+1} - \ln GTFP_{i,t} = \alpha + \beta \ln GTFP_{i,t} + \varepsilon_{i,t+1} \tag{7}$$

In the model, $g_{i,t+1}$ denotes growth rate of logarithm of GTFP in province i from year t to year t+1. If β is significantly negative, it means that the growth rate of GTFP of marine carbon sink fisheries in each province is negatively correlated with the initial level and there is absolute β convergence.

Conditional β-convergence adds control variables to study whether provinces can converge to their own steady-state levels after controlling for influencing factors. The model of conditional β-convergence is constructed as follows:

$$g_{i,t+1} = \alpha + \beta \ln GTFP_{i,t} + \theta_1 \ln STI_{i.t+1} + \theta_2 \ln Ystr_{i.t+1} + \theta_3 \ln ES_{i.t+1} + \varepsilon_{i,t+1} \tag{8}$$

STI is science and technology input, Ystr is yield structure, and ES is economic scale. Conditional β-convergence exists if β is less than 0 and passes the significance test.

Data sources

The raw data for GTFP input-output index of marine carbon sink fisheries mainly come from *China Fishery Statistical Yearbook*, *China Statistical Yearbook*, *China Rural Statistical Yearbook* and *China Agricultural Yearbook*. For some missing data, the interpolation method was adopted to fill in the gap. Drawing on Qin H et al.'s method of discounting the coefficient of area and production value[16], the data of the variables related to marine carbon sink fisheries were all derived by discounting the coefficient of area and production value of shellfish and algae aquaculture. Due to the adjustment of the statistical yearbook, the intermediate consumption value of fisheries will no longer be counted from 2019 onwards. In this paper, the intermediate consumption value of agriculture, forestry, animal husbandry and fisheries is obtained by subtracting the value added from total value of agriculture, forestry, animal husbandry and fisheries, and the intermediate consumption value of fisheries is converted by the ratio coefficient of a=total value of fisheries/total value of agriculture, forestry, animal husbandry and fisheries.

Results and analysis

Dynamic evolution

Based on the provincial panel data of China's marine carbon sink fisheries from 2009 to 2020, the GTFP of China's marine carbon sink fisheries and its decomposition terms in nine provinces were measured by MaxDEA Ultra 9.1 software using the super-efficient EBM model and GML index (see Table 2).

Table 2. GTFP index and decomposition of China marine carbon sink fisheries from 2009 to 2020.

Period	GML	GEC	GTC
2009—2010	1.0218	0.9683	1.0741
2010—2011	1.0474	0.9998	1.047
2011—2012	0.9163	0.984	0.9327
2012—2013	1.0256	1.0144	1.0109
2013—2014	1.0132	1.016	0.9971
2014—2015	1.0647	1.0623	0.9912
2015—2016	0.9669	0.9973	0.9694
2016—2017	1.1227	1.0067	1.1166
2017—2018	0.9472	1.0054	0.9419
2018—2019	1.1382	0.9809	1.1579
2019—2020	1.1057	1.0091	1.0985
Mean[a]	1.0313	1.0038	1.0283

[a] Means taken are geometric means, same below.

Overall, GTFP index of China's marine carbon sink fisheries as a whole shows a fluctuating upward trend from 1.0218 in 2009 to 1.1057 in 2020 with increase of 8.22%, indicating that green development of China's marine carbon sink fisheries has been better implemented and enforced. Further decomposition shows that the average value of GEC from 2009 to 2020 is 1.0038, with an average annual growth rate of 0.38%, contributing 11.84% to GTFP of marine carbon sink fisheries; while the average value of GTC is 1.0283, with an average annual growth rate of 2.83%, contributing 88.16%. It indicates that both green efficiency change and green technological change contributed to the improvement of GTFP of China's marine carbon sink fisheries during the sample period, but it mainly relies on green technological change.

As can be seen from Table 3, GTFP of marine carbon sink fisheries in three major regions of China has generally shown an upward trend since 2009, but there are differences in the level of growth, with the highest average annual growth rate of GTFP in marine carbon sink fisheries in Yangtse River Delta (3.09%), followed by Bohai Rim (2.66%), and the lowest in Pearl River Delta(2.25%). In terms of changes in GTFP index, the Beijing-Tianjin-Hebei region as a whole shows a fluctuating upward trend, Bohai Rim shows a downward trend, and Pearl River Delta shows a trend of "downward and then M-shaped fluctuating upward". Observing the decomposition of GTFP index of marine carbon sink fisheries in each region, the average annual growth rate of GTC in each region is significantly higher than that of GEC, which indicates that green technological change is the most important driving force to enhance GTFP of marine carbon sink fisheries in the three major regions.

Table 3. GTFP index and decomposition of China marine carbon sink fisheries in three regions from 2009 to 2020.

Period	Bohai			Yangtze River			Pearl River		
	GML	GEC	GTC	GML	GEC	GTC	GML	GEC	GTC
2009—2010	0.9402	0.8756	1.1313	1.1513	1.0270	1.1184	1.0182	1.0085	1.0090
2010—2011	1.1102	0.9793	1.1274	1.0655	0.9988	1.0661	0.9912	1.0157	0.9773
2011—2012	0.8250	0.9568	0.8698	0.9617	1.0024	0.9593	0.9622	0.9952	0.9667
2012—2013	1.0861	1.0489	1.0358	0.9360	1.0007	0.9356	1.0251	0.9953	1.0299
2013—2014	1.0954	1.0299	1.0639	1.0146	0.9970	1.0177	0.9508	1.0151	0.9368
2014—2015	1.2325	1.1788	1.0185	1.0316	0.9883	1.0436	0.9555	1.0120	0.9445
2015—2016	0.9003	0.9911	0.9085	1.0819	0.9992	1.0830	0.9592	1.0009	0.9583
2016—2017	1.0147	1.0050	1.0075	1.1056	1.0412	1.0675	1.2123	0.9907	1.2230
2017—2018	1.0816	0.9903	1.0906	0.9716	1.0180	0.9542	0.8343	1.0105	0.8243
2018—2019	0.8401	0.9884	0.8503	1.0316	0.9648	1.0698	1.4150	0.9832	1.4326
2019—2020	1.2728	0.9965	1.2800	1.0087	1.0443	0.9671	1.0289	1.0009	1.0282
Mean	1.0266	1.0014	1.0278	1.0309	1.0072	1.0239	1.0225	1.0025	1.0194

Table 4 reports GTFP index and its decomposition for nine coastal provinces in China. It can be seen that GTFP indexes of nine provinces are all greater than 1, maintaining a positive growth of GTFP in marine carbon sink fisheries. Hainan and Liaoning show the most prominent growth trends. From the decomposition index, only Guangxi's GTC index is less than 1, slightly regressive trend, the rest of provinces have maintained the growth trend, and the fastest growth is Hainan. Among them, except for Hebei, Shandong and Guangdong, where GEC index is less than 1 offsetting part of benefits of green technological change, most provinces have improved their GEC. Overall, relative to the improvement in green efficiency change, the contribution of green technological change to GTFP in marine carbon sink fisheries is still stronger at the provincial level, which is basically consistent with the evolutionary dynamics of the country and three major regions. This suggests that, regardless of the level, the key to enhancing GTFP of marine carbon sink fisheries is to continue promoting green technological change while improving green efficiency change.

Table 4. GTFP index and decomposition of China marine carbon sink fisheries in coastal provinces from 2009 to 2020.

Province	GML	GEC	GTC
Hebei	1.0038	0.9974	1.0034
Liaoning	1.1028	1.0197	1.0932
Shandong	1.0022	0.9941	1.0080
Jiangsu	1.0294	1.0122	1.0180
Zhejiang	1.0361	1.0027	1.0333
Fujian	1.0015	1.0015	1.0000
Guangdong	1.0021	0.9977	1.0043

Guangxi	1.0006	1.0110	0.9918
Hainan	1.1240	1.0000	1.1240
Mean	1.0327	1.0040	1.0298

Regional differences

To a certain extent, Theil index can reflect the magnitude of differences and trends in green development of marine carbon sink fisheries in various regions. Based on principles and formulas of Theil Index, this paper obtained the overall differences, inter-and intra-regional differences and contribution rates of GTFP of marine carbon sink fisheries in China and three major regions. This is shown in Table 5.

Table 5. Theil index and contribution rate of China marine carbon sink fisheries from 2009 to 2020.

Year	Overall Difference	Theil Index					Contribution Rate				
		Bohai	Yangtze River	Pearl River	Inter-regional	Intra-regional	Bohai	Yangtze River	Pearl River	Inter-regional	Intra-regional
2010	0.0116	0.0169	0.0112	0.0018	0.0028	0.0088	44.77	24.17	6.82	24.24	75.76
2011	0.0088	0.0178	0.0030	0.0013	0.0013	0.0075	71.62	7.70	6.23	14.46	85.54
2012	0.0098	0.0222	0.0009	0.0008	0.0025	0.0072	68.17	2.04	3.91	25.88	74.12
2013	0.0028	0.0014	0.0022	0.0010	0.0014	0.0014	17.84	15.63	15.70	50.83	49.17
2014	0.0030	0.0001	0.0004	0.0024	0.0019	0.0011	1.21	2.61	32.47	63.71	36.29
2015	0.0326	0.0648	0.0004	0.0026	0.0065	0.0261	76.70	0.25	3.20	19.85	80.15
2016	0.0066	0.0033	0.0000	0.0073	0.0023	0.0043	15.49	0.00	49.08	35.43	64.57
2017	0.0252	0.0119	0.0038	0.0369	0.0030	0.0222	14.28	3.35	70.45	11.92	88.08
2018	0.0362	0.0142	0.0005	0.0616	0.0066	0.0296	14.95	0.29	66.61	18.15	81.85
2019	0.0928	0.0505	0.0000	0.0988	0.0258	0.0670	13.40	0.00	58.81	27.79	72.21
2020	0.0259	0.0512	0.0005	0.0013	0.0056	0.0203	75.92	0.41	2.01	21.66	78.34
Mean	0.0140	0.0099	0.0003	0.0047	0.0035	0.0097	23.52	0.50	14.79	25.28	69.44

First of all, during the sample period, the overall Theil index showed a "W" shape, with a decreasing value during 2009-2014, a fluctuating upward trend during 2014-2019, and a decreasing trend after 2019, reflecting the unbalanced development of marine carbon sink fisheries in various regions of China. Secondly, in terms of structure of differences, differences in the level of green development of China's marine carbon sink fisheries mainly come from intra-regional differences, with the average value of its contribution rate reaching 69.44%, and the contribution rate even reached 88.08% in 2017, indicating that there is a large gap in the development of China's marine carbon sink fisheries within the region. Finally, as far as the three major regions are concerned, intra-regional differences in Bohai Rim and Pearl River Delta are large (mean values of intra-regional Theil index in Bohai Rim and Pearl River Delta are 0.0099 and 0.0047 respectively), and the degree of intra-regional differences in Yangtze River Delta is small (the mean value of intra-regional Theil index in Yangtze River Delta is 0.0003), which implies that there is a large imbalance in green development efficiency of marine carbon sink fisheries in Bohai Rim and Pearl River Delta. Bohai Rim contributes the most to intra-regional differences, with a contribution rate higher than 13% in all years except 2014 (which was 1.21%), reaching a maximum of 76.70%, followed by Pearl River Delta, and Yangtze River Delta, which has the smallest contribution rate and shows a decreasing trend from year to year. The above analysis shows that the main source of GTFP in China's marine carbon sink fisheries is intra-regional variation, which in turn mainly originates from Bohai Rim and Pearl River Delta, while the contribution of inter-regional variation is smaller.

Convergence

From the previous analysis, it can be seen that there are large differences in GTFP and its growth in marine carbon sink fisheries in different regions of China. Will this gap narrow over time, or is there a tendency of convergence? If so, does the convergence tend to be consistent? In this section, absolute β-convergence and absolute β-convergence will be used to measure the convergence of GTFP of marine carbon sink fisheries.

Absolute β-convergence

From the test results, we can see from Table 6 that the β-values of the national level and Bohai Rim, Yangtze River Delta and Pearl River Delta regions are all significantly negative at the 1% statistical level, indicating that there is an absolute β-convergence, and that the growth rate of GTFP in China's marine carbon sink fisheries is negatively correlated with its initial level, and there is a "catching-up effect" within each region.

Table 6. Absolute β-convergence test results of GTFP at the national and regional levels.

Absolute β-convergence test	National	Bohai	Yangtze River	Pearl River
β	-1.5408***	-1.4545***	-1.1743***	-1.6360***
	(0.0923)	(0.1840)	(0.1777)	(0.1251)
α	0.0088	0.0036	0.0235	0.0009
	(0.0203)	(0.0446)	(0.0169)	(0.0307)
R^2	0.7600	0.6905	0.7080	0.8182
F statistics	278.73***	62.46***	43.65***	171.06***

***It indicates that the parameters are significant at the 1% level,same below.

Conditional β-convergence

Different from absolute β-convergence, conditional β-convergence is to study the β-convergence dynamics of China's marine carbon sink fisheries development after incorporating a series of control variables. In this paper, science and technological input, yield structure and economic scale are included as control variables in the conditional β-convergence model. Science and technological input (STI) is measured by the sum of standardized values of funding for marine carbon sink fisheries technological promotion institutions and number of trainers in each region. The increase of technology input can drive development of marine carbon sink fisheries. Yield structure (Ystr) is measured by the proportion of marine carbon sink fisheries production to marine aquaculture production in each region. The larger the proportion, the higher the efficiency of green development of marine carbon sink fisheries[28]. Economic scale (ES) is measured by the production value of marine carbon sink fisheries in each region. The economic base of marine carbon sink fisheries in each region is also an important factor affecting its green development.

Table 7 shows the results of the analysis of β-convergence of GTFP condition for marine carbon sink fisheries in China and the three regions. After adding the control variables of scientific and technological inputs, yield structure, and economic scale, the β coefficients of the country and Bohai Rim, Yangtze River Delta, and Pearl

River Delta are all negative and pass the 1% significance test, which verifies the existence of conditional convergence in the growth of GTFP of marine carbon sink fisheries. This indicates that GTFP gap will persist in the whole country and provinces within three regions due to differences in production conditions and economic environment, but will converge towards their respective steady state levels.

Table 7. Conditional β-convergence test results of GTFP at the national and regional levels.

Conditional β-convergence test	National	Bohai	Yangtze River	Pearl River
β	-1.5233***	-1.4144***	-1.2166***	-1.6567***
	(0.0987)	(0.227)	(0.2041)	(0.1284)
α	-0.0098	0.0146	0.0347	-0.0436
	(0.0316)	(0.0770)	(0.0335)	(0.0314)
θ_1	-0.0030	-0.0184	-0.0143	0.0079
	(0.0242)	(0.0684)	(0.0265)	(0.0684)
θ_2	-0.0740	0.0042	0.0372	-0.1296
	(0.0564)	(0.1900)	(0.0661)	(0.0905)
θ_3	0.0670	0.1197	0.0011	0.1087
	(0.0583)	(0.1704)	(0.0451)	(0.0464)
R^2	0.7776	0.6988	0.7170	0.8621
F statistics	74.28***	14.50***	9.50***	54.71***

Conclusion

Based on the super-efficient EBM-GML model with non-expected output, this paper measures the GTFP of marine carbon sink fisheries in nine coastal provinces of China from 2009 to 2020, and analyzes its regional differences and convergence characteristics by using Theil index and the convergence model, and mainly draws the following conclusions.

1.From the perspective of GTFP index, the GTFP of marine carbon sink fisheries has been on rise at national, regional and provincial level, and both green technological change and green technology efficiency have contributed to the improvement of GTFP of China's marine carbon sink fisheries, but the main reliance is on green technological change. However, there are differences in the level of growth, with the highest average annual growth rate of GTFP in marine carbon sink fisheries in Yangtze River Delta, followed by Bohai Rim, and the lowest in Pearl River Delta. The average annual growth rate at provincial level, in descending order, are Hainan, Liaoning, Zhejiang, Jiangsu, Hebei, Shandong, Guangdong, Fujian, and Guangxi.

2.From results of the decomposition of Theil index, there are differences in the green development level of marine carbon sink fisheries in various regions of China, and intra-regional differences are the main source of regional differences in GTFP of China's marine carbon sink fisheries, while intra-regional differences mainly originate from Bohai Rim and Pearl River Delta, and inter-regional differences have a smaller contribution.

3.There is absolute β-convergence and conditional β-convergence in China and the Bohai Rim, Yangtze River Delta and Pearl River Delta regions, which suggests that GTFP of marine carbon sink fisheries in each province will not only converge towards its own steady state level but also converge to the same steady state equilibrium value as time passes.

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ABOUT THE AUTHOR

Shengnan Chen was born in Nantong, Jiangsu. China, in 1997. She obtained a bachelor's degree from Jiangsu University in China. She currently studying at the School of Economics and Management, Shanghai Ocean University. Her main research direction is marine economy.

E-mail: quinna_chen@163.com