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Study on Green Output Bias of China's Mariculture Technological Progress

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Abstract

With the rapid development of mariculture, environmental pollution is becoming more and more serious. It is particularly important to study the green output bias of technological progress for the long-term sustainable development of mariculture. Based on the input-output data of the mariculture in 10 Chinese coastal areas from 2008 to 2018, the DEA-Malmquist index decomposition method is used to calculate output-biased technological progress index and combines with the change of marginal substitution rate of output factors in different periods to identify the bias of technological progress between output factors, and analyze the green output bias of mariculture technological progress. The results show that green technological progress is a crucial factor affecting green total factor productivity's growth in China's mariculture. During the study period, the number of regions where technological progress tends to reduce pollutant emissions shows a fluctuating upward trend, and the degree of technological progress toward green output is high. There are obvious differences among regions. The green output bias of technological progress in the South China Sea area is the highest, followed by the East China Sea area, and the Bohai Sea area is poor. Specifically, the green output bias of technological progress in Fujian, Guangdong and Hainan is higher, while the green output bias of technological progress in Tianjin, Hebei, Shandong and Guangxi is lower. According to the research results, corresponding policy suggestions are provided to realize the green and sustainable development of China's mariculture.

Keywords

Mariculture; Green TFP; Biased technological progress; Green output bias

36 Introduction

37 Mariculture is an important part of marine fisheries. Since the establishment of the
38 “mariculture-based” fishery development strategy in the 1970s, China’s mariculture
39 has developed rapidly, and it is the only major fishery country in the world where the
40 total amount of mariculture products exceeds the total amount of fishing. According to
41 the China Fisheries Statistics Yearbook, the yield of mariculture in China in 2019 was
42 2065.33 million tons, an increase of 1.68% from 2018. The output of mariculture
43 accounts for approximately 32% of the total output of aquatic products. The total output
44 value of mariculture was 354.203 billion yuan. However, in the context of high-
45 intensity mariculture development, mariculture pollution has become one of the main
46 marine environmental problems that people pay attention to. Most mariculture
47 organisms are heterotrophic, and the metabolic wastes generated by their physiological
48 activities, such as ammonia nitrogen and phosphate, are increasingly polluting
49 mariculture water, which seriously damages the ecological balance system of the
50 mariculture environment (Schwitzguébel and Wang 2007). The accumulation of toxic
51 and harmful substances increases the incidence of mariculture diseases and causes
52 economic losses to mariculture. The contradiction between the development of China’s
53 mariculture and the resources and environment is increasing, and the traditional
54 development mode is unsustainable. In the future, China’s mariculture must rely on
55 green technological progress to achieve sustainable development and improve
56 environmental problems. According to the theory of induced technological innovation,
57 technological progress will affect the marginal substitution rate of output factors, which
58 is manifested as the output bias of technological progress. For the mariculture,
59 distinguishing the specific bias of technological progress between expected and
60 unexpected outputs, and analyzing whether technological progress is biased toward
61 green output (that is, whether it is biased toward reducing unexpected output) are
62 conducive to achieving green production and optimizing resource allocation. Therefore,
63 it is very important to study the green output bias of technological progress.

64 Neoclassical growth theory holds that technological progress is the source of economic
65 growth, but this theory assumes that the elasticity of substitution between capital and
66 labor is 1, which is contrary to realistic conditions. According to the changes in the
67 relative marginal output of production factors caused by technological progress, Hicks
68 (1932) defined biased technological progress, and Acemoglu et al. (1998, 2002, 2007,
69 2012) further enriched the research on it. Since then, research on technological progress
70 bias has gradually increased, and some scholars have empirically verified the existence
71 of capital biased technological progress in developed countries (Klump et al. 2007; Sato
72 and Morita 2009). Biased technological progress measurements include parametric and
73 non-parametric methods. Specifically, the parametric method is to construct the
74 corresponding production function and establish a model to measure the biased
75 technological progress, for example, CES production function (Dupuy 2006; Dissou
76 2012), trans-log production function (Sanstad et al. 2006; Karanfil et al. 2010), but there
77 are some shortcomings in measuring biased technological progress by using the
78 parameter method. CES production function assumes that the element substitution
79 elasticity is unchanged, which is contrary to the actual conditions; while the trans-log
80 production function model with variable substitution elasticity has many parameters,
81 which is easy to lead to multicollinearity problems. In view of some problems in the
82 parameter method, the nonparametric method began to be applied to measure the bias
83 of technological progress, mainly based on the DEA model of linear programming
84 method, calculated by Malmquist productivity index decomposition (Barros 2009; Yu
85 et al. 2012; Chang et al. 2014). Compared with the parametric method, the

nonparametric method has the advantages of no need to set the form and error structure of production function, and the constructed productivity index does not need the price information of input and output variables. Based on research on technological progress bias, some scholars have discussed its influencing factors, mainly involving international trade (Lawrence 1996; Acemoglu 2002), energy intensity (Wang et al., 2014) and government environmental policies (Greaker et al. 2018).

Mariculture belongs to agriculture, research on agricultural technological progress is the basis of this study. The research on agricultural technological progress can be traced back to Kendrick (1973). He pointed out that the main factors affecting technological progress include resource allocation, resource quality, technological innovation and internal and external saving. Agricultural technology refers to some ways to improve production efficiency and agricultural economy. After agricultural technological progress was proposed, some scholars used stochastic frontier production function method to decompose the growth rate of total factor productivity into two parts : technological progress and technological efficiency, and further found that technological progress is the driving force of total factor productivity growth (Taylor and Shonkwiler 1986; Battese 1992). Hayami and Ruttan (1971) established the induced technological progress theory in the field of agriculture, expounded the source of technological progress bias, and thought that the bias of technological progress was induced by economic forces. With the development of induced change theory, the research on agricultural technological progress bias is increasing. Kawagoe et al. (1986) constructed an agricultural input-output system based on the factor-enhanced CES production function, assumed that the speed of technological progress was a constant value and linearized the original production function, and estimated various parameters by first-order derivation method to analyze the technological progress bias of agriculture in the United States and Japan. Managi and Karemera (2004) and Singh et al. (2012) used the DEA model to measure the biased technological progress of agriculture and identify what factors are biased.

In the field of mariculture, there are few studies on technological progress bias. The technological progress bias stems from the study of total factor productivity and technological progress. The related research on total factor productivity and technological progress lays the foundation for this paper. From the perspective of the research context, the research on the technological progress of mariculture mainly experienced the following stages: The first is the evaluation of technological progress based on production frontier. Based on the stochastic frontier production function, scholars calculated the efficiency of mariculture in Greece, the Philippines and southern Tripura, and pointed out that the scale of mariculture, the area of mariculture and the education level and age of farmers were the positive factors affecting the efficiency (Karagiannis et al. 2000; Dey et al. 2000; Singh 2008), further total factor productivity can be decomposed into technological progress. Based on the data envelopment analysis method without setting the production function, another part of scholars measured total factor productivity and technological progress (Vassdal and Holst 2011), and found that technological progress was the source of total factor productivity growth (Hassanpour et al. 2010), and economic environment and other factors would affect the technological progress of mariculture (Aripin et al. 2020). The second is the green technological progress research. The increase of output value will also cause environmental pollution problems. Scholars began to measure green technological progress from the perspective of green development, and found that the increase of unexpected output led to the technological decline (Martinez-Cordero and Leung 2004), and explored the path to realize the green growth of mariculture. Relevant

136 policies and regulations were introduced to encourage farmers to adopt
 137 environmentally friendly production methods (Nielsen 2011). Reward-based fisheries
 138 regulation and balance ecosystem services are important means to achieve green growth
 139 (Nielsen et al. 2014). The third is the research on technological progress bias. In recent
 140 years, some scholars have studied the technological progress bias in mariculture from
 141 the perspective of input. Data envelopment analysis (Ren and Zeng 2021; Sun and Ji,
 142 2021) is used to analyze the bias among different input factors, and to explore the
 143 desirability between technological progress bias and factor endowments.

144 By combining the existing literature, it can be found that the shortcomings of the existing
 145 research are mainly reflected in the following aspects. Firstly, the existing research
 146 mostly studies the total factor productivity and technological progress of mariculture
 147 under the assumption of neutral technological progress, and there are relatively few
 148 studies on the technological progress bias. Secondly, it does not reflect the
 149 environmental pollution problem in the development of mariculture. The research on
 150 the technological progress bias from the perspective of input mainly takes into account
 151 the utilization of input factors and marginal output. It is more suitable to study the green
 152 development of mariculture from the perspective of output. However, few literature
 153 studies the bias of technological progress between expected output and unexpected
 154 output from the perspective of output. Based on the above considerations, this paper
 155 studies the technological progress bias of mariculture from the perspective of output,
 156 discusses the environmental pollution problems in the development of mariculture, and
 157 pays attention to the green development of mariculture. This study incorporates the
 158 unexpected outputs, namely, total nitrogen, total phosphorus, and chemical oxygen
 159 demand, into the analysis framework. The data envelopment analysis method is used to
 160 measure the green total factor productivity index of China's mariculture industry, and
 161 the technological progress index and technological efficiency change index are
 162 obtained by decomposition. The output-biased technological progress index is further
 163 decomposed by the technological progress index. On this basis, the green output bias
 164 of China's mariculture industry in technological progress is judged to provide relevant
 165 policy suggestions for the sustainable development of China's mariculture industry.

166 **Methods**

167 **Measurement of output biased technological progress index**

168 Assuming that there are K decision-making units (each coastal area is regarded as a
 169 decision-making unit in this study), N production factors $x = (x_1, x_2, \dots, x_N) \in R_+^N$,
 170 M expected output $y = (y_1, y_2, \dots, y_M)$, I unexpected output $b = (b_1, b_2, \dots, b_I)$,
 171 output set $P(x) = \{(y, b): x \text{ can produce } (y, b)\}$. The traditional method is to use the
 172 Shephard output distance function to express technological efficiency, that is,
 173 $D_0(x, y, b) = \inf \left\{ \theta: \frac{(y, b)}{\theta} \in P(x) \right\}$, but the formula shows that the expected and
 174 unexpected output are increased or decreased in the same proportion, which is not
 175 consistent with the actual conditions. Therefore, this paper introduces the directional
 176 distance function with reference to Chung (1997), which is defined as $\vec{D}_0(x, y, b; g) =$
 177 $\sup \{ \beta: (y, b) + \beta g \in P(x) \}$. In the formula, g represents the direction vector, and $g =$
 178 $(y, -b)$ is set to represent the same proportion of the unexpected output when the
 179 expected output increases.

180 This study uses the Malmquist-Luenberger productivity index based on directional
 181 distance function estimation to measure the TFP change rate. From the perspective of

output orientation, the Malmquist-Luenberger productivity index from period t to period $t + 1$ is defined as follows :

$$MI = \sqrt{\frac{(1 + \overline{D}_0^t(x^{t+1}, y^{t+1}, b^{t+1}, y^{t+1}, -b^{t+1})) (1 + \overline{D}_0^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}, y^{t+1}, -b^{t+1}))}{(1 + \overline{D}_0^t(x^t, y^t, b^t, y^t, -b^t)) (1 + \overline{D}_0^{t+1}(x^t, y^t, b^t, y^t, -b^t))}}$$

(1)

The TFP index can be decomposed into the technological efficiency index and technological progress index :

$$MI = TFCH * TECH \quad (2)$$

$$TFCH = \frac{(1 + \overline{D}_0^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}, y^{t+1}, -b^{t+1}))}{(1 + \overline{D}_0^t(x^t, y^t, b^t, y^t, -b^t))}$$

(3)

$$TECH = \sqrt{\frac{(1 + \overline{D}_0^t(x^t, y^t, b^t, y^t, -b^t)) (1 + \overline{D}_0^t(x^{t+1}, y^{t+1}, b^{t+1}, y^{t+1}, -b^{t+1}))}{(1 + \overline{D}_0^{t+1}(x^t, y^t, b^t, y^t, -b^t)) (1 + \overline{D}_0^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}, y^{t+1}, -b^{t+1}))}}$$

(4)

TFCH measures the change in the output of the decision-making unit from period t to period $t+1$ to the production frontier, and TECH measures the change in the production frontier itself. According to the different directions of production frontier changes, technological progress changes can be divided into neutral technological progress, technological progress, and technological regression. Technological progress is usually referred to as the production efficiency frontier of period $t+1$ moves outward relative to period t ; that is, given the same input, the optimal output of period $t + 1$ is higher than that of period t .

Färe et al. (1997) further decomposed the technological progress index into output-biased technological progress index, input-biased technological progress index, and technological change scale index. The specific expressions are as follows :

$$TECH = OBTECH * IBTECH * MATECH \quad (5)$$

$$OBTECH = \sqrt{\frac{(1 + \overline{D}_0^t(x^{t+1}, y^{t+1}, b^{t+1}, y^{t+1}, -b^{t+1})) (1 + \overline{D}_0^{t+1}(x^{t+1}, y^t, b^t, y^t, -b^t))}{(1 + \overline{D}_0^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}, y^{t+1}, -b^{t+1})) (1 + \overline{D}_0^t(x^{t+1}, y^t, b^t, y^t, -b^t))}}$$

$$IBTECH = \sqrt{\frac{(1 + \overline{D}_0^{t+1}(x^t, y^t, b^t, y^t, -b^t)) (1 + \overline{D}_0^t(x^{t+1}, y^t, b^t, y^t, -b^t))}{(1 + \overline{D}_0^t(x^t, y^t, b^t, y^t, -b^t)) (1 + \overline{D}_0^{t+1}(x^{t+1}, y^t, b^t, y^t, -b^t))}}$$

$$MATECH = \sqrt{\frac{(1 + \overline{D}_0^t(x^t, y^t, b^t, y^t, -b^t))}{(1 + \overline{D}_0^{t+1}(x^t, y^t, b^t, y^t, -b^t))}}$$

(7)

The OBTECH index is an output-biased technological progress. If the OBTECH index > 1 , it shows that the bias of technological progress between the output factors promotes the improvement of total factor productivity. If the OBTECH index is less than 1, the bias of technological progress among the output factors inhibits the increase in total factor productivity. If OBTECH index = 1, there is no output-biased technological progress. The IBTECH index is input-biased technological progress, which measures the degree of bias among input factors. The MATECH index is the scale index of technological change, which measures the extent of technological progress in the two adjacent periods after removing bias factors. Based on the constraint condition of constant returns to scale, this study uses the linear programming method to solve the above expression.

Output technological progress bias judgement

The output-biased technological progress index does not give the bias of technological progress between different combinations of output factors. Therefore, this study uses the Weber and Domazlicky (1998) method to identify the factor bias of technological progress based on the change in factor ratio in period $t+1$ and period t and the different combinations of OBTECH and 1. Figure 1 shows the output possibility set and output-biased technological progress in the two periods. It is assumed that $P^t(x)$ represents the production possibility curve of period t , $P^{HN}(x)$, $P^{t+1,1}(x)$ and $P^{t+1,2}(x)$ represent the three production possibility curves of period $t+1$, respectively. A represents the output combination of period t , and E_1 and E_2 represent two different output combinations of period $t+1$.

Fig. 1 Output-biased technological progress

If from period t to period $t + 1$, the marginal conversion rates of output factors y_1 and y_2 remain unchanged, then technological progress presents Hicks neutrality, and the output possibility set shifts from $P^t(x)$ to $P^{HN}(x)$. If from period t to period $t + 1$, the marginal conversion rates of the output factors y_1 and y_2 will change. At this time, technological progress shows output-biased technological progress, details discussed below: When the output combination of period $t + 1$ is E_1 , the two outputs satisfy $y_1^{t+1}/y_2^{t+1} < y_1^t/y_2^t$. If the production possibility curve at this time is $P^{t+1,1}(x)$, then the output technological progress from period t to period $t + 1$ tends to produce y_1 , at this time $OBTECH = \sqrt{\frac{OD/OF}{OB/OC}} > 1$; if the production possibility curve is $P^{t+1,2}(x)$ at this time, technological progress tends to produce y_2 , at this time $OBTECH = \sqrt{\frac{OD/OG}{OB/OC}} < 1$. When the output combination of period $t + 1$ is E_2 , the two outputs satisfy $y_1^{t+1}/y_2^{t+1} > y_1^t/y_2^t$. If the production possibility curve at this time is $P^{t+1,1}(x)$, technological progress tends to produce y_1 , and the output-biased technological progress index from period t to period $t + 1$ is $OBTECH = \sqrt{\frac{OR/OP}{OB/OC}} < 1$. If the

production possibility curve at this time is $P^{t+1,2}(x)$, technological progress tends to produce y_2 , $OBTECH = \sqrt{\frac{OR/OM}{OB/OC}} > 1$.

To summarize, the above situation to obtain the technological progress output bias judgment criteria is shown in Table 1.

Table 1 Criteria for output bias of technological progress

	OBTECH>1	OBTECH=1	OBTECH<1
$\frac{y_1^{t+1}}{y_2^{t+1}} > \frac{y_1^t}{y_2^t}$	y_2 -producing	neutral technological progress	y_1 -producing
$\frac{y_1^{t+1}}{y_2^{t+1}} < \frac{y_1^t}{y_2^t}$	y_1 -producing	neutral technological progress	y_2 -producing

Research Design

This section describes the selection of variables.

Output variables

For the selection of the expected output variable, this study refers to most studies to select the output value of the mariculture. Since this variable involves price factor, it has been deflated. The above variable data are from the China Fisheries Statistics Yearbook.

In this study, the pollution factors of mariculture are considered, and the unexpected output variables are selected as the production of total nitrogen (N), total phosphorus (P), and chemical oxygen demand (COD). Because the existing yearbook data do not statistically account for the above variable data, this paper refers to the relevant literature and data to calculate the amount of various pollutants. In view of the availability of data and the characteristics of mariculture, this paper refers to the "Handbook of Pollution Discharge Coefficients of mariculture Pollution Sources in the First National Pollution Source Census"(hereinafter referred to as the "Handbook") and the "China Fishery Statistical Yearbook" and selects fish (10 species), crustaceans (6 species), shellfish (a total of 8 species, including 6 species of filter-feeding shellfish) and other categories (4 species), a total of 28 mariculture organisms that produce pollution. The relevant data of five breeding methods, namely pond culture, factory culture, cage culture, raft culture and beach culture, were estimated. The specific accounting methods are as follows :

$$E_{u,n} = \sum_{i,j} Y_{i,n} w_{i,j,n} e_{u,i,j,n} \quad (9)$$

where $E_{u,n}$ represents the total amount of pollutants u ($u = N, P, COD$) generated by mariculture in province n , $Y_{i,n}$ represents the output of marine product i in province n , $w_{i,j,n}$ represents the proportion of output obtained by breeding method j in the output of marine product i in province n , and $e_{u,i,j,n}$ represents the pollution coefficient of pollutant u generated by breeding method j in province n .

The yield of seafood of various varieties in coastal provinces $Y_{i,n}$ can be directly obtained from China Fishery Statistical Yearbook. The pollution coefficient of

mariculture $e_{u,i,j,n}$ varies with the sea area, breed and mode of mariculture. According to whether feeding is needed in the growth process, mariculture organisms can be divided into feeding type and acquisition type. Due to the different pollution mechanisms, the estimation methods of pollution generated by them should also be different. The pollution production coefficient in the manual is mainly obtained by direct water quality monitoring and material balance, while the pollution production coefficient of the acquired organisms represented by filter-feeding shellfish is not appropriate based on this method. In order to objectively calculate the pollutant production of different types of mariculture organisms in China, the pollutant production coefficients of 22 feeding organisms were obtained from the "manual", and the pollutant production coefficients of 6 acquiring organisms were obtained according to the method of Zong et al. (2017). There is no specific value of the output ratio of the various mariculture methods used in the marine products of each province $w_{i,j,n}$. Referring to the method of Chen et al. (2016), the proportion of the above-mentioned mariculture methods in the total output of mariculture in each province in the "China Fisheries Statistical Yearbook" is estimated. Due to the different types of mariculture methods adopted by different seafoods, this method is improved in this paper, and the specific formula is :

$$w_{i,j,n} = w_{j,n} r_{i,j} / \sum_j w_{j,n} r_{i,j} \quad (10)$$

where $w_{j,n}$ represents the proportion of the above-mentioned breeding methods in the total output of each province; $r_{i,j}$ is a dummy variable. When seafood i can be cultured by breeding method j , 1 is taken; otherwise, 0 is taken. The corresponding relationship between different seafoods and breeding methods is referred to the manual.

Input variables

The input variables are mainly related to capital, labor and mariculture areas. The capital stock, the number of mariculture professionals, and the area of mariculture are selected. The data for the labor variable and mariculture area variable are from the China Fisheries Statistics Yearbook, while the capital stock does not have relevant data in the existing yearbook data. This study estimates them using the perpetual inventory method. Referring to Wang et al. (2007), this study estimates the agricultural capital stock data from 2008 to 2019 and further assumes that mariculture and agriculture have the same capital output ratio, thus calculating the capital stock of mariculture.

$$K_{At} = I_{At} + (1 - \delta)K_{At-1} \quad (11)$$

$$K_t = \frac{Y_t}{Y_{At}} K_{At} \quad (12)$$

In the formula, K_{At} 、 K_{At-1} represents the current and previous capital stock, respectively, where δ represents the depreciation rate and I_{At} represents the new agricultural fixed assets in the current period. Since there is no statistical data on the new agricultural fixed assets in the current period since 2000, this study calculates the average value of the proportion of agriculture in the total investment in fixed assets of agriculture, forestry, animal husbandry, and fishery from 1995 to 2000 to obtain the investment in agricultural fixed assets, and eliminate the impact of inflation based on the price index of agricultural means of production. Y_{At} represents the value-added agricultural value and Y_t 、 K_t represents the added value of mariculture and the estimated capital stock. The above variables are from the China Fisheries Statistics

Yearbook, China Statistical Yearbook on Fixed Asset Investment, and China Rural Statistical Yearbook.

China's coastal areas include nine coastal provinces and two coastal municipalities. Due to the serious lack of data in Shanghai, we do not consider information mariculture in the region, namely, Liaoning, Hebei, Tianjin, Shandong, Fujian, Jiangsu, Zhejiang, Guangdong, Guangxi, and Hainan. The descriptive statistical analysis of each input-output variable is presented in Table 2.

Table 2 Descriptive statistics of input-output variables

Variables	Symbol	Unit	Mean	Standard Deviation	Minimum	P50	Maximum
Total output value of mariculture	Y	Ten thousand yuan	1.400e+06	1.200e+06	15648	910000	4.700e+06
Total nitrogen	N	Tons	2304	3340	10.74	964.2	17424
Total phosphorus	P	Tons	440.8	647.0	2.860	173.6	3125
Chemical oxygen demand	COD	Tons	7404	6625	236.3	4858	26828
Mariculture capital	K	Ten thousand yuan	2.400e+06	3.000e+06	53221	1.300e+06	1.200e+07
Mariculture employees	L	Millions	88598	66447	621	61106	230000
Mariculture area	S	Hectare	210000	240000	813	130000	940000

Research results and discussion

Analysis of green biased technological progress index

Based on the above methods and models, this study calculates the green total factor productivity index and its decomposition index of China's mariculture from 2008 to 2019. To analyze the green technological progress in the mariculture in China, the geometric averages of the green total factor productivity index (MI) and decomposition index in 10 coastal areas of China during the study period were calculated from the time and regional dimensions. Note that TC and EC are decomposed by MI, referring to technological progress index and technological efficiency index. IBTC, OBTC, and MATC are decomposed by TC, which refer to input-biased technological progress index, output-biased technological progress index, and technological change scale index respectively.

From Figure 2, it can be seen that the change of MI index shows an "inverted V" type during the sample study period. The green total factor productivity of China's mariculture shows a fluctuating trend of increasing first and then decreasing. Specifically, the MI index is less than 1 in the early stage, reaching the lowest point in 2011, and the green total factor productivity decreases obviously. The main reason may be that the early mariculture shows extensive development mode, which causes damage to the resources and environment. Therefore, the production efficiency of mariculture considering resource and environment constraints is not high. Moreover, drought, frequent floods and serious fishery disasters in 2011 had a negative impact on green

total factor productivity. In 2012, the MI index jumped to the highest point. Under the guidance of the Twelfth Five-Year Plan for National Fishery Development, the green development of mariculture has achieved remarkable results. The national favorable policies have formed a good guidance for the growth of green total factor productivity. After that, the MI index fluctuates steadily, and the change of green total factor productivity tends to be stable. From the change trend of the MI, EC, and TC indices, the trends of the MI and TC indices are more consistent, indicating that green technological progress is an important factor affecting the growth of green total factor productivity in China's mariculture. The TC index is further decomposed into the IBTC, OBTC, and MATC indices. It can be seen from the figure that the trends of the IBTC and OBTC indices are consistent and the change range is relatively small, while the change range of the MATC index is large, indicating that the change in scale is an important factor affecting the production efficiency of mariculture. In addition, before 2014, the OBTC index is located above the IBTC index, indicating that compared with input-biased technological progress, output-biased technological progress contributes more to green total factor productivity. In 2014 and beyond, input-biased technological progress contributes more to green TFP. The OBTC index has declined since 2014, mainly due to disease damage to the development of mariculture, rising feed prices and other increased mariculture costs, resulting in lower output and slower mariculture development.

Fig. 2 Trends of green TFP index and decomposition index of China's mariculture

Table 3 illustrates the output-biased technological progress index for different regions. The results show that there is obvious output-biased technological progress in China's mariculture. It can be seen from the graph that the OBTC index of most regions is greater than 1. Considering the existence of unexpected outputs, this result shows that output-biased technological progress has a different proportion of promoting effect on expected output and unexpected output. There are significant differences in the degree of index fluctuations in different regions. The output-biased technological progress index in Liaoning, Fujian, Shandong and Tianjin is greater than 1 and the fluctuation is small, indicating that the mariculture in the region has formed a relatively stable production mode. However, the OBTC index in Jiangsu, Zhejiang, Guangdong, Guangxi, Hebei and Hainan fluctuated greatly and showed a trend of first increase and then decrease, indicating that the promoting effect of output-biased technological

progress on output showed an increasing trend in the early stage of the study, but the promoting effect on output was weakened in the late stage due to the resource and environmental constraints of mariculture and local government policies. It can also be seen from the table that during the sample study period, the change trend of the OBTC index shows an inverted V-shaped trend, which first increases in the initial stage. During 2011-2012, the average contribution of output-biased technological progress to productivity is relatively large, and then decreases and remains stable. The geometric mean of OBTC index of mariculture in each region is 1.03, indicating that the contribution of output-biased technological progress to total factor productivity of mariculture in China is generally positive.

Table 3 Output-biased technological progress index in different regions

OBTECH	2008-	2019-	2010-	2011-	2012-	2013-	2014-	2015-	2016-	2017-	2018-	Geometric
	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Mean
Tianjin	1.00	1.00	1.01	1.05	1.10	1.02	1.05	1.02	1.02	1.04	1.01	1.03
Hebei	1.00	1.01	1.10	1.13	1.02	1.00	1.00	1.00	1.00	1.00	1.05	1.03
Liaoning	1.02	1.03	1.06	1.06	1.02	1.01	1.00	1.02	1.00	1.00	1.00	1.02
Jiangsu	1.04	1.04	1.03	1.13	1.17	1.01	1.00	1.01	1.00	1.01	1.00	1.04
Zhejiang	1.00	1.01	1.03	1.13	1.09	1.00	1.01	1.00	1.04	1.02	1.03	1.03
Fujian	1.02	1.03	1.05	1.07	1.02	1.01	1.01	1.02	1.00	1.02	1.00	1.02
Shandong	1.04	1.02	1.02	1.08	1.04	1.01	1.03	1.04	1.01	1.00	1.01	1.03
Guangdong	1.00	1.04	1.06	1.11	1.00	1.01	1.02	1.01	1.03	1.02	1.01	1.03
Guangxi	1.01	1.05	1.13	1.10	1.04	1.03	1.00	1.01	1.01	1.04	1.04	1.04
Hainan	1.02	1.00	1.01	1.11	1.04	1.07	1.00	1.03	1.03	1.01	1.00	1.03
Geometric Mean	1.01	1.02	1.05	1.10	1.05	1.02	1.01	1.02	1.02	1.02	1.02	1.03

Green output bias of technological progress

The output-biased technological progress index calculated above indicates the technological change range of different outputs under the condition of constant input, and combines this index with the ratio of output factors in different periods to determine the bias of technological progress. From the perspective of output, this study involves four output factors, namely, the expected output value of mariculture, and the unexpected output emissions of total nitrogen, total phosphorus, and chemical oxygen demand. The output value of the mariculture was combined with total nitrogen, total phosphorus, and chemical oxygen demand to determine the specific output bias of technological progress. Technological progress will change the marginal substitution rate of each output factor, preferring to increase the expected or unexpected output. When technological progress is biased toward reducing total nitrogen, total phosphorus, and chemical oxygen demand emissions, there is a green output bias in the technological progress of mariculture in China. Table 4 is the result of output bias of technological progress in mariculture in China. It can be found that technological progress tends to increase output value and reduce pollutant emissions in most years, showing a green output bias.

Table 4 Results of output bias of China ' s mariculture technology progress

Year	OBTECH	Output bias of technological progress			Y vs COD
		$\frac{(Y/N)^{t+1}}{(Y/N)^t}$	$\frac{(Y/P)^{t+1}}{(Y/P)^t}$	$\frac{(Y/COD)^{t+1}}{(Y/COD)^t}$	
					Y vs N K vs P

2008- 2009	1.01	0.89	0.90	0.90	Y	Y	Y
2009- 2010	1.02	1.05	1.04	1.02	N	P	COD
2010- 2011	1.05	0.58	0.48	0.59	Y	Y	Y
2011- 2012	1.10	1.62	2.15	1.72	N	P	COD
2012- 2013	1.05	0.87	0.71	0.84	Y	Y	Y
2013- 2014	1.02	1.14	1.24	1.10	N	P	COD
2014- 2015	1.01	0.87	0.89	0.93	Y	Y	Y
2015- 2016	1.02	0.96	0.88	0.94	Y	Y	Y
2016- 2017	1.02	0.97	1.03	0.93	Y	P	Y
2017- 2018	1.02	1.03	0.99	1.02	N	Y	COD
2018- 2019	1.02	0.83	0.89	0.90	Y	Y	Y

In order to further analyze the output bias of technological progress, this paper calculates the proportion of the number of regions that technological progress tends to reduce total nitrogen, total phosphorus and chemical oxygen demand from 2009 to 2019, and draws Fig. 3. Overall, the number of regions that technological progress tends to reduce pollutants fluctuates greatly during the study period. This is mainly because the development of mariculture is greatly affected by natural environment and national policies, and has certain sensitivity and vulnerability. Sometimes it is difficult to balance economic and environmental benefits. Specifically, each curve reached a low point in 2010, 2012 and 2018, respectively. Among them, the green output bias of technological progress in 2012 was the lowest, which was mainly due to the fact that catastrophic anomalies restricted the sustainable development of mariculture. The pollution of mariculture sea area caused by the discharge of mariculture pollutants led to the reduction of mariculture output, and the green output bias of mariculture was low. In other years, technological progress tends to reduce the proportion of total nitrogen, total phosphorus and chemical oxygen demand more than the proportion of

reduced output value, and technological progress achieves green output bias. This is mainly due to the good orientation of national policies, the promulgation and implementation of documents such as “Several opinions of the State Council on promoting the sustainable and healthy development of marine fisheries” and “Several opinions on accelerating the green development of mariculture”, improving the mariculture environment, developing ecologically healthy mariculture and realizing the green and sustainable development of marine mariculture. Under the guidance of policy favorable factors, the green output of technological progress tends to form an obvious upward trend in 2018-2019. Overall, the number of areas where technological progress tends to reduce pollutants shows a fluctuating upward trend during the study period, and technological progress tends to green output.

Fig. 3 Technological progress in mariculture in China tend to reduce the proportion of total nitrogen, total phosphorus and chemical oxygen demand (%)

From the regional perspective, the proportion of years biased towards reducing total nitrogen, total phosphorus and chemical oxygen demand in different regions from 2009 to 2019 was calculated. Table 3 shows that the proportion of technological progress biased towards reducing pollutant emissions is generally at a high level. In addition to the relatively low proportion of reducing total nitrogen emissions in Hebei and Shandong, Hebei and Shandong belong to the Bohai Sea area. The mariculture in this area is mainly shallow sea and beach farming, showing extensive farming, while the industrial mariculture mode covers a relatively small area and the breeding technology level is relatively backward. The green development of mariculture in this area is facing great pressure. In the future, green and fine mariculture methods should be actively promoted. Other regions tend to reduce total nitrogen and increase the number of output value than increase total nitrogen and reduce the number of output value. Technological progress shows a green output bias. By comparing various regions, it can be found that the proportion of technological progress bias in reducing pollutant emissions in Fujian, Guangdong and Hainan is relatively high, and the green output bias of technological progress is relatively high, indicating that the development of mariculture in the above regions takes into account economic development and environmental protection. On

the contrary, the situation in Tianjin, Hebei, Shandong and Guangxi is opposite. The green output bias of technological progress is relatively low, and the green sustainable development of mariculture should be paid attention to in the future. Overall, the green output bias of technological progress in the South China Sea is the highest, followed by the East China Sea and the Bohai Sea. The differences in marine resource endowments and natural geographical characteristics of mariculture in different regions lead to the unbalanced green output bias of technological progress. Therefore, different regions should formulate differentiated development policies according to the actual situation to promote technological progress biased towards increasing green output.

Table 5 Coastal areas tend to reduce the proportion of total nitrogen, total phosphorus, and chemical oxygen demand (%)

region		Reducing N emission	Reducing P emission	Reducing COD emission
Bohai Sea Area	Tianjin	54.55	54.55	54.55
	Hebei	45.45	63.64	54.55
	Liaoning	72.73	63.64	72.73
	Shandong	45.45	63.64	63.64
East China Sea Area	Jiangsu	72.73	63.64	63.64
	Zhejiang	72.73	72.73	63.64
	Fujian	81.82	72.73	81.82
	Guangdong	72.73	72.73	81.82
South China Sea Area	Guangxi	54.55	54.55	63.64
	Hainan	81.82	81.82	63.64

Conclusions

At present, resource and environmental problems have become an important bottleneck restricting the sustainable development of China's mariculture. Therefore, in this study, the unexpected outputs of mariculture area factors, total nitrogen, total phosphorus, and chemical oxygen demand are included in the input-output factor system. The DEA-Malmquist index decomposition method is used to calculate the green total factor productivity growth rate of China's mariculture, and the output-biased technological progress index is decomposed to identify the green technological progress output bias of China's mariculture. The main conclusions are as follows: Firstly, the overall green total factor productivity of China's mariculture shows a fluctuating trend of increasing first and then decreasing. The low development efficiency of mariculture may be caused by unreasonable resource allocation and pollution emissions. Green technological progress is an important factor affecting the growth of green total factor productivity of China's mariculture. Therefore, we should improve the contribution of technological progress to economic growth, increase the marginal productivity of input factors, focus on the optimal allocation of resources, reduce dependence on resources and environment, and promote the growth of green total factor productivity. Secondly, a discriminant analysis was conducted on the bias of technological progress between the output value of mariculture and pollutant emissions, and it was found that the number of areas where technological progress was biased towards reducing pollutant emissions during the study period was large but fluctuated, and the green output bias

of technological progress was high, which was consistent with the requirements of current green economic development, and the effectiveness of national environmental governance policies was remarkable. Thirdly, there are significant differences in the results of green output bias among regions. The green output bias of technological progress in the South China Sea is the highest, followed by the East China Sea, and the Bohai Sea area is poor. Specifically, the green output bias of technological progress in Fujian, Guangdong and Hainan is higher, while the green output bias of technological progress in Tianjin, Hebei, Shandong and Guangxi is lower. Therefore, the government should actively support the green development of mariculture. Taking into account the heterogeneity of resource endowment conditions and the development level of green technology in various regions, the government should formulate various oriented policies, strengthen environmental regulation, establish pollution compensation mechanism, restrict the environmental pollution behavior in the process of mariculture, protect the mariculture environment, actively develop environmental protection technology and green farming methods, promote green output bias. In addition, technological exchanges among regions have been strengthened to spread green technologies from developed regions to less developed regions and to promote the application of green technologies. Multi-measures should be taken to improve the green output bias of technological progress in mariculture and realize the sustainable development of mariculture.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Availability of data and materials Data and materials will be available from the corresponding author on reasonable request.

Competing interests The authors declare that they have no competing interests.

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Authors' contributions Jianyue Ji: conceptualization and formal analysis. Yanan Sun: data curation; investigation; methodology; software; visualization; writing—original draft. Xingmin Yin: Writing—Review and Editing. All authors have read and agreed to the published version of the manuscript.

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