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# Evaluation of China's Marine Aquaculture Sector's Green Development Level Using the Super-Efficiency Slacks-Based Measure and Global Malmquist–Luenberger Index Models

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**Abstract:** Given China's rapidly expanding marine aquaculture industry, the associated ecological issues have garnered widespread attention. Therefore, it is crucial to speed up the green growth of marine aquaculture in order to save the environment and use resources sustainably. In order to statically assess and dynamically analyze the green development efficiency levels of marine aquaculture in nine coastal provinces of China from 2012 to 2021, this study uses the non-expected output super-efficiency Slacks-Based Measure model and the Global Malmquist–Luenberger index method. Additionally, it integrates input–output redundancy rates to analyze the causes of efficiency loss. Static efficiency primarily reflects whether a region's inputs and outputs at a given point in time reach an effective efficiency level, while the level of dynamic efficiency mainly gauges the dynamic changes in the efficiency of green production. The results show that, from 2012 to 2021, China's marine aquaculture industry's average static efficiency of green output was 0.705. The southern marine economic zone exhibited the highest static efficiency value in the green development of marine aquaculture, displaying a stepped distribution pattern of "south–north–east" in decreasing order. The input–output redundancy analysis reveals that the primary causes of static efficiency loss in China's marine aquaculture industry are attributed to varying degrees of redundant inputs and carbon emission outputs. Looking through the lens of the GML index, the annual average growth rate of the green total factor productivity in China's marine aquaculture stands at 11.1%, with an annual average change in technical efficiency of 1.8%, while the annual average change in technological progress amounts to 9.1%, suggesting that technological advancement is the primary driver of the rise in green total factor productivity in China's marine aquaculture sector. According to the study, in order to encourage China's marine aquaculture industry to grow sustainably, efforts should be made not only to accelerate technological advancements but also to enhance technical efficiency. Policies that are specifically designed for the local environment should be developed to support the sustainable development of the marine aquaculture sector and to make resource allocation easier.

**Keywords:** super-efficiency slacks-based measure model; global Malmquist–Luenberger index; marine aquaculture industry; green total factor productivity



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## 1. Introduction

People's standard of living has steadily increased since being reformed and opening up. Seafood, characterized by its high protein, low fat, and low calorie content, has become immensely popular among the populace. Marine aquaculture has emerged as a crucial component of fisheries development. As per the "China Fishery Statistical Yearbook 2021", China's total marine aquaculture production reached 22.11 million tons, marking a 3.55% year-on-year increase, accounting for approximately 41% of the nation's total aquaculture output. The rapid expansion of marine aquaculture has significantly contributed to addressing the challenges of seafood scarcity in inland areas, enhancing public health, and promoting coastal economic development. However, alongside the rapid growth of aquaculture, the discharge of exogenous pollutants during the farming process, such as industrial wastewater and solid waste, has adversely affected marine environments, leading to environmental degradation [1]. The "Several Opinions on Accelerating the Green Development of Aquaculture," published in 2019 by the Ministry of Agriculture and Rural Affairs, is the first set of guidelines devoted exclusively to aquaculture since the People's Republic of China was established. This document, approved by the State Council, holds significant importance in promoting the green transformation of aquaculture [2]. The "Five Major Actions for Green and Healthy Aquaculture" were put into action by the Ministry of Agriculture and Rural Affairs in 2020, which is crucial for advancing green aquaculture technologies and protecting the ecological environment [3]. Against this backdrop, the imperative of harmonizing the rapid development of marine aquaculture with environmental conservation to achieve green development has become a pivotal research topic in contemporary discourse.

Through reviewing the relevant literature on the green development of aquaculture, scholars have identified three primary areas of focus within the realm of green aquaculture development research. Firstly, the meaning and implications of "green aquaculture development" are highlighted. According to scholars, the development of aquaculture with consideration for ecological environmental safety and resource conservation is the essence of green aquaculture development. Lu C.C. [4] proposed that green development in aquaculture is established under the dual constraints of aquatic ecological capacity and resource carrying capacity. This is achieved through advanced management concepts, scientific technologies, and material equipment, thus forming a novel development model characterized by efficient resource utilization, ecosystem stability, favorable local environmental conditions, and product quality assurance. Cao J.H. [5] posited that the term "green" emphasizes the protection of the ecological environment and resource conservation, while "development" underscores economic growth and social progress. Therefore, "green development" emphasizes the growth of economic and social welfare under the dual constraints of resource conservation and ecological environmental protection. Yue D.D. [6] suggested that green development in aquaculture aims to achieve a harmonious coexistence among people, aquaculture activities, and the natural environment. This is accomplished through the formulation of plans and standards for green aquaculture development, innovation in aquaculture technologies and mechanisms, and the realization of a whole-process green development mechanism characterized by environmentally friendly aquaculture, efficient technology, safe products, increased income for fishers, and consumer satisfaction.

Secondly, a particular topic of focus for scholarly research in this sector is aquaculture's assessment of its green development level, concentrating primarily on two aspects. One facet involves assessing the green development level of aquaculture through the comprehensive construction of an evaluation index system. Xing Y. [7] established an evaluation system for the green development of aquaculture, selecting 18 indicators based on four dimensions: the input of aquaculture resources, technological advancement and diffusion, managerial oversight, and stage of development. The entropy method was employed for calculations. Yue D.D. [8] created a thorough assessment index system for the environmentally friendly growth of marine aquaculture from four angles: product eco-friendliness, geographic expansion, environmental friendliness, and resource conservation. Furthermore, there is a need to assess the effectiveness of ecofriendly practices in aquaculture by evaluating resource utilization, economic performance, and environmental impact. This evaluation chiefly encompasses metrics like the efficiency of green technologies and overall green productivity. When it comes to research methodologies, primary approaches encompass stochastic frontier analysis (SFA) and data envelopment analysis (DEA), among other relevant methods. Within the domain of SFA methodology, Zhu A.F. [9] employed stochastic frontier analysis (SFA) to gauge the green productivity of China's marine fisheries sector. Yu L. [10] utilized the SFA methodology, incorporating white noise into the computational framework, to assess the efficiency of novel agricultural operators in the aquaculture industry. Indeed, while stochastic frontier analysis (SFA) offers the advantage of accounting for the influence of random errors, it requires a predefined functional form and distinguishes between error and inefficiency terms, which limits its applicability. In the realm of DEA methodology, the main models predominantly focus on the radial paradigm, as demonstrated by the CCR (Charnes, Cooper, and Rhodes) and BCC (Banker, Charnes, and Cooper) models, and the non-radial paradigm mainly represented by the SBM (Slacks-Based Measure) model. Ji J.Y. [11] conducted a comprehensive analysis of green efficiency in Chinese mariculture using a global DEA model. Yang Z.Y. [12] measured the green index of Chinese mariculture using the super-efficient SBM model. Qin H. [13] assessed the ecological–economic efficiency of Chinese marine aquaculture utilizing the SBM model. In the scholarly evaluation of green development in aquaculture using output indicators, the focus is primarily on measuring the anticipated output against the total output value of aquaculture. In terms of non-anticipated output indicators, scholars predominantly take into account pollutants in aquaculture, such as nitrogen (N), phosphorus (P), and chemical oxygen demand (COD).

Lastly, there is the aspect of factors influencing the green development of aquaculture. Xu Y. [14] conducted a study utilizing Feasible Generalized Least Squares (FGLS) estimation, revealing that intertidal aquaculture exerts a negative impact on the overall green productivity of marine aquaculture. Zhang Y. [15] employed the method of Feasible Generalized Least Squares (FGLS) to conclude that there exists a negative correlation between the regulatory level of marine environment and the overall green productivity. Furthermore, investments in marine science and education, the intensity of fisherman training, and dissemination of technological advancements contribute positively to the enhancement in green productivity. Jiang Q.J. [16] utilized the Analytic Hierarchy Process (AHP) to examine the factors that impact the sustainable development of aquaculture. The study revealed that the primary influencers of sustainable aquaculture development are the main stakeholders in aquaculture.

After reviewing the literature, researchers have made significant advancements in the field of sustainable aquaculture development. However, there is room for further optimization in the selection of indicators for evaluating the green development of aquaculture. It has been noted that, during aquaculture operations, both carbon sequestration and carbon emissions are present. Previous studies have tended to focus solely on aquaculture value or production when selecting desirable output indicators, often overlooking the carbon sequestration component. Similarly, in the context of non-desirable output indicators, the emphasis has been predominantly on pollution outputs, neglecting the crucial aspect of carbon emissions. Building upon these observations, this study aims to estimate carbon sequestration and carbon emissions in marine aquaculture in China. These estimations are categorized into desired and undesired outputs. The study assesses the extent of green development in Chinese marine aquaculture by employing the Super-Efficiency Slacks-Based Measure (SBM) model and the Global Malmquist–Luenberger (GML) index methodology. This analytical approach aims to deliver a comprehensive evaluation of the influence of carbon sequestration and emissions on the green development of aquaculture in China.

## 2. Research Methods and Index Selection

### *2.1. Research Methods*

#### 2.1.1. Superefficient SBM Model with Undesired Outputs

Data Envelopment Analysis (DEA) is a non-parametric efficiency analysis method that provides various advantages, such as avoiding assumptions about indicator weights and uniform measurement units. This approach eliminates the impact of subjective factors on efficiency evaluation and is suitable for assessing the green development level of marine aquaculture, particularly in scenarios involving multiple inputs and outputs. The traditional DEA model solely assesses the efficiency of various radial input–output combinations, overlooking the impacts of slack variables and non-desirable outputs, which may introduce inherent inaccuracies into the results. In contrast, the SBM model comprehensively addresses both radial enhancements in input–output dimensions and slack improvements, mitigating such limitations. Tone [17] proposed the SBM model to address this limitation, but this approach still has its drawbacks. For example, when multiple evaluated objects achieve an effective status simultaneously, it becomes difficult to perform further ranking and comparative analysis. Hence, Tone [18] proposed the super-efficiency SBM model to address the limitation where all evaluated entities reach an efficiency score of 1, thereby impeding further comparative analysis. In the assessment of green development efficiency levels, this model incorporates environmental pollution and carbon emissions as non-desirable outputs. Therefore, this study opts for the super-efficiency SBM model that integrates non-desirable outputs for evaluation, as illustrated in Equations (1) and (2).

$$\min\rho = \frac{1+\frac{1}{m}\sum_{i=1}^{m} s_i^- / x_{ik}}{1-\frac{1}{q_1+q_2}\left(\sum_{r=1}^{q_1} s_r^+ / y_{rk} + \sum_{t=1}^{q_2} s_t^{b-} / b_{tk}\right)} \tag{1}$$

$$s.t.\begin{cases} \sum_{j=1,j\neq k}^{n} x_{ij}\lambda_j - s_i^- \leq x_{ik} \\ \sum_{j=1,j\neq k}^{n} y_{rj}\lambda_j + s_r^+ \geq y_{rk} \\ \sum_{j=1,j\neq k}^{n} b_{tj}\lambda_j - s_t^{b-} \leq b_{tk} \\ 1-\frac{1}{q_1+q_2}\left(\sum_{r=1}^{q_1} s_r^+ / y_{rk} + \sum_{t=1}^{q_2} s_t^{b-} / b_{tk}\right) > 0 \\ \lambda, s^-, s^+ \geq 0 \\ i = 1,2\ldots,m; r = 1,2\ldots,q; j = 1,2\ldots,n(j \neq k) \end{cases} \tag{2}$$

In the above equations, n represents the number of decision-making units, where each unit consists of (m) types of inputs, $q_1$ types of expected outputs, and $q_2$ types of non-expected outputs. The vectors x, y, and b denote the indicators for inputs, expected outputs, and non-expected outputs, respectively. The symbol S represents the slack variable. The symbol λ represents the weight vector, while ρ signifies the green development efficiency value of marine aquaculture. When ρ is lower than 1, it indicates that the efficiency level of green development is relatively inefficient. Conversely, when ρ is greater than 1, it suggests that the efficiency level of green development is relatively effective. A higher value of ρ signifies a higher level of green development efficiency and overall green development performance. This study calculated the green production efficiency of marine aquaculture in coastal provinces of China from 2012 to 2021 by integrating the evaluation index system of green development level in marine aquaculture, using MATLAB2021a software and a super-efficiency SBM model based on non-expected outputs.

### 2.1.2. Global Malmquist–Luenberger

The super-efficiency SBM model, which incorporates undesired outputs, is utilized for the evaluation of the static level of green development efficiency, lacking the capability to effectively assess its dynamic changes. As a result, integrating the GML index method is essential for analyzing variations in green total factor productivity. This approach enables the measurement of changes in green total factor productivity from period t to t + 1, facilitating a dynamic analysis of green development efficiency. In contrast, the traditional Malmquist index overlooks the consideration of undesired outputs. Chung [19] combined the Malmquist index with directional distance functions and proposed a Malmquist index that takes into account undesired outputs. The issue of linear programing infeasibility during the intertemporal computation of the Malmquist index has been effectively addressed by Oh [20] through the development of the Global Malmquist–Luenberger (GML) index, which integrates a global approach with directional distance functions. This advancement is documented in Equation (3).

$$
\begin{aligned}
&GML^{t,t+1}(x^t, y^t, b^t, x^{t+1}, y^{t+1}, b^{t+1}) \\
&= \frac{1+D^G(x^t,y^t,b^t)}{1+D^G(x^{t+1},y^{t+1},b^{t+1})} = \frac{1+D^t(x^t,y^t,b^t)}{1+D^{t+1}(x^{t+1},y^{t+1},b^{t+1})} \\
&\times \frac{(1+D^G(x^t,y^t,b^t))/(1+D^t(x^t,y^t,b^t))}{(1+D^G(x^{t+1},y^{t+1},b^{t+1}))/(1+D^{t+1}(x^{t+1},y^{t+1},b^{t+1}))} \\
&= \frac{TE^{t+1}}{TE^t} \times \frac{BPG_{t+1}^{t,t+1}}{BPG_t^{t,t+1}} = EC^{t,t+1} \times BPC^{t,t+1}
\end{aligned}
\tag{3}
$$

In Equation (3), $D^G$ represents the global directional distance function, and the value of $GML^{t,t+1}$ indicates the green total factor productivity change from period t to t + 1. Specifically, when the $GML^{t,t+1}$ index for period t to t + 1 is greater than 1, it indicates an increase in green total factor productivity compared to the previous period. Conversely, if the GML index is lower than 1, it signifies a decrease in green total factor productivity. Furthermore, it can be decomposed into changes arising from technical efficiency (EC) and changes resulting from the gap with best practice (BPC). Technical efficiency gauges the ability to achieve more outputs without increasing resource inputs, whereas technological progress measures the contribution of changes in production technology to outputs. In this context, EC is used to assess the diffusion of green technologies, where $EC^{t,t+1} > 1$ (<1) indicates an improvement (decline) in efficiency over adjacent periods for the decision-making unit. On the other hand, BPC measures the progression of green technological advancements, with $BPC^{t,t+1} > 1$ (<1) indicating progress (regression) in technology over adjacent periods for the decision-making unit.

### *2.2. Index Selection*

During the development of marine aquaculture, the labor force and fixed assets, among other input factors in the industry, are closely correlated with the growth of the total output value in the marine aquaculture sector. This study, considering the characteristics of marine aquaculture and data availability, chose labor force, aquaculture area, fixed assets, training intensity, and intermediate consumption as resource input indicators. Specifically, labor force refers to individuals engaged in production and management, represented by the professional workforce in marine aquaculture; the aquaculture area represents resources formed naturally and through artificial means, quantified by the area dedicated to marine aquaculture; fixed assets denote the aquaculture fishing vessels utilized in marine aquaculture, indicated by the total power of motorized fishing vessels used for aquaculture purposes; training intensity in the marine aquaculture industry measures the level of technical training engagement by practitioners, calculated by multiplying the number of individuals in fisheries training by the proportion of marine aquaculture practitioners in the total workforce in aquaculture; intermediate consumption in marine aquaculture refers to the daily operational expenses, converted from fisheries' intermediate consumption to marine aquaculture intermediate consumption, and adjusted to comparable prices in 2012 using the agricultural production input price index to mitigate the impact of price fluctuations.

In terms of indicator selection, the expected outputs were categorized into economic and environmental aspects. For the economic output, the indicator chosen was the economic output value of marine aquaculture, with relevant data obtainable from the "China Fishery Statistical Yearbook". On the other hand, for the environmental output, the indicator selected was the carbon sequestration capacity of marine aquaculture. Bivalves and algae aquaculture, which do not require the input of feed, have the ability to absorb a significant amount of carbon through carbon fixation. Moreover, they represent the primary species in Chinese marine aquaculture. Consequently, this study primarily focused on bivalves and algae in the calculation of the carbon sequestration capacity within marine aquaculture. The carbon sequestration levels of major bivalves and algae species with carbon sequestration functions can be obtained from the research findings of Li X. [21] and colleagues. The carbon sequestration assessment method for bivalves and algae in marine aquaculture is referred to in He J.B.'s [22] accounting framework, whose specific formula is as follows:

$$\begin{aligned}
&C_t = \sum C_s + \sum C_{al} \\
&\sum C_s = \sum C_{sh} + \sum C_{st} \\
&\sum C_{sh} = \sum Q_i \cdot \alpha_i \cdot P_i \cdot \beta_i \\
&\sum C_{st} = \sum Q_i \cdot \alpha_i \cdot P_j \cdot \beta_j \\
&\sum C_{al} = \sum Q_k \cdot \beta_k
\end{aligned} \tag{4}$$

In the above equation, $C_t$ denotes the total carbon sequestration of bivalves and algae in marine aquaculture; $C_s$ and $C_{al}$ represent the carbon sequestration from bivalves and algae, respectively; and $C_{sh}$ and $C_{st}$ denote the carbon sequestration of bivalve soft tissue and shell, respectively. Qi signifies the yield of bivalves; $\alpha_i$ represents the dry weight coefficient of bivalves; Pi and $P_j$ represent the mass proportions of bivalve soft tissue and shell, respectively; $\beta_i$ and $\beta_j$, respectively, denote the carbon fixation capacity of bivalve soft tissue and shell; $Q_k$ signifies the yield of algae; and $\beta_k$ represents the carbon fixation capacity of algae.

In the context of unintended output indicators, the pollutants generated by marine aquaculture primarily include nitrogen (N), phosphorus (P), and chemical oxygen demand (COD), with emission rates sourced from the data published in the "Announcement of the Second National Pollution Source Census in China" as follows: nitrogen emissions at 2.5 kg/t, phosphorus emissions at 0.33 kg/t, and COD emissions at 13.6 kg/t. Aside from pollutant emissions, carbon emissions during the process of marine aquaculture also bear environmental implications. Carbon emissions from marine aquaculture can be categorized into two components: firstly, carbon emissions resulting from energy combustion, with this study focusing on the carbon emissions generated during the operation of marine aquaculture vessels utilizing diesel fuel; and secondly, indirect carbon emissions stemming from the use of electricity. While most aquaculture methods primarily rely on natural resources, such as the sea area, thereby exhibiting a low energy dependency, pond aquaculture and intensive aquaculture exhibit a higher degree of energy reliance, primarily attributed to carbon emissions arising from activities such as aeration and electrical operation. The calculation methodology for carbon emissions in marine aquaculture can be obtained from the accounting system proposed by Shao G.L. [23], whose specific formula is as follows:

$$C_{ef} = P \cdot \chi \cdot \theta_1 \cdot \omega + \left(P_{pa} \cdot \kappa + P_{ia} \cdot \eta + S_{pa} \cdot \mu + S_{ia} \cdot \rho\right) \cdot \theta_2 \cdot \omega$$

The formula includes various parameters: $C_{ef}$ represents the total carbon emissions from marine aquaculture; P indicates the total power of marine aquaculture vessels; $\chi$ denotes the fuel consumption factor for marine aquaculture vessels, whose value of 0.225 tons per kilowatt was obtained from the "Domestic Motorized Fishing Vessel Fuel Subsidy Fuel Consumption Calculation Reference Standard"; $P_{pa}$ and $P_{ia}$, respectively, represent the output of marine pond aquaculture and marine intensive aquaculture; $\kappa$ and $\eta$ represent the single-unit electricity consumption coefficients for marine pond aquaculture and marine intensive aquaculture, determined as 0.37 kilowatts per kilogram and 8.66 kilowatts per kilogram based on the research findings of Xu H. [24] and Yang Z.Y. [25], respectively; $\theta_1$ and $\theta_2$, respectively, indicate the coefficients for diesel and electricity conversion to standard coal, set at 1.46 kg of standard coal per kilogram and 0.12 kg of standard coal per kilowatt according to the "China Energy Statistical Yearbook"; $S_{pa}$ and $S_{ia}$ represent the area of marine pond aquaculture and the volume of marine intensive aquaculture, respectively; $\mu$ and $\rho$, respectively, denote the unit area oxygenation electricity consumption coefficient and the unit volume oxygenation electricity consumption coefficient for marine pond aquaculture and marine intensive aquaculture, with the coefficients determined as 1440.17 kilowatts per hectare and 37.76 kilowatts per cubic meter based on the research findings of Xu H. [26]; and w represents the carbon emission coefficient, set at 0.68 kg per kilogram of standard coal based on the research findings of Xu D.L. [27] and Yue D.D. [28]. In consideration of the aforementioned indicators, this paper established the following evaluation index system for the sustainable development of marine aquaculture, as shown in Table 1.

**Table 1.** Evaluation index system of the green development level of mariculture industry.

| Index | Index Class | Variable | Unit |
|---|---|---|---|
| Input | Resource input | Breeding area<br>Labor force<br>Intermediate consumption<br>Training intensity<br>Aquaculture fishing vessel | Hectare<br>Population<br>CNY Ten thousand<br>Population<br>Kilowatt |
| Output | Expected output | Economic value of mariculture<br>Carbon sink of mariculture | CNY Ten thousand<br>Ton |
| | Undesirable output | N, P, and COD emissions from mariculture<br>Carbon emissions from mariculture | Ton<br>Ton |

### *2.3. Data Source*

This paper's input–output indicator data mainly originated from the "China Fishery Statistical Yearbook" (2012–2021), "China Statistical Yearbook" (2012–2021), and the "Handbook of Pollution Source Production and Emission Coefficients for Aquaculture in the First National Pollutant Source Census." For the missing data, interpolation methods were utilized for completion, while certain indicators were derived through calculations. Due to substantial data gaps in Tianjin, Shanghai, Hong Kong, Macau, and Taiwan, coupled with the relatively smaller aquaculture scales in these regions, the analysis in this paper focused solely on examining the level of sustainable development in marine aquaculture in 9 provinces, including Liaoning, Hebei, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong, Guangxi, and Hainan. The northern region encompasses three areas: Liaoning, Hebei, and Shandong. The eastern region comprises Jiangsu and Zhejiang. The southern region includes Fujian, Guangdong, Guangxi, and Hainan. Descriptive statistics for the variables are presented in Table 2.

**Table 2.** Descriptive statistics of input and output variables.

| Indicators | Min | Max | Avg | Sd |
|---|---|---|---|---|
| Breeding area | 15,845 | 942,050 | 237,788 | 247,029 |
| Labor force | 23,037 | 226,137 | 100,159 | 63,997 |
| Intermediate consumption | 115,658 | 1,519,737 | 594,078 | 374,997 |
| Training intensity | 1108 | 108,321 | 18,420 | 17,646 |
| Aquaculture fishing vessel | 700 | 323,379 | 115,544 | 94,430 |
| Economic value of mariculture | 662,215 | 10,728,457 | 3,587,035 | 2,720,635 |
| Carbon sink of mariculture | 1807 | 688,737 | 201,638 | 198,289 |
| N, P, and COD emissions from mariculture | 6207 | 155,247 | 62,163 | 45,874 |
| Carbon emissions from mariculture | 9402 | 252,097 | 69,058 | 57,748 |

## 3. Empirical Analysis

### *3.1. Static Efficiency Analysis of Green Production in the Chinese Mariculture Industry*

Table 3 presents the findings derived from computations using panel data. Table 3 presents the marine aquaculture industry's green production efficiency level for the period from 2012 to 2021 in China. Nationally, from 2012 to 2021, China's marine aquaculture industry's green production efficiency only surpassed 1 in 2021; the other years fell short of 1, yielding an average of 0.705, which suggests a moderate level of green production efficiency in China's marine aquaculture industry. The southern marine economic circle had an average green production efficiency of 0.927, higher than the northern and eastern marine economic circles (0.590 and 0.533), respectively, when comparing the average green production efficiency of the three major marine economic circles from 2012 to 2021.

This suggests a stepwise decline in the green production efficiency of China's marine aquaculture industry from south to north to east. Regionally, Fujian predominantly had green production efficiency values exceeding 1 during the calculation period, with values below 1 only in 2012 and 2015, indicating a relatively high level of green development and rational input–output in the marine aquaculture industry of this region. Other regions showed varying levels of fluctuation in green development efficiency, suggesting insufficient stability and significant room for improvement in green development efficiency. In terms of regional averages, Fujian had the highest green production efficiency average of 1.257, while Hebei had the lowest green production efficiency at only 0.294. Although China's green production efficiency in marine aquaculture has seen rapid development in recent years, its overall efficiency remains relatively low, highlighting the considerable potential for raising the green production efficiency of China's marine aquaculture sector and showing areas for development when compared to the frontier.

**Table 3.** Static efficiency of the green production of mariculture in Chinese provinces from 2012 to 2021.

| Province | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Hebei | 0.203 | 0.227 | 0.242 | 0.248 | 0.271 | 0.277 | 0.303 | 0.321 | 0.383 | 0.631 | 0.294 |
| Liaoning | 0.476 | 0.578 | 0.580 | 0.570 | 0.705 | 1.151 | 0.719 | 1.147 | 1.159 | 1.353 | 0.791 |
| Jiangsu | 0.244 | 0.419 | 0.428 | 0.384 | 0.506 | 0.567 | 0.767 | 0.407 | 1.131 | 1.124 | 0.535 |
| Zhejiang | 0.379 | 0.392 | 0.419 | 0.453 | 0.420 | 0.554 | 0.560 | 0.604 | 0.783 | 1.025 | 0.531 |
| Fujian | 0.875 | 1.265 | 1.270 | 0.966 | 1.120 | 1.127 | 1.491 | 1.517 | 1.533 | 1.657 | 1.257 |
| Shandong | 0.476 | 0.505 | 0.954 | 0.797 | 1.143 | 1.091 | 1.043 | 1.049 | 1.036 | 1.099 | 0.882 |
| Guangdong | 0.575 | 0.597 | 0.583 | 0.613 | 0.662 | 0.904 | 1.061 | 1.114 | 1.076 | 1.254 | 0.807 |
| Guangxi | 0.542 | 0.528 | 0.694 | 0.680 | 1.060 | 0.867 | 1.152 | 1.131 | 1.052 | 1.049 | 0.842 |
| Hainan | 0.495 | 0.587 | 0.839 | 1.012 | 1.024 | 1.015 | 1.062 | 1.056 | 0.682 | 1.180 | 0.864 |
| Northern mean | 0.358 | 0.405 | 0.512 | 0.483 | 0.602 | 0.703 | 0.610 | 0.728 | 0.772 | 0.979 | 0.590 |
| Eastern mean | 0.304 | 0.405 | 0.423 | 0.417 | 0.461 | 0.561 | 0.655 | 0.496 | 0.941 | 1.074 | 0.533 |
| Southern mean | 0.606 | 0.695 | 0.810 | 0.799 | 0.947 | 0.973 | 1.180 | 1.192 | 1.043 | 1.267 | 0.927 |
| National mean | 0.436 | 0.515 | 0.602 | 0.585 | 0.694 | 0.772 | 0.831 | 0.832 | 0.922 | 1.120 | 0.705 |

Figure 1 shows the evolution of green production efficiency from 2012 to 2021 in the national and three key marine economic zones. From 2012 to 2014, the national efficiency grew progressively, reaching a peak of 0.602 before seeing a slight decline. After making a comeback in 2016, it increased gradually. The State Council's 2019 publication of "Several Opinions on Accelerating the Green Development of Marine Aquaculture," which somewhat raised the cost of marine aquaculture, may have contributed to the less noticeable rise in efficiency between 2018 and 2019. A minor peak was observed in 2020, signifying a noteworthy rise in the green production efficiency of China's marine aquaculture sector. This was possibly a result of the release of the "Five Major Actions for Green Aquaculture in 2020" by the Ministry of Agriculture and Rural Affairs of China, which promoted the demonstration of eco-friendly aquaculture technologies and facilitated the application of green and healthy aquaculture technologies to promote the green development of marine aquaculture nationwide. Looking at the evolving trends in green production efficiency in the three major marine economic zones, the southern and northern economic zones exhibited similar patterns of gradual fluctuating improvement. The eastern economic zone experienced a slow increase initially, followed by fluctuations and a decline in 2019, and a subsequent fluctuating increase in 2020. In the initial stages of the study, the green production efficiency of marine aquaculture in the southern economic zone was the highest, followed by the northern economic zone, and the eastern economic zone ranked the lowest. However, by 2020, the green production efficiency of marine aquaculture in the eastern economic zone surpassed that of the northern economic zone.

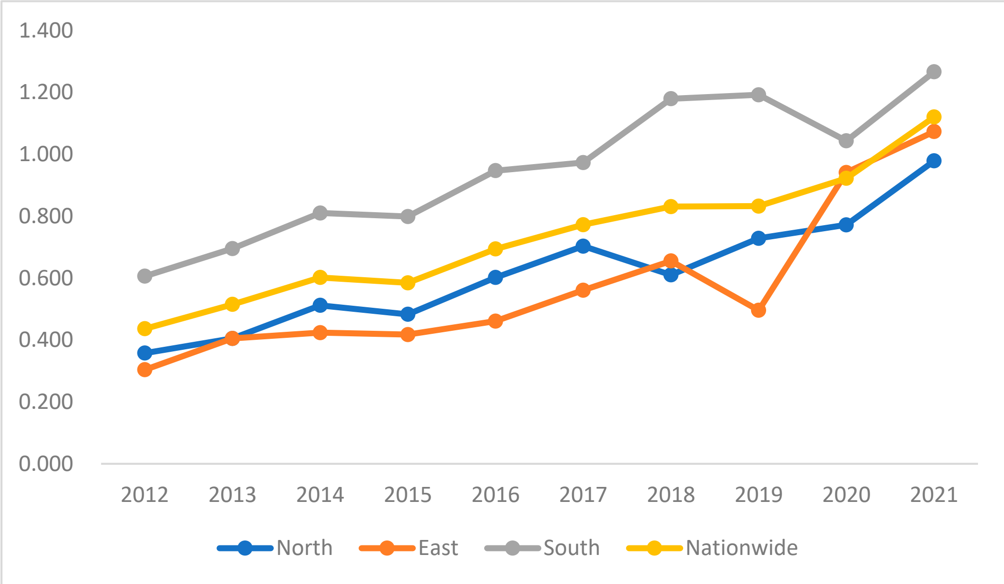


**Figure 1.** The annual changes in green production efficiency in the national and three major marine economic zones from 2012 to 2021.

Tables 4 and 5, respectively, present the redundancy rates of input and non-desirable output indicators for the national level and each province, as calculated by the super-efficiency SBM model. These rates reflect the distance between each indicator and the green production frontier. A higher value indicates a greater distance from the green production frontier, which exerts a more significant influence on green production efficiency.

Based on the analysis of the redundancy rate of various indicators in Table 4, it is evident from the national average that China's marine aquaculture industry generally involves significant input of resources, leading to considerable waste. Among the input indicators, the average redundancy of training intensity is the largest at 0.400, indicating that excessive investment in training during the sample period is the primary cause of the low green production efficiency in China's marine aquaculture industry. In addition, the aquaculture area and total power of fishing vessels are also important factors contributing to the decrease in green production efficiency, with redundancy degrees of 0.327 and 0.274, respectively. Considering the average redundancy of non-desired outputs, it is observed that there is an issue of excessive output in carbon emissions, nitrogen, phosphorus, and COD, the three major pollutants. Over time, there has been an overall downward trend in the redundancy of both non-desired output indications and input indicators. Only labor redundancies, training intensity, and carbon emissions were zero as of 2021, which explains why China's marine aquaculture sector has been able to continuously increase its green production efficiency. In addition, this draws attention to the crucial areas that need to be addressed in order to improve China's marine aquaculture industry's green production efficiency. These areas include the carbon emissions, aquaculture area, total power of fishing vessels, and intermediate consumption.

According to Table 5, when examining the input–output redundancies of marine aquaculture industry across provinces in China, it is observed that Hebei, Zhejiang, Guangdong, and Guangxi exhibit significant redundancy in labor force. Hebei and Zhejiang have redundancies in all five input factors and two non-desired output factors higher than the national average. Liaoning shows higher redundancies in aquaculture area and training intensity input factors compared to the national average. Jiangsu demonstrates higher redundancies in the total power of fishing vessels, aquaculture area, training intensity as input factors, and carbon emissions compared to the national average. Fujian only has a higher redundancy in training intensity as an input factor, which is lower than the national average. Shandong shows a higher redundancy in the training intensity as an input factor. Guangdong exhibits high redundancies in labor force input and pollutant emission rates. Guangxi has higher redundancies in the total power of fishing vessels and training intensity as input factors. Hainan's redundancy in labor force input is higher than the national average. Therefore, excessive input from a variety of sources and excessive carbon emissions are the primary causes of the decline in green production efficiency in China's marine aquaculture sector. Looking at the longitudinal perspective of inputs and non-desired outputs, the training intensity input redundancy is the highest, followed by aquaculture area. In terms of non-desired output indicators, except for Guangxi and Hainan, the redundancy in carbon emissions is higher than that of pollutant emissions in all other provinces. This suggests that, compared to pollutant emissions, carbon emissions constitute a greater barrier to the improvement in green production efficiency in the marine aquaculture sector. The main causes of China's marine aquaculture industry's decline in production efficiency are high carbon emissions and excessive resource inputs. Thus, the marine aquaculture business may effectively promote the increase in green production efficiency by minimizing non-desired outputs and enhancing input–output efficiency. Therefore, improving aquaculture technologies and reducing carbon emission rates are essential for China's marine aquaculture industry to experience an efficient and sustainable growth in the future.

**Table 4.** Average input–output redundancy rate of mariculture in China.

| Index | Input Redundancy Rate | | | | | Redundancy Rate of Undesirable Output | |
|---|---|---|---|---|---|---|---|
| | Labor Force | Aquaculture Fishing Vessel | Breeding Area | Training Intensity | Intermediate Consumption | Carbon Emissions | Pollutant Discharge |
| 2012 | 0.383 | 0.493 | 0.612 | 0.779 | 0.196 | 0.296 | 0.206 |
| 2013 | 0.281 | 0.422 | 0.537 | 0.662 | 0.155 | 0.279 | 0.208 |
| 2014 | 0.220 | 0.365 | 0.448 | 0.565 | 0.144 | 0.252 | 0.133 |
| 2015 | 0.184 | 0.372 | 0.488 | 0.593 | 0.158 | 0.213 | 0.155 |
| 2016 | 0.126 | 0.256 | 0.404 | 0.386 | 0.141 | 0.175 | 0.129 |
| 2017 | 0.081 | 0.277 | 0.231 | 0.329 | 0.116 | 0.165 | 0.068 |
| 2018 | 0.119 | 0.165 | 0.198 | 0.265 | 0.102 | 0.146 | 0.054 |
| 2019 | 0.015 | 0.195 | 0.223 | 0.253 | 0.115 | 0.155 | 0.017 |
| 2020 | 0.018 | 0.108 | 0.092 | 0.171 | 0.070 | 0.080 | 0.015 |
| 2021 | 0.000 | 0.085 | 0.041 | 0.000 | 0.025 | 0.070 | 0.000 |
| Mean | 0.143 | 0.274 | 0.327 | 0.400 | 0.122 | 0.183 | 0.098 |

**Table 5.** Average input–output redundancy rate of Chinese mariculture by province.

| Index | Input Redundancy Rate | | | | | Redundancy Rate of Undesirable Output | |
|---|---|---|---|---|---|---|---|
| | Labor Force | Aquaculture Fishing Vessel | Breeding Area | Training Intensity | Intermediate Consumption | Carbon Emissions | Pollutant Discharge |
| Hebei | 0.225 | 0.817 | 0.795 | 0.743 | 0.473 | 0.724 | 0.198 |
| Liaoning | 0.143 | 0.231 | 0.468 | 0.212 | 0.009 | 0.162 | 0.138 |
| Jiangsu | 0.086 | 0.550 | 0.502 | 0.561 | 0.284 | 0.356 | 0.031 |
| Zhejiang | 0.308 | 0.291 | 0.485 | 0.722 | 0.141 | 0.250 | 0.223 |
| Fujian | 0.078 | 0.071 | 0.059 | 0.171 | 0.018 | 0.013 | 0.006 |
| Shandong | 0.012 | 0.119 | 0.193 | 0.335 | 0.014 | 0.113 | 0.051 |
| Guangdong | 0.181 | 0.077 | 0.302 | 0.349 | 0.099 | 0.029 | 0.186 |
| Guangxi | 0.107 | 0.256 | 0.092 | 0.256 | 0.032 | 0.000 | 0.053 |
| Hainan | 0.144 | 0.053 | 0.049 | 0.254 | 0.030 | 0.000 | 0.000 |
| Mean | 0.143 | 0.274 | 0.327 | 0.400 | 0.122 | 0.183 | 0.098 |

### 3.2. Dynamic Efficiency Analysis of Green Production in the Chinese Mariculture Industry

The GML index approach was used in this study to examine how China's marine aquaculture industry's overall green production efficiency changed between 2012 and 2021. Based on this, the study divided the analysis into two categories: best practice gap change (BPC) and technical efficiency change (EC). BPC was used to quantify changes in green technological advancement, while EC was used to gauge the spread of green aquaculture technology.

Table 6 displays the GML index and its breakdown for the marine aquaculture sector in China. The findings show that, between 2012 and 2021, China's marine aquaculture industry's green overall production efficiency changed on average by 1.111, growing at an annual rate of 11.1%. This shows that, over the sample period, China's marine aquaculture business had an overall increase trend in green production efficiency. Examining the decomposition of the GML index, it is observed that both the technical efficiency change and technological progress have contributed to the growth in green production efficiency, accounting for 1.8% and 9.1%, respectively. This indicates that the progress of green technology in China's marine aquaculture industry is the driving force behind the growth of the overall green production efficiency, while the contribution of technical efficiency is relatively limited. This is consistent with China's increasing emphasis on green aquaculture technology and the continuous increase in research investment in aquaculture. The GML index mainly experiences positive growth during the sample period, with only a negative growth observed in 2014–2015. Minor variations exist in the growth rates as well. The greatest increase in growth occurred between 2013 and 2014, when it reached an annual growth rate of 18.5%. The State Council published "Several Opinions on Promoting the Sustainable and Healthy Development of Marine Fisheries" at this time, offering recommendations for the advancement of technology and the sustainable growth of the marine aquaculture sector.

**Table 6.** The changing trends of the GML index, EC index, and BPC index in marine aquaculture in China.

| Year/Factor Breakdown | GML | EC | BPC |
|---|---|---|---|
| 2012–2013 | 1.181 | 1.051 | 1.123 |
| 2013–2014 | 1.169 | 0.986 | 1.185 |
| 2014–2015 | 0.971 | 0.997 | 0.975 |
| 2015–2016 | 1.187 | 0.960 | 1.236 |
| 2016–2017 | 1.113 | 1.003 | 1.110 |
| 2017–2018 | 1.076 | 1.003 | 1.072 |
| 2018–2019 | 1.002 | 1.035 | 0.968 |
| 2019–2020 | 1.108 | 1.097 | 1.010 |
| 2020–2021 | 1.215 | 1.032 | 1.178 |
| Mean | 1.111 | 1.018 | 1.091 |

The green total factor productivity, technical efficiency, and technological advancement in China's marine aquaculture business showed a varying upward trend between 2012 and 2021. The green total factor production had a notably small fluctuation amplitude, which can be attributable to its breakdown into the product of technological development and technical efficiency. Changes in technical efficiency and advancements in technology work together to produce variations in green total factor productivity. Technology is the main driver of green development in China's marine aquaculture business, as evidenced by the close correlation between the trend of technological advancement and changes in green total factor productivity.

Using the GML index method and MATLAB software, we calculated the level of green total factor productivity. Figure 2 shows the GML index of the marine aquaculture industry in different Chinese regions. When considering changes in green total factor productivity (TFP), the nine provinces that were sampled for the study had an average GML index that was greater than 1, which suggests that, from 2012 to 2021, the green

TFP in the marine aquaculture sector in these provinces continued to improve. Among the provinces, the top five in terms of average GML index were Jiangsu (1.185), Hebei (1.135), Liaoning (1.123), Zhejiang (1.117), and Hainan (1.101), with annual growth rates of 18.5%, 13.5%, 12.3%, 11.7%, and 10.1%, respectively, ranking high in growth rates and exhibiting rapid improvements. Given the constraints of resource and environment, coastal regions have shown an increased attention to green total factor productivity, consistently looking for ways to advance the marine aquaculture sector's green development. The regional heterogeneity along the coastal areas may be attributed to the diverse climate and ecological conditions, as China's maritime territory extends from the Bohai Sea in the north to the South China Sea in the south, spanning 44 degrees of latitude. Consequently, different regions face varying conditions and constraints at different stages of industrial development in the marine aquaculture sector.

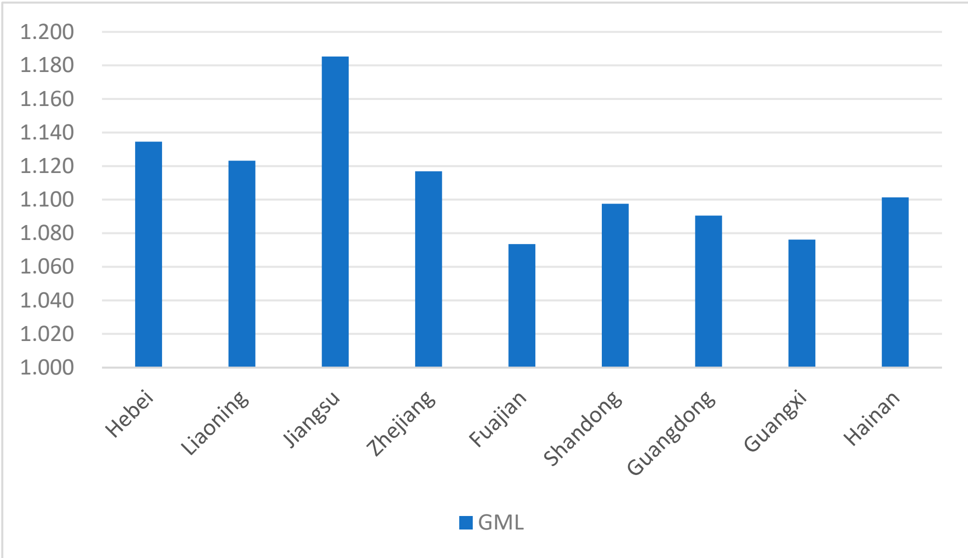


**Figure 2.** GML index by province.

From 2012 to 2021, the BPC and EC indices of various provinces in China are presented in Figure 3. Looking at the BPC index, the average BPC index of the nine coastal provinces was consistently above 1, indicating progress in the marine aquaculture technology of these regions. Among them, Zhejiang showed the fastest technological progress, with an annual growth rate of 11.3%. Additionally, Liaoning and Hainan also demonstrated notable progress in technology, with annual growth rates of 10.5% and 10%, respectively. However, Fujian exhibited relatively slower growth with an annual average of 3.7%, underscoring the need to enhance the technological level in the aquaculture process and elevate the green aquaculture technology in the marine aquaculture industry. Regarding the EC index, seven provinces had an annual average EC index exceeding 1, indicating a gradual convergence of production efficiency towards the production frontier. The provinces were ranked in descending order of annual average EC index as Jiangsu, Hebei, Liaoning, Fujian, Shandong, Zhejiang, and Hainan; Guangdong and Guangxi had average EC indices below 1, indicating a decline in green production efficiency in the marine aquaculture industry due to an irrational allocation of resource elements. When considering the combined effects of the EC and BPC indices, provinces with both indices exceeding 1 demonstrated continuous progress in the production process while maintaining a rational proportion of input factors. This combined effect has facilitated the improvement in green total factor productivity. For Guangdong and Guangxi, where the BPC index exceeded 1 but the EC index was below 1, it suggests that, while technological progress is occurring in the production process, the ineffective allocation of resources led to a decrease in green total factor productivity in the marine aquaculture industry, despite advancements in production technology.

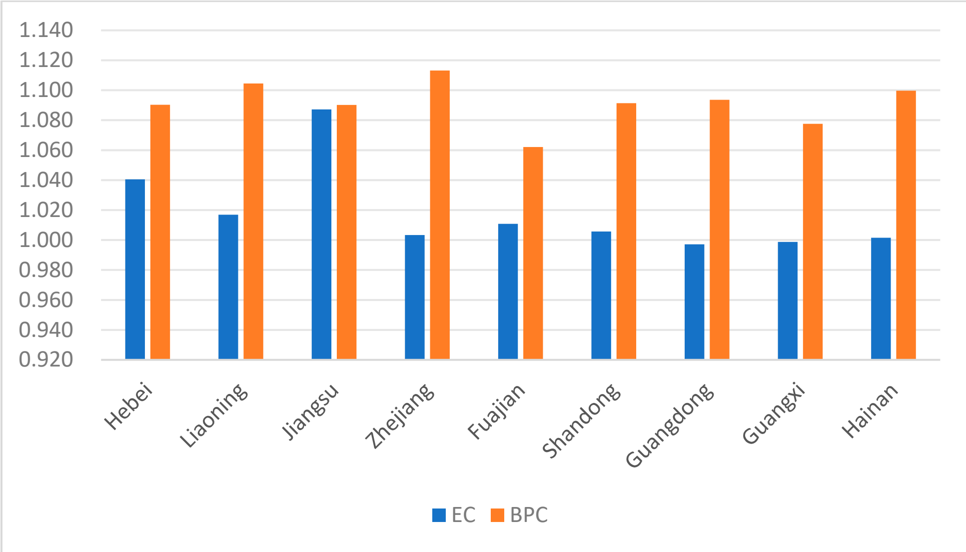


**Figure 3.** Distribution of EC and BPC indices by province.

Based on the analysis of the GML index, BPC index, and EC index as described above, we can conduct an analysis on the dynamic level of green development in the marine aquaculture industry of various provinces from 2012 to 2021. Solutions are proposed according to the issues faced by each province. In this article, we analyze two provinces that are representative. Firstly, let us focus on Guangdong. With a GTFP index of 1.090, it is positioned at a moderate level nationwide. The BPC index stands at 1.094, also ranking at a moderate level nationally. However, the EC index is below 1, placing Guangdong at the bottom nationally. In the Shandong region, the green total factor productivity in the marine aquaculture industry is mainly influenced by its technical efficiency index, with the progress in catching up to the production frontier significantly slower than other regions. Therefore, to enhance the green total factor productivity of the marine aquaculture industry in Shandong, it is essential to elevate the EC index by actively learning from the management and resource allocation models of other regions.

## 4. Conclusions and Suggestions

### *4.1. Conclusions*

Using the super-efficiency SBM model, this study measured the green production efficiency in China's marine aquaculture sector from 2012 to 2021. It employed the GML index to examine the trend of the green total factor productivity in China's marine aquaculture sector and integrated the analysis of input–output redundancy rates to pinpoint the reasons behind losses in green production efficiency. The findings suggest that, from 2012 to 2021, China's marine aquaculture industry's average static green production efficiency was 0.705, at a moderate level, exhibiting a stepwise falling pattern of "south–north–east." Province-specific averages for green production efficiency ranged from 0.294 to 1.257, with an apparent rising trend in green production efficiency following 2016. The southern marine economic circle had the highest average green production efficiency during the study period. Excessive unexpected outputs and excessive inputs of factors like total fishing vessel power, aquaculture area, and training were found to be the primary causes of the losses in green production efficiency in China's marine aquaculture industry. These factors also impeded the improvement in green production efficiency. China's marine aquaculture business saw an average annual rise in green total factor production of 11.1%, when seen through the lens of the GML index technique and its decomposition. The technical efficiency grew by 1.8% annually, and the index of changes in the gap to the optimal practice increased by 9.1% annually. This indicates that the growth of green total factor productivity in China's marine aquaculture industry primarily relies on advancements in technology, with the contribution from changes in technical efficiency being relatively limited.

### 4.2. Suggestions

Based on the research conclusions above, the following strategic recommendations are proposed to enhance the level of green development in China's marine aquaculture industry. Firstly, it is essential to accelerate technological progress while improving technical efficiency in the marine aquaculture industry. The research within the sample period has demonstrated that technological progress is a crucial driver for promoting green total factor productivity, while the contribution from technical efficiency is relatively limited. Therefore, prioritizing the enhancement in technical efficiency is crucial for the green development of marine aquaculture across various provinces. Firstly, it is imperative to improve the communication channels between research institutions and aquaculture markets. If necessary, government support should be leveraged to strengthen the close linkage between research institutions and aquaculture markets, constructing a dynamic linkage mechanism among the government, research institutions, and aquaculture markets to ensure that the technological achievements of research institutions can be applied in aquaculture markets. Secondly, the evaluation of research institutions should be refined, with extended assessment periods and the inclusion of multiple indicators in the evaluation system to promote the technological research and development progress of research institutions. Secondly, efforts should be made to drive the coordinated development of the regional marine aquaculture industry. Coordinated and efficient resource allocation should be planned across provinces to collectively promote the high-quality green development of the marine aquaculture industry. Firstly, the differentiated development of various provinces should be coordinated. This should involve strengthening the close connections of marine aquaculture across different provinces, deepening exchanges and cooperation, and promoting the adoption of advanced aquaculture technologies. Secondly, it is important to expedite the training of large-scale aquaculture enterprises and leading businesses in embracing new knowledge and technologies, as they play a leading role in innovation and serve as exemplary leaders in green development. Lastly, efforts should be focused on enhancing the standardization of the marine aquaculture industry. This involves accelerating the establishment of a standardized system for the green development of the marine aquaculture industry, refining the relevant standards for input factors, pollutants, and carbon emissions, promoting the rational allocation of resources, and advancing the standardized development of green aquaculture.

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