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Study on the Spatial Imbalance and Polarization of Marine Green Aquaculture Efficiency in China

Wei Wang [1], Wei Mao [1,2], Renhong Wu [3,*], Jianzhen Zhu [1,4,*] and Zhenbo Yang [1]

[1] School of Economics, Guangdong Ocean University, Zhanjiang 524088, China; 13802381359@163.com (W.W.); maowei31@126.com (W.M.)
[2] Guangdong Coastal Economic Belt Development Research Institute, Zhanjiang 524088, China
[3] Graduate School of Technology Management, Kyung Hee University, Yongin 17104, Republic of Korea
[4] Marine Economy and Management Research Center, Guangdong Ocean University, Zhanjiang 524088, China
* Correspondence: wurenhongbini@163.com (R.W.); gdzhujz@163.com (J.Z.); Tel.: +86-0759-2396009 (J.Z.)

Abstract: In-depth analyses of the spatial imbalance and polarization of marine green aquaculture efficiency have a profound impact on the realization of high-quality development of fisheries. Based on the data on mariculture in nine coastal provinces of China from 2006 to 2019, this research analyzed the spatial imbalance and polarization of green mariculture efficiency using quantitative measurements and explored their causes. The results showed that (1) the efficiency of marine green aquaculture in China is relatively effective, but there is still room for improvement. The spatial imbalance of the whole country and the three marine economic circles shows an increasing trend, and the efficiency of marine green aquaculture in China has two levels of differentiation characteristics. Compared with the coastal provinces with low and high levels of marine green aquaculture efficiency, the degree of spatial imbalance in the medium-level coastal provinces is greater. In the long run, the efficiency of China's marine green aquaculture will slowly evolve to a high-level state, and it is particularly important to break the "self-locking trap" of the low-level state. (2) The differences in mariculture yield among coastal provinces are the main factor affecting the spatial imbalance of green mariculture efficiency in China. Promoting the development of low-carbon, resource-saving and high-added-value mariculture products and achieving a win–win situation of economic and ecological benefits is an important means to alleviate the spatial imbalance of China's mariculture efficiency. (3) There is a certain polarization trend in the efficiency of marine green aquaculture in China, and the polarization degree shows an overall upward trend. Compared with the northern and eastern marine economic circles, the spatial polarization of green aquaculture efficiency in the southern marine economic circle is the lowest. During the observation year, the change in green aquaculture efficiency in coastal provinces did not converge into minority groups, and the main reason for spatial polarization was that there was a large gap in green aquaculture efficiency among coastal provinces. The research results can provide a reference for accelerating the green transformation of mariculture and promoting the high-quality development of fisheries.

Keywords: seawater green culture efficiency; spatial disequilibrium and polarization; identity-alienation framework; QAP method

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1. Introduction

Accelerating the green transformation of mariculture and building the spatial pattern, industrial structure and production mode of the green development of mariculture fisheries are not only an important path to promoting the high-quality development of fisheries but also the only way to promote the transformation of China into a country with a strong fishing industry and with an accelerating construction of agricultural power. The "14th Five-Year Plan" period is an important window to promote green and healthy aquaculture and improve the modernization level of the fishery industry. Only by promoting the resource-saving, environmentally friendly, green and low-carbon development of the marine aquaculture fishery can we continue to promote the green transformation of mariculture in China. The report to the 20th CPC National Congress clearly pointed out that we should accelerate the green transformation of the development model, further promote environmental pollution prevention and control, improve the diversity, stability and sustainability of ecosystems, and actively yet prudently promote carbon peak and carbon neutrality. We must closely focus on two aspects of low-carbon, green and ecological environmental protection to promote China's green seawater aquaculture. The "Several Opinions on Accelerating the Green Development of Aquaculture Industry" jointly issued by 10 ministries and commissions proposed to closely focus on high-quality development, integrate the concept of green development into the whole process of mariculture production, and strengthen the innovation of the green development system and mariculture processes. It is worth noting that, on the one hand, the green transformation of mariculture in China started late. Although certain achievements have been made, there is still a large gap compared to developed countries. On the other hand, considering the different resource endowments, location conditions and local policies of coastal provinces, there may be an obvious spatial disequilibrium in the efficiency of marine green aquaculture in China. At present, China is facing the severe challenge of unbalanced and inadequate development, and the spatial imbalance of and polarization trend in the efficiency of marine green aquaculture are barriers to achieving the high-quality development of fisheries. There is an urgent need to solve these key problems to build a country with a strong fishery industry.

To promote the green transformation of mariculture in China, it is necessary to accurately grasp the connotations of green mariculture. From the perspective of policy tools, marine green aquaculture can be understood as promoting green technology innovation, mechanisms and system innovations through the formulation of green development plans and the establishment of standards for marine aquaculture fisheries to realize the harmonious coexistence of human beings, aquaculture production activities and the marine ecological environment [1–3]. From the perspective of fishery carbon sinks, marine green aquaculture can be understood as a fishery production activity that can give full play to the carbon sequestration capacity of aquatic organisms, form carbon sinks and help to directly or indirectly reduce carbon emissions [4–6]. From the perspective of the whole process of the industry, green seawater aquaculture can be defined as a new model of whole-process green development with the goal of promoting the harmony and unity of humans and nature, and the sustainable development of mariculture is guided by green consumer demand, supported by green aquaculture scientific and technological innovations, and driven by institutional and mechanism reforms [7,8]. At present, there are two mainstream methods to measure the efficiency of green mariculture. One is Stochastic Frontier Analysis (SFA), which is based on the parametric method and uses the unexpected output to construct the translog production function to measure the efficiency of mariculture [9]. The other method, based on non-parametric Data Envelopment Analysis (DEA), is the Super-SBM model that uses the unexpected output to measure the efficiency of green seawater aquaculture [10,11] or the SBM-GML model that uses the unexpected output to measure green TFP [12,13].

Spatial disequilibrium and spatial polarization are closely related and different [14–16]. Generally speaking, most studies use a series of inequality indicators to analyze spatial disequilibria, but the use of an inequality index cannot fully reflect the changes in the distribution of the measured indicators [17–19]. The polarization effect indicates that two or more groups have different distributions of the measured index, emphasizing that the members of the group are clustered around the local mean and there are large differences between the groups—i.e., there is alienation between the groups. However, a non-equilibrium reflects that minority groups occupy a large proportion of the measured indicators, emphasizing the dispersion of regional members from the global mean regardless of whether there is clustering. Therefore, the urgent questions to be addressed are as follows: is the degree of spatial imbalance in the green marine aquaculture efficiency in China increasing or shrinking and does it clearly showing a trend towards polarization? However, there is little literature on the spatial disequilibrium and polarization trend of marine green aquaculture efficiency, and there is a lack of literature on their formation mechanisms. The existing literature mainly analyzes the different performances of marine green aquaculture efficiency in different regions based on time series and regional comparisons of marine green aquaculture efficiency [11,13,20], or the studies focus on the spatial spillover effect of influencing factors on the efficiency of marine green aquaculture in surrounding regions [7,21].

The existing literature has provided a rich reference for the development of this study, but there are still some areas that can be expanded upon. This research aims to create a beneficial supplement to the relevant research on the spatial imbalance of marine green aquaculture efficiency in China.

2. Research Methods and Data Sources

2.1. Consideration of the Super-SBM Model with Undesired Output

Compared with the traditional DEA model, the Super-SBM model is more accurate and efficient and has more advantages in the horizontal comparison of decision units (DMUs). It not only fully reflects the relaxation improvement values of each input and output but also distinguishes the efficiency values of DMUs when the efficiency values are all 1, which can effectively solve the relaxation phenomenon of inputs and outputs and the juxtaposition problem. This research selected the relevant data of nine coastal provinces in China—a total of nine DMUs. Each DMU consists of three parts: an input, expected output and unexpected output, which are denoted by q, w and e, respectively. There is a input in the process of mariculture in each province, which is denoted as q_a^i, indicating the input value of the i production unit in the j year; type b is the expected output, denoted as w_b^i, which represents the expected output value of production unit i in year j; type c is the undesired output, denoted by e_c^i, which represents the undesired output value of production unit i in year j. In Equation (1), θ^* represents the efficiency value; λ_i^x and λ_i^y represent the weights of each input value and output value of the production unit, respectively; and s_a^x, s_b^y and s_c^z represent relaxation variables.

$$\theta^* = \min \frac{1 - \left(\frac{1}{A}\sum_{a=1}^{A}\frac{s_a^q}{q_a^{i\prime}}\right)}{1 + \left[\frac{1}{B+1}\left(\sum_{b=1}^{B}\frac{s_b^w}{w_b^{i\prime}}\right) + \sum_{c=1}^{C}\frac{s_c^e}{e_c^{i\prime}}\right]}$$

$$s.t.\begin{cases} \sum_{i=1}^{I}\lambda_i^q q_a^i - s_a^q = q_a^{i\prime}, a = 1, \ldots, A \\ \sum_{i=1}^{I}\lambda_i^w w_b^i - s_b^w = w_b^{i\prime}, b = 1, \ldots, B \\ \sum_{i=1}^{I}\lambda_i^e e_c^i - s_c^e = e_c^{i\prime}, c = 1, \ldots, C \\ \lambda_i^q \geq 0, s_a^q \geq 0, s_b^w \geq 0, s_c^e \geq 0, i = 1, 2, \ldots, I \end{cases} \tag{1}$$

2.2. Kernel Density Estimation

As a non-parametric estimation method widely used in the study of regional gaps, kernel density estimation has a low dependence on the model, has good robustness and can better reflect the overall status and spatial and temporal distribution characteristics of marine green aquaculture efficiency [22–25]. Therefore, this research used a three-dimensional kernel density estimation based on the Gaussian kernel function, and the specific formula is as follows [26,27]:

$$\begin{cases} f(x) = \frac{1}{mh}\sum_{i=1}^{n} k\left(\frac{x - X_i}{h}\right) \\ k(x) = \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{x^2}{2}\right) \end{cases} \tag{2}$$

In Formula (2), $f(x)$ is the marine green aquaculture efficiency value of coastal province m, m is the number of provinces, X_i is the probability density function, k is the Gaussian kernel function, and h is the bandwidth, which is used to adjust the precision, with a smaller bandwidth indicating higher precision.

2.3. Gini Coefficient, MLD Index, Theil Index

The *Gini* coefficient (GINI), *MLD* index (GE_0) and *Theil* index (GE_1) have been widely used in the study of spatial disequilibrium, and they have certain complementarity [28–30]. The *Gini* coefficient is a common measure of inequality used to measure the degree of inequality in a set of data or distribution. Its value ranges from 0 to 1. The higher the Gini coefficient, the higher the degree of inequality. The *MLD* index and *Theil* index mainly use the concept of entropy in information theory to calculate the degree of inequality, and their values range between 0 and 1. If an individual deviates from the mean, the spatial disequilibrium is stronger. Specifically, the *Gini* coefficient is more sensitive to changes at the middle level, the *MLD* index is more sensitive to changes at the bottom part, and the *Theil* index is more sensitive to changes in the upper part [31–33]. The *Gini* coefficient, *MLD* index and *Theil* index are calculated as follows:

$$\begin{cases} GINI = \frac{2}{n^2\mu}\sum\limits_{i=1}^{n} ie_i - \frac{n+1}{n} \\ GE_0 = \frac{1}{n}\sum\limits_{i=1}^{n} \ln\frac{e_i}{\mu} \\ GE_1 = \frac{1}{n}\sum\limits_{i=1}^{n} \frac{e_i}{\mu}\ln\frac{e_i}{\mu} \end{cases} \tag{3}$$

The larger the $GINI$, GE_0 and GE_1 values, the greater the spatial disequilibrium of the marine green aquaculture efficiency. In Equation (3), n is the number of coastal provinces; μ is the mean value of green aquaculture efficiency in seawater, and i indicates the coastal province and its value ranges from 0 to n. e_i is the value of the marine green aquaculture efficiency in region i after the aquaculture efficiency is ranked from lowest to highest.

2.4. Markov Chain

In this research, the Markov Chain method was used to analyze the dynamic evolution trend of marine green aquaculture efficiency in China. The core idea of a Markov chain is to construct a Markov transfer matrix to describe the dynamic evolution of marine green aquaculture efficiency in each province. Specifically, a Markov chain is essentially a random process and satisfies $\{x(t), t\in T\}$, where $x(t)$ is any value of finite state space, L, and has a first-order no aftereffect property, and T is the observation period of the study sample [34–36]. The variable x has states j and I in periods t and $t-1$, respectively, and states in other periods are i_k (k = 0, 1, . . ., $t-2$). p_{ij} is the state transition probability, which is the probability of a state transition occurring, and the no aftereffect property means that the state of the variable x at period t is only related to the state of the previous period, $t-1$, and not to the state of the earlier period. The specific formula is as follows:

$$P\{x(t) = j|x_{t-1} = i_{t-1}, x_{t-2} = i_{t-2}, \ldots, x_0 = i_0\} = \{x(t) = j|x_{t-1} = i_{t-1}\} \tag{4}$$

$$P = p_{ij} = \begin{bmatrix} p_{11} & p_{12} & p_{13} & \cdots \\ p_{21} & p_{22} & p_{23} & \cdots \\ p_{31} & p_{32} & p_{33} & \cdots \\ \cdots & \cdots & \cdots & \cdots \end{bmatrix}, \ p_{ij} \geq 0, \ \sum_{j\in n} p_{ij} = 1, \ i,j \in n \tag{5}$$

In Equations (4) and (5), the green aquaculture efficiency of China's seawater is divided into n states, and an $n \times n$ transfer matrix, p_{ij}, can be obtained, which represents the probability that the state j of the green aquaculture efficiency of China's seawater in the current period will be transformed into state i in the next period, and all state transition probabilities constitute the state transition probability matrix, P. The maximum likelihood method was used to estimate the state transition probability, and the specific formula is as follows:

$$p_{ij} = \frac{n_{ij}}{n_i} \tag{6}$$

$$F_{t+r} = F_t \times P^r \tag{7}$$

In Equations (6) and (7), n_i is the occurrence times of state i, n_{ij} is the number of times state i changes to state j, Ft is the initial distribution vector, and F_{t+r} is the state vector after period r. With continuous increase in r, the state transition matrix, P^r, will converge to the limit matrix of rank 1, which means that the space as a whole enters a state of convergence, and finally the steady state distribution of the green aquaculture efficiency in Chinese seawater can be obtained.

2.5. QAP

After analyzing the spatial disequilibrium of marine green aquaculture efficiency, it is necessary to further analyze the influencing factors. When discussing the efficiency of marine green aquaculture, the existing studies usually only analyze the impact of explanatory variables on the regional efficiency gap of marine green aquaculture but fail to measure the impact of the disequilibrium of explanatory variables on the regional efficiency gap of marine green aquaculture. Since there may be multicollinearity and autocorrelation problems among the explanatory variables [37–39], the lack of bias in the regression results will be affected. The QAP model does not need the assumption of independence and a normal distribution, and it can handle the collinearity of relational data better. Therefore, the QAP model is used to analyze relational data, and the results obtained are more robust [40–42]. In this research, the QAP model was used to analyze the factors affecting the efficiency of marine green aquaculture. With the difference matrix of the marine green aquaculture efficiency as the explained variable and the difference matrix of the number of marine aquaculture professionals, mariculture area, per capita disposable income of fishermen, mariculture production and the number of fishermen technical training programs as the explanatory variable, the relationship model is constructed as follows:

$$Y = \beta_0 + \beta_1 x + \varepsilon \tag{8}$$

In Equation (8), Y is the explained variable—that is, the difference matrix of marine green aquaculture efficiency. β_0 and β_1 are the parameters to be estimated, and X is the explanatory variable. Five difference matrix variables, including the number of mariculture professionals (PEM), mariculture area (MA), per capita disposable income of fishermen (PF), mariculture production (MC) and the number of fishermen technical training programs (FT), are random disturbance terms. Different from the attribute measurement model, the data form of the difference matrix variable is an n-order square matrix, and the specific formula is as follows:

$$Y = \begin{bmatrix} 0 & C_{1,2} & \cdots & C_{1,n-1} & C_{1,n} \\ C_{2,1} & 0 & \cdots & C_{2,n-1} & C_{2,n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ C_{n-1,1} & C_{n-1,2} & \cdots & 0 & C_{n-1,n} \\ C_{n,1} & C_{n,2} & \cdots & C_{n,n-1} & 0 \end{bmatrix}, X_q = \begin{bmatrix} 0 & C_{q,1,2} & \cdots & C_{q,1,n-1} & C_{q,1,n} \\ C_{q,2,1} & 0 & \cdots & C_{q,2,n-1} & C_{q,2,n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ C_{q,n-1,1} & C_{q,n-1,2} & \cdots & 0 & C_{q,n-1,n} \\ C_{q,n,1} & C_{q,n,2} & \cdots & C_{q,n,n-1} & 0 \end{bmatrix} \tag{9}$$

In Equation (9), C_{ij} is the difference level of the explained variables between two provinces, and $C_{q,i,j}$ is the difference level of the explained variables between two provinces, $q \in [1,5]$, which is obtained according to $C_i - C_j$ and $C_{q,i} - C_{q,j}$, respectively. The main diagonal is the difference between the same province variables, all of which are 0.

2.6. Wolfson Index, DER Index, EGR Index

Foster and Wolfson discussed the relationship between the *Lorenz* curve and polarization curve when they introduced polarization to study the decline of the middle class in the United States and Canada and proposed a range-free method based on partial ranking to measure the degree of polarization [43]. The Wolfson index is based on the following formula:

$$FW = 2 \times \left[2 \times \left[\frac{1}{2} - Lorenz(0.5)\right] - G\right] \frac{\mu}{Median} \tag{10}$$

In Equation (10), *Lorenz*(0.5) is the share of the green aquaculture efficiency values of low level seawater, which accounts for 50% of the total of the province, G is the Gini coefficient, μ is the mean of green aquaculture efficiency in seawater, and *Median* is the median of the green aquaculture efficiency in seawater.

Based on the "identification-alienation" framework proposed in [44], the authors of [45] proposed the DER index. This index divides different groups using the income density function, which can solve the problem of random sample grouping when measuring income polarization. "Identity" refers to the process of individuals entering different groups in the process of polarization, and individuals in the same group have similar properties. "Alienation" refers to the obvious differences between individuals in different groups, which can lead to many conflicts. The specific formula is as follows:

$$DER = P_a(f) = \iint f(x)^{1+a} f(y)|x-y|dxdy \tag{11}$$

In Equation (11), a is a sensitivity parameter, which satisfies $a \in [0.25, 1]$. x and y are the marine green aquaculture efficiency values of two provinces, and the alienation of the marine green aquaculture efficiency between the two provinces is $|x-y|$. The density functions, $f(x)$ and $f(y)$ of x and y, are the identities of marine green aquaculture efficiency, x and y, respectively. Equation (11) can be further written as Equation (12):

$$\begin{cases} DER = P_a(F) = \int f(y_i) a(y_i)^a dF(y_i) \\ a(y) \equiv \mu + y(2F(y) - 1) - 2 \int\limits_{-\infty}^{y} xdF(X) \end{cases} \tag{12}$$

It is assumed that the marine green aquaculture efficiency, y_i, is randomly independent and uniformly distributed, and $y_1 \leq y_2 \leq \ldots \leq y_n$. $F(y)$ is the income distribution function. The DER index can be further expressed as Equation (13):

$$\begin{cases} DER = P_a(F) = n^{-1} \sum\limits_{i=1}^{n} \hat{f}(y_i)^a \hat{a}(y_j) \\ a(y_i) \equiv \mu + y_i\left(\frac{2}{n}(i-1) - 1\right) - \frac{1}{n}\left(2\sum\limits_{j=1}^{i-1} y_i + y_j\right) \end{cases} \tag{13}$$

In Equation (13), $f(y_i)^\alpha$ is the result of the estimation based on non-parametric kernel density, and μ is the mean value of the marine green aquaculture efficiency. The *DER* index is further decomposed, and the specific formula is as follows:

$$\begin{cases} DER = \bar{\imath}(a) \times \bar{\ell}(a) \times (1+\rho) \\ \bar{\imath}(a) = \int f(y)^{1+a} dy \\ \bar{\ell}(a) = \iint f(x)|x-y|dxdy \end{cases} \tag{14}$$

In Formula (14), $\bar{\imath}(a)$ is the average identification of the green aquaculture efficiency in seawater, $\bar{\ell}(a)$ is the average identification of the marine green aquaculture efficiency, ρ

is the average identification of the efficiency of marine green aquaculture, and its specific formula is shown in Equation (15):

$$\begin{cases} \rho = \frac{\operatorname{cov}[\iota(a), a(y)]}{\bar{\iota}(a)\bar{a}} = \frac{1}{\bar{\iota}(a)\bar{a}} \int [\iota(a) - \bar{\iota}(a)][a(y) - \bar{a}]dy \\ \iota(a) = f(y)^a \\ a(y) = \int f(x)|x - y|dx \end{cases} \tag{15}$$

Based on the intra- and inter-group heterogeneity of different groups, Esteban and Ray proposed that individuals within a group would naturally gather, while individuals within a group would naturally alienate, thus building an ER model [44]. Suppose that marine green aquaculture efficiency follows a normal distribution with interval $[q,w]$ and density f, and the expected efficiency is $\mu = 1$, then $\rho = (y_0, y_1, \ldots, y_n; \pi_1, \ldots, \pi_n; \mu_1, \ldots, \mu_n)$, where $q = y_0 < \ldots < y_n = w$ for a total of n groups, and y_n is the average marine green aquaculture efficiency of each group.

$$\begin{cases} ER(q,\rho) = \sum\limits_i \sum\limits_j \pi_i^n |\mu_i - \mu_j| \pi_i \pi_j \\ \pi_i = Prob(y_{i-1} < y < y_i) = \int\limits_{y_{i-1}}^{y_i} f(y)dy \\ \mu_i = E(y|y_{i-1} < y < y_i) = \frac{1}{\pi_i} \int\limits_{y_{i-1}}^{y_i} yf(y)dy \\ i = 1, \ldots, n \end{cases} \tag{16}$$

In Equation (16), π_i is the probability distribution of group i individuals, and μ_i is the probability distribution of group i's marine green aquaculture efficiency. π_i^n is the homogeneity of individuals within a group, $|\mu_i - \mu_j|$ is the heterogeneity of individuals between groups, and a is the sensitivity parameter, satisfying $a \in [1,1.6]$. When $a = 0$, the ER index is equal to the Gini coefficient. Improving on the work of Esteban et al., Duclos, and Esteban et al., the new formula of the ER index is as follows [45,46]:

$$\begin{cases} P(f;q,\beta) = ER(q,\dot{\rho}) - \beta\tau(f,\dot{\rho}) \\ \dot{y}_i = \lambda\dot{\mu}_i + (1-\lambda)\dot{\mu}_{i+1}, \lambda = \frac{\dot{\pi}_i}{(\dot{\pi}_i + \dot{\pi}_{i+1})} \end{cases} \tag{17}$$

In Equation (17), $\tau(f,\dot{\rho})$ is the random error term, reflecting the differences in average marine green aquaculture efficiencies of individuals in different groups, β is the coefficient of random error, reflecting the sensitivity of clustering within the group, and $\dot{\rho}$ is the optimal grouping set—that is, the separation point of any two adjacent groups is the average marine green aquaculture efficiency of two groups of individuals.

According to the above improved ER index, assuming that y is the efficiency separation point of the optimal two groups, π is the probability distribution function of the lower efficiency group, $L(\pi)$ is the Lorentz curve at π and the density function is f, the EGR index is as follows:

$$\begin{cases} P(f;q,\beta,y) = [\pi^q + (1-\pi)^q][\pi - L(\pi)] - \beta\{G - [\pi - L(\pi)]\} \\ \mu_1 = \frac{L(\pi)}{\pi}, \mu_2 = \frac{[1-L(\pi)]}{(1-\pi)} \\ \tau(f,\rho) = G - [\pi - L(\pi)] \end{cases} \tag{18}$$

In Equation (18), G is the *Gini* coefficient and the value of β in this study is 1.

2.7. Data Sources and Variable Descriptions

Due to the serious lack of data for Tianjin and Shanghai, the data of the other nine coastal provinces excluding Hong Kong, Macao and Taiwan were used. The data used in this study were as follows: the data for mariculture fisheries are from the China Fishery

Statistical Yearbook; the original data on the pollution production coefficients are from the Manual of the First National Pollution Source Census of Aquaculture Pollution Source; the original data for the carbon emission coefficients are from the IPCC National Greenhouse Gas Inventory Guide; and the original data for the fuel consumption conversion coefficients of marine fishing vessels are from the Reference Standard for the Calculation of the Oil Amount of Oil Subsidy for Domestic Motor Fishing Vessels; the energy (diesel and electricity) and standard coal data are from the China Energy Statistical Yearbook. The input and output indicators are shown in Table 1.

Table 1. Index system for measuring the efficiency of green seawater aquaculture.

Index	Variables	Indicator Description	Unit
Input	Fixed assets per unit of breeding area	Marine motor fishing vessels (production fishing vessels) at the end of the year/mariculture area	Kilowatt/hectare
	Farming area per unit of labor force	Mariculture area/number of mariculture professionals	Hectare/pcs
	Fishery seedlings per unit of cultivation area	Number of mariculture seedlings/mariculture area	100 million tails/hectare
	Labor force per unit of breeding area	Number of professionals in mariculture/number of professionals in fisheries	%
	Technical training intensity	Number of fishermen technical training × number of professional mariculture practitioners/number of professional fishery aquaculture practitioners	—
Expected output	Economic output per unit of labor	Mariculture output value/number of mariculture professionals	100 million CNY/pcs
	Carbon sequestration per unit of farming area	Carbon sequestration in mariculture/mariculture area	Tons/hectare
Undesirable output	Nitrogen and phosphorus pollution per unit of farming area	Nitrogen and phosphorus pollution output/mariculture area	Tons/hectare
	Carbon emissions per unit of farming area	Mariculture carbon emissions/mariculture area	Tons/hectare

Some special notes on the treatment of indicators are as follows. This study adopted the methodology of Shao et al. [47] to measure the carbon sequestration per unit of aquaculture area. The amount of carbon sequestration produced in the cultivation of shellfish and algae was calculated, and the amount of carbon sequestration in mariculture was obtained. Based on the method by Shi et al. [11], this research selected nitrogen and phosphorus pollution per unit of aquaculture area and carbon emissions per unit of aquaculture area as the undesired output indicators of marine green aquaculture efficiency. Using the method by Xu et al. [48], the amount of nitrogen and phosphorus pollution per unit of breeding area were measured. From the two aspects of feeding culture and non-feeding culture, the nitrogen and phosphorus pollution yields were obtained by calculating and adding the total. Based on the method by Shi et al. [11], the carbon emissions per unit of farming area were measured. Based on the energy combustion and power consumption, the carbon emissions of mariculture were calculated and added together.

When the QAP regression was used for the empirical research, UCINET6.0 was used to analyze the effect of various influencing factors on the efficiency of marine green aquaculture. Considering the availability and reliability of data, the following variables were selected by referring to the method by Shi et al. [11]: the number of mariculture professionals, mariculture area, per capita disposable income of fishermen, mariculture output and the number of technical training programs for fishermen. The number of professionals in mariculture can reflect the level of human capital in the mariculture fishery industry. The index of the mariculture area can better reflect the use of the mariculture sea area. The per capita disposable income of fishermen is an important variable that reflects the income level and living conditions of fishermen. The yield of mariculture reflects the yield of mariculture in tons. The number of fishermen technical training programs can reflect the intensity of investment in technical training for fishermen. See Table 2 for details.

Table 2. Selected influencing factors of seawater green culture efficiency.

Variables	Indicator Description	Unit
PEM	Number of professionals working in mariculture	pcs
MA	Mariculture area	hectare
PF	Per capita disposable income of fishermen	10 thousand CNY
MC	Mariculture yield	tons
FT	Number of fishermen technical training programs	pcs

3. Results and Analysis

3.1. Spatial Disequilibrium Analysis of Marine Green Aquaculture Efficiency in China

3.1.1. Efficiency Measurement of Marine Green Aquaculture

The mean values of marine green aquaculture efficiency in Liaoning Province, Hebei Province and Shandong Province were used to characterize the value of marine green aquaculture efficiency in the northern marine economic circle. The average values of marine green aquaculture efficiency in Jiangsu Province and Zhejiang Province were used to characterize the marine green aquaculture efficiency of the eastern marine economic circle. The mean values of marine green aquaculture efficiency in Fujian, Guangdong, Guangxi and Hainan were used to characterize the value of marine green aquaculture efficiency in the southern marine economic circle.

As can be seen from Figure 1, the fluctuation range of the efficiency of marine green aquaculture in China as a whole from 2006 to 2019 was [1.089, 1.336] and the efficiency values were all above 1, indicating that the efficiency of marine green aquaculture in China is relatively effective on the whole, but there is still room for improvement. In terms of the three major marine economic circles, the fluctuation ranges of marine green aquaculture efficiency in the northern, eastern and southern marine economic circles were [0.810, 1.360], [1.061, 1.352] and [1.239, 1.431], respectively, indicating that marine green aquaculture efficiency in the southern marine economic circle was higher than that in the northern and eastern marine economic circles. According to the fluctuation patterns, the fluctuation range of marine green aquaculture efficiency was the largest in the northern marine economic circle, followed by the eastern marine economic circle, and the southern marine green aquaculture efficiency is relatively stable. Specifically, the efficiency of marine green aquaculture in the northern marine economic circle was relatively ineffective in 2008, 2009 and 2017, which is closely related to the changes in the international political and economic situation. In fact, the efficiency of marine green aquaculture in the whole country also declined in the same years. Whether it was the global economic crisis in 2008 or the South China Sea dispute that began in 2016, they both hindered the development of the import and export trade of mariculture products in China to a certain extent [2,49], affecting the economic and ecological benefits of China's marine aquaculture fisheries.

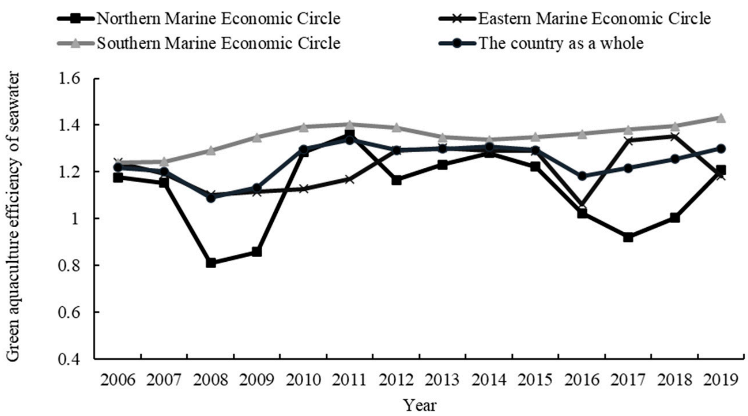

Figure 1. Diagrams of changes in the efficiency of seawater green aquaculture in the national, northern, eastern and southern marine economic circles.

The ArcGIS10.8 software was used for visualization of the results. According to the quartile method, namely, 0–1/4, 1/4–1/2, 1/2–3/4 and 3/4–1, the green aquaculture efficiency of seawater was divided into four categories: low level, lower level, higher level and high level, respectively. The spatial distribution maps of the efficiency of marine green aquaculture in China in 2006, 2010, 2015 and 2019 were drawn and is shown in Figure 2.

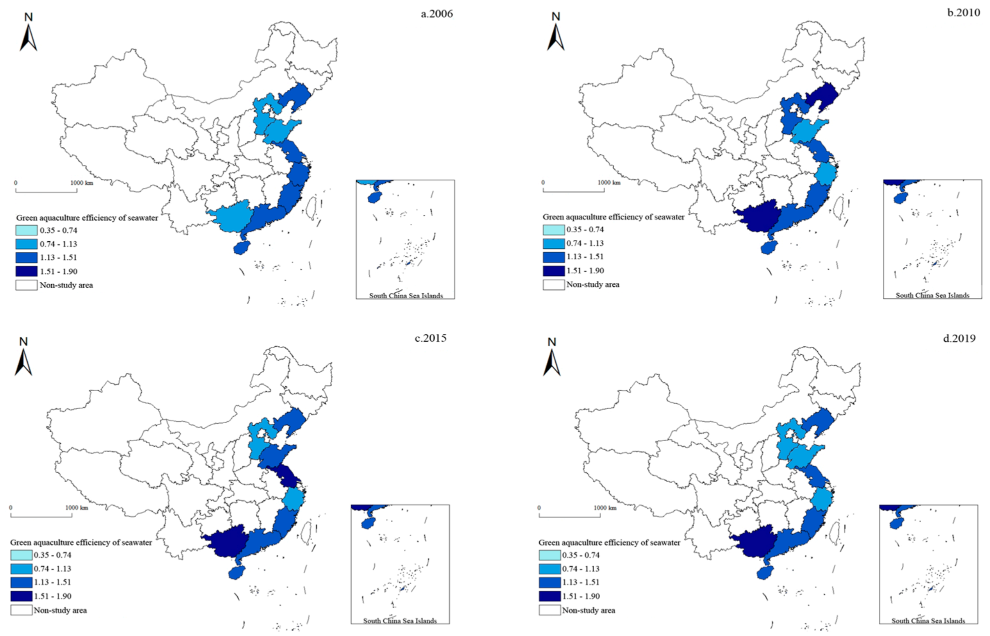

Figure 2. Spatio–temporal variation in seawater green aquaculture efficiency in China.

As can be seen from the time series in Figure 2, the marine green aquaculture efficiency fluctuated greatly in the nine coastal provinces of China. Except for Guangdong, Guangxi and Hainan, the state level of marine green aquaculture efficiency was relatively stable, and the other coastal provinces experienced state-level changes in the noted four years. From a geographical perspective, the state-level marine green aquaculture efficiency of the southern marine economic circle presented a concentrated distribution, and the efficiency of marine green aquaculture in different provinces had a large gap, which increased with the passage of time.

3.1.2. Analysis of Spatial Disequilibrium Characteristics of Marine Green Aquaculture Efficiency

Nuclear density estimation can analyze the spatial disequilibrium characteristics of green aquaculture efficiency in China's seawater from the perspectives of distribution position, distribution form, distribution ductility and polarization status to better understand the spatial–temporal evolution of green aquaculture efficiency in seawater and analyze its spatial disequilibrium and polarization characteristics. According to Equation (2), the kernel density maps of the national, northern, eastern and southern marine economic circles were obtained using Gaussian kernel density estimation and are shown in Figure 3.

As can be seen from Figure 3, the evolution of the nuclear density curve of the whole country and the three major marine economic circles had a right-shifting trend. Specifically, the overall efficiency of marine green aquaculture in China showed a slight upward trend, which is consistent with the above measurement results. Although China's mariculture green transformation started late with the promulgation of a series of policy documents supporting the green development of marine aquaculture fisheries, coastal provinces have accelerated the pace of mariculture green transformation, constantly improving the mechanisms and regulatory system of green mariculture [50,51] by increasing technological and human capital investments and promoting research into key technologies [52,53]. After a series of technological transformations and applications, the desirable output of marine green aquaculture has been significantly improved and the non-desirable outputs have been effectively reduced, which ultimately led to the increase in marine green aquaculture efficiency.

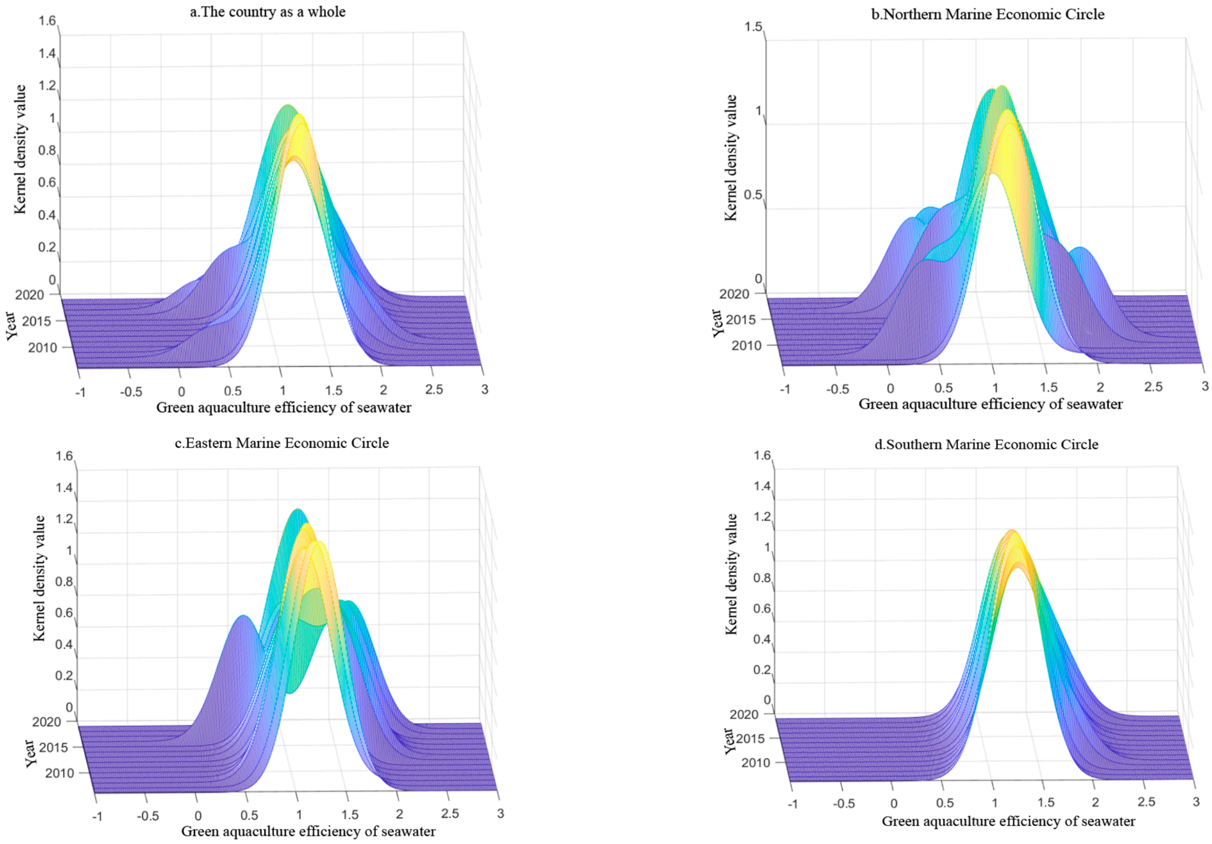

Figure 3. Three−dimensional kernel density maps of green seawater aquaculture efficiency in China.

In terms of the distribution pattern, the value of the main peak of the whole country and the three major marine economic circles became smaller and the width expanded, which indicates that the absolute difference between the whole country and the three major marine economic circles showed an increasing trend. Specifically, the distribution patterns of the whole country and the three marine economic circles were different, and the peak declined and degree of the width expansion was different. The absolute difference of the southern marine economic circle showed an increasing trend; however, this absolute difference was the smallest among the three marine economic circles.

In terms of distribution changes, the national, eastern and southern marine economic circles of the country were skewed to the right, while the northern marine economic circle was skewed to the left, mainly because there were coastal provinces with high marine green aquaculture efficiency in the eastern and southern marine economic circles and the coastal provinces with high efficiencies were more differentiated. The gap between coastal provinces with low efficiency, such as Guangxi and Jiangsu, was small, while in the northern marine economic circle, there were coastal provinces with low efficiency, such as Hebei. In addition, the distribution of the whole country and the three major marine economic circles showed a widening trend, indicating that the provinces with high marine green aquaculture efficiency will show a strong "Matthew effect", with their values higher than the average value of the regional marine green aquaculture efficiency and the distance from the average continuing to increase. As a result, the absolute difference between the whole country and the three major marine economic circles will be further expanded.

In terms of polarization, the whole country, eastern and northern marine economic circles have the characteristic of two-level differentiation, while the southern marine economic circle does not show polarization. Specifically, at the beginning of the observation period, there was no obvious polarization in the nuclear density curve of the three major marine economic circles, and the growth rate of the marine green aquaculture efficiency in each coastal province was different over time. The northern marine economic circle gradually showed a two-stage differentiation in the observation years and the main peak was always higher than the lateral peak, indicating that there was a certain gradient in the efficiency of marine green aquaculture but the green transformation of marine aquaculture in the northern marine economic circle was relatively synchronous. The southern marine economic circle always presented a unimodal distribution, indicating that there was no two-stage or multistage differentiation, but its nuclear density curve gradually expanded and broadened, and the efficiency of marine green aquaculture had a differentiation trend.

3.1.3. Analysis of the Degree of Spatial Disequilibrium of Marine Green Aquaculture Efficiency

The greater the value of the three indices, the greater the regional gap—that is, the degree of spatial disequilibrium is strong and vice versa. According to Equation (3), the Gini coefficient, Theil index, MLD index and the growth rate of the three indexes can be calculated, and the results are shown in Figure 4.

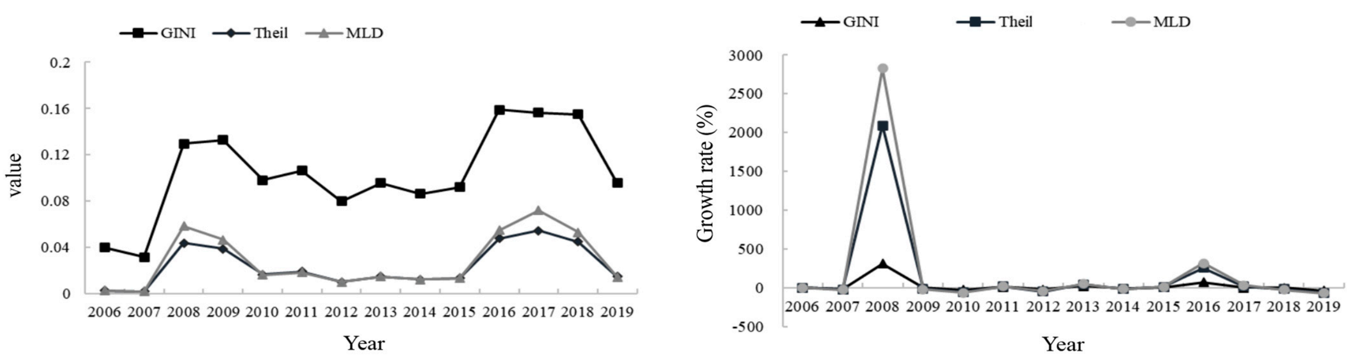

Figure 4. Spatial–disequilibrium degree and change in growth rate of seawater green aquaculture efficiency in China.

It can be seen from Figure 4 that the changing trends of the Gini coefficient, Theil index and MLD index of China's green seawater aquaculture efficiency were basically the same, showing a fluctuating upward trend of first rising, then falling, then rising and falling again. From 2007 to 2008, the Gini coefficient, Theil index and MLD index fluctuated significantly, and they all had significant upward trends. Compared with the coastal provinces at the medium level (the lower and higher levels mentioned in Section 3.1.1), the regional differences in the coastal provinces at the high level (the high level mentioned in Section 3.1.1) and the low level (the low level mentioned in Section 3.1.1) are more obvious. From 2012 to 2017, the differences in the marine green aquaculture efficiency in the high-, medium- and low-level coastal provinces in China gradually increased. The Gini coefficient reached the highest value in 2016 and the Theil index and MLD index reached their highest values in 2017, indicating that there was a large regional gap in marine green aquaculture efficiency in China and a large degree of spatial disequilibrium. From 2018 to 2019, the efficiency of marine green aquaculture in China declined year by year, and the degree of spatial disequilibrium narrowed.

The Gini coefficient, Theil index and MLD index of the efficiency of marine green aquaculture in China changed greatly between 2008 and 2016 (increased from 310.13%, 2090% and 2830%, respectively, in 2008 to 72.93%, 256.72% and 313.53%, respectively, in 2016). It can be seen that when the international political and economic situation changed significantly, the spatial disequilibrium of China's marine green aquaculture efficiency was further enhanced. Whether it is the global economic crisis or the geopolitical conflict caused by the South China Sea dispute, it affected the improvement and coordinated development of marine green aquaculture efficiency through the free flow of production factors, trade development setbacks, and the pace of technical cooperation slowdown, which leads to the differentiation of the green development of marine aquaculture fisheries in various coastal provinces [54–56].

The Gini coefficient was always greater than the Theil index and MLD index, which indicates that the coastal provinces with a medium level of marine green aquaculture efficiency have a large regional difference and a large degree of spatial disequilibrium, while the coastal provinces with low and high levels of marine green aquaculture efficiency have a small regional gap and a small degree of spatial disequilibrium. From 2006 to 2019, the Gini coefficient, Theil index and MLD index of the efficiency of marine green aquaculture in China increased by 140.201%, 473.077% and 437.037%, respectively, and the degree of change of the Theil index was greater than that of the Gini coefficient and MLD index. The results showed that the regional gap in the coastal provinces with a high level of marine green aquaculture efficiency changed obviously, and the regional gap in the coastal provinces with a medium level changed the least compared with the coastal provinces with high and low levels of efficiency.

3.1.4. Dynamic Evolution of Spatial Non-Equilibrium Marine Green Aquaculture Efficiency

When the efficiency value was in the range of [0, 0.741], [0.741, 1.128], [1.128, 1.514] or [1.514, 1.901], the efficiency state of seawater green aquaculture was categorized as low level, lower level, higher level or high level, respectively. The maximum likelihood method was used to obtain the state transition matrix of seawater green aquaculture efficiency, which is shown in Table 3.

Table 3. State transition probability matrix of seawater green aquaculture efficiency.

$t/t+1$	Low Level	Lower Level	Higher Level	High Level
Low level	0.9194	0.0806	0	0
Lower level	0.0048	0.8619	0.1333	0
Higher level	0	0.0097	0.8786	0.1117
High level	0	0	0.0155	0.9845

As shown in Table 3, the value on the diagonal represents the self-locking probability of each state, the value on the right of the diagonal represents the state transition probability, and the value on the left of the diagonal represents the state degradation probability. The self-locking probabilities of the low, lower, higher and high levels were 91.94%, 86.19%, 87.86% and 98.45%, respectively. The self-locking probability of the high-level state was the highest, reaching 98.45%, which indicates that any coastal province with a high level of marine green aquaculture efficiency has a 98.45% probability of maintaining a high level in the next year, and the minimal state degradation probability is conducive to promoting the green development of marine aquaculture fisheries. The self-locking probability for a low level state was 91.94%, second only to the high level's self-locking probability, and the low level's self-locking probability is not conducive to the green transformation of mariculture in China. The high self-locking probability of the low-level and high-level states indicates that there are both opportunities and challenges in the process of the gradual transformation of China's marine green aquaculture efficiency from spatial disequilibrium to spatial equilibrium. For a long period of time in the future, breaking the "self-locking trap" of a low-level state is the key to realizing the balanced spatial development of China's marine green aquaculture efficiency. Compared with the low-level and high-level states, the self-locking probability of the lower-level and higher-level states was smaller but higher than 80% (86.19% and 87.86%, respectively). By comparing and analyzing the values on the right side of the diagonal, we can see that the "state transition" of the efficiency of marine green aquaculture in China mainly occurred between two adjacent states, there was no cross-stage transition phenomena, and the state transition mainly occurs in the higher-level and high-level states. In the case of state transitions, the probability of "lower level → higher level" was the highest, which was 13.33%. The probability of "higher level → high level" was the second highest (11.17%). The probability of "low level → lower level" was the lowest (8.06%). In addition to the state transition, there was also the possibility of state degradation in the marine green aquaculture efficiency in China, but its probability was generally low. Among them, the highest probability of degradation was from a high-level to higher-level state (1.55%), followed by the degradation from a higher-level to lower-level state (0.97%), and the lowest probability of degradation was from a lower-level to low-level state (0.48%). In summary, during the dynamic evolution of the spatial distribution of marine green aquaculture efficiency in China, the state self-locking situation was more serious in the coastal provinces with a low level status, the state transition phenomenon mainly occurred in two ways ("lower level → higher level" and "higher level → high level"), and the risk of state degradation of marine green aquaculture efficiency in China is small.

As can be seen from Table 4, the long-term equilibrium of green aquaculture efficiency in China was at the higher level and high level. Among them, the high level accounted for the highest proportion, reaching 85.4%, followed by the higher level, accounting for 13.1%, while the low level and lower level accounted for the smallest proportions at 0.2% and 1.3%, respectively. Compared with the initial distribution state of the marine green aquaculture efficiency in China, under the steady state distribution state, the proportion of high-level coastal provinces significantly increased, while the proportion of higher-level coastal provinces showed a significant contraction. Among them, the proportion of coastal provinces with a high level of marine green aquaculture efficiency increased by 68.7%, the proportion of higher level coastal provinces decreased by 40.9%, the proportion of lower level coastal provinces decreased by 23.3%, and the proportion of low level provinces decreased by 4.5%. This means that in the long run, China's marine green aquaculture efficiency will slowly evolve to a high level.

Table 4. Initial distribution and steady state analysis of seawater green culture efficiency.

Distribution	Low Level	Lower Level	Higher Level	High Level
Initial distribution	0.047	0.246	0.54	0.167
Steady state distribution	0.002	0.013	0.131	0.854

3.1.5. Factors Affecting the Spatial Disequilibrium of Marine Green Aquaculture Efficiency

From the above analysis, it can be seen that there was a significant spatial disequilibrium in the efficiency of marine green aquaculture in China. What causes these regional differences? What factors have a significant impact on the efficiency of marine green aquaculture in China? In order to better answer the above questions, this research uses the QAP method to analyze and explore the causes of the changes in the spatial imbalance of marine green aquaculture efficiency in China. The QAP regression analysis was conducted based on Equations (8) and (9), and the specific results are shown in Table 5. In this research, the absolute differences between the index means from 2006 to 2019 were used to construct a difference matrix for QAP regression to test the robustness of the model.

As can be seen from Table 5, the regression results for the factors affecting the efficiency of marine green aquaculture in China are relatively robust, and the mean matrix regression results were similar to the regression results of each year. On the whole, the difference in mariculture outputs among the coastal provinces was the main factor affecting the spatial disequilibrium of the efficiency of marine green aquaculture in China. Mariculture output determines the economic output of marine aquaculture fisheries to a certain extent. The rational selection and combination of aquatic seeds can promote the development of mariculture products [57,58] toward low carbonization, resource savings and higher added value [59,60]. Promoting mariculture production by taking into account the economic and ecological benefits can increase the efficiency of China's mariculture and lead to a spatial equilibrium. Although the differences in the number of professional mariculture practitioners and the number of technical training programs for fishermen among the coastal provinces were not the main influencing factors, they played a significant role. In the context of promoting the green transformation of mariculture, attention should also be paid to prevent the worsening of regional differences for these two influencing factors. Regional differences in the mariculture area and per capita disposable income of fishermen have significant but weak effects on the spatial disequilibrium of efficiency of mariculture in China. A possible reason is that in the context of urbanization and the development of fishermen, the contribution of the rising output value of marine aquaculture fisheries to fishermen's income shows a weak trend, and the short-term improvement of marine green aquaculture efficiency cannot significantly promote farmers' income [61]. In the current development of mariculture towards resource conservation, environmental friendliness and green and low-carbon development, increasing the area of mariculture cannot bring more economic benefits and its contribution to the efficiency of green mariculture is low [62]. More attention should be paid to improving the quality of mariculture areas, improving the comprehensive utilization efficiency of mariculture areas, and rationally developing and utilizing water resources. This will help improve the efficiency of marine green aquaculture.

Table 5. QAP regression of green aquaculture efficiency in seawater.

Variable	**2006**		**2010**		**2015**	
	Coefficient	***t* Value**	**Coefficient**	***t* Value**	**Coefficient**	***t* Value**
PEM	1.191 *	0.094	0.320 *	0.061	0.917 *	0.083
MA	0.367 ***	0.008	0.246	0.138	0.492 *	0.08
PF	0.072 *	0.063	0.089 **	0.042	0.054	0.421
MC	2.374 ***	0.008	6.542 **	0.034	0.775 *	0.084
FT	0.255 *	0.099	0.519 *	0.068	0.112 *	0.061
R^2	0.245		0.229		0.298	
p value	0.050 **		0.010 ***		0.056 *	

Variable	2019		Mean value	
	Coefficient	*t* value	Coefficient	*t* value
PEM	1.418 **	0.047	1.520 **	0.013
MA	0.355 *	0.081	0.649 ***	0.004
PF	0.345 *	0.052	0.072 **	0.049
MC	1.190 *	0.074	5.262 ***	0.001
FT	0.266 *	0.06	1.131 ***	0.000
R^2	0.304		0.282	
p value	0.030 **		0.001 ***	

Note: *, ** and *** indicate significance at the level of 10%, 5% and 1%, respectively.

3.2. Spatial Polarization Analysis of Green Aquaculture Efficiency in Seawater

The Gini coefficient, MLD index, Theil index and other indicators to measure the spatial disequilibrium of marine green aquaculture efficiency in China mainly analyze the average difference in marine green aquaculture efficiency in different provinces, which cannot reflect the degree of confrontation between different provinces and cannot explain the phenomenon of local aggregation in efficiency distribution. Spatial polarization pays more attention to inter-group alienation and intra-group identity. With the increase in inter-group alienation and intra-group identity, the degree of spatial polarization will gradually increase. It is worth noting that, on the one hand, if other conditions remain unchanged, intra-regional differences weaken and the whole tends to be balanced, but the degree of polarization may still increase. On the other hand, from the actual situation, polarization is one of the obstacles to the coordinated and adequate development between regions. Therefore, as a special form of spatial disequilibrium, it is necessary to study spatial polarization on the basis of spatial disequilibrium. The Wolfson index, DER index and EGR index of the efficiency of marine green aquaculture in China from 2006 to 2019 are shown in Table 6.

Table 6. The degree of spatial polarization of green aquaculture efficiency in seawater.

Year	Wolfson	DER					EGR		
		$\alpha = 0$	$\alpha = 0.25$	$\alpha = 0.5$	$\alpha = 0.75$	$\alpha = 1$	$\alpha = 1$ $\beta = 1$	$\alpha = 1.3$ $\beta = 1$	$\alpha = 1.6$ $\beta = 1$
2006	0.0372	0.0398	0.0504	0.0630	0.0782	0.0967	0.0191	0.0125	0.0080
2007	0.0244	0.0316	0.0409	0.0527	0.0677	0.0871	0.0132	0.0084	0.0052
2008	0.0829	0.1296	0.1153	0.1026	0.0914	0.0815	0.0583	0.0384	0.0252
2009	0.0845	0.1328	0.1191	0.1064	0.0950	0.0847	0.0655	0.0458	0.0323
2010	0.0786	0.0981	0.0971	0.0950	0.0926	0.0901	0.0458	0.0297	0.0191
2011	0.0821	0.1063	0.1031	0.0990	0.0948	0.0906	0.0500	0.0328	0.0211
2012	0.0652	0.0800	0.0848	0.0889	0.0927	0.0964	0.0368	0.0238	0.0150
2013	0.0935	0.0957	0.0976	0.0982	0.0981	0.0976	0.0487	0.0329	0.0222
2014	0.0761	0.0865	0.0898	0.0921	0.0938	0.0953	0.0418	0.0284	0.0193
2015	0.0796	0.0920	0.0946	0.0960	0.0968	0.0973	0.0439	0.0291	0.0192
2016	0.1108	0.1591	0.1411	0.1236	0.1077	0.0936	0.0711	0.0454	0.0284
2017	0.0963	0.1564	0.1361	0.1179	0.1020	0.0881	0.0674	0.0434	0.0276
2018	0.1107	0.1551	0.1379	0.1215	0.1066	0.0934	0.0634	0.0390	0.0229
2019	0.0829	0.0956	0.0962	0.0959	0.0952	0.0943	0.0456	0.0304	0.0202

As can be seen from Table 7, the three major polarization indices showed an overall upward trend. Take DER index, $\alpha = 0.25$, for example, which experienced a fluctuating upward trend of first rising, then falling, and then falling again, reaching the highest value of 0.1411 in 2016 and maintaining a high polarization value for three years from 2016 to 2018. This shows that there was a certain polarization trend in the efficiency of marine green aquaculture in China. For the polarization index with multiple parameters, the average increase in the EGR index was the highest at 144.764%, followed by the Wolfson Index (123.002%). The DER index increased the least (60.435%). From the comparative analysis of the α and β sensitivity values of the DER index and EGR index, it can be seen that although the values of the α and β parameters were different, almost all their corresponding polarization indices showed an increasing trend, which indicates that the results showing an increase in the polarization degree of the efficiency of green aquaculture in China's seawater from 2006 to 2019 are robust. In addition, the DER index (Gini coefficient) of $\alpha = 0$ was compared with the EGR index, and it was found that the larger the parameter α value, the smaller the corresponding EGR index value and the larger the gap with the Gini coefficient. This further verified the difference between the Gini coefficient and the polarization index. Compared with the Gini coefficient, the polarization index considers the identity of the members in the group, which demonstrates that it is necessary to use the polarization index to analyze the spatial polarization of the efficiency of marine green aquaculture in China. The changes in the three polarization indices of the three major marine economic circles from 2006 to 2019 are shown in Figure 5, where the setting parameters of the DER index were $\alpha = 0.5$ and $\alpha = 1.3$ and $\beta = 1$ for the EGR index.

Table 7. Decomposition table of DER index of seawater green aquaculture efficiency.

Year	DER Index	Alienation	Identity	Correlation $(1 + \rho)$
2006	0.0630	0.0398	1.2482	1.2673
2007	0.0527	0.0316	1.2676	1.3155
2008	0.1026	0.1296	0.8550	0.9255
2009	0.1064	0.1328	0.8624	0.9291
2010	0.0950	0.0981	0.9967	0.9718
2011	0.0990	0.1063	0.9726	0.9578
2012	0.0889	0.0800	1.0875	1.0222
2013	0.0982	0.0957	1.0193	1.0066
2014	0.0921	0.0865	1.0531	1.0114
2015	0.0960	0.0920	1.0375	1.0059
2016	0.1236	0.1591	0.8227	0.9440

Table 7. *Cont.*

Year	DER Index	Alienation	Identity	Correlation (1 + ρ)
2017	0.1179	0.1564	0.8236	0.9155
2018	0.1215	0.1551	0.8398	0.9324
2019	0.0959	0.0956	1.0206	0.9830

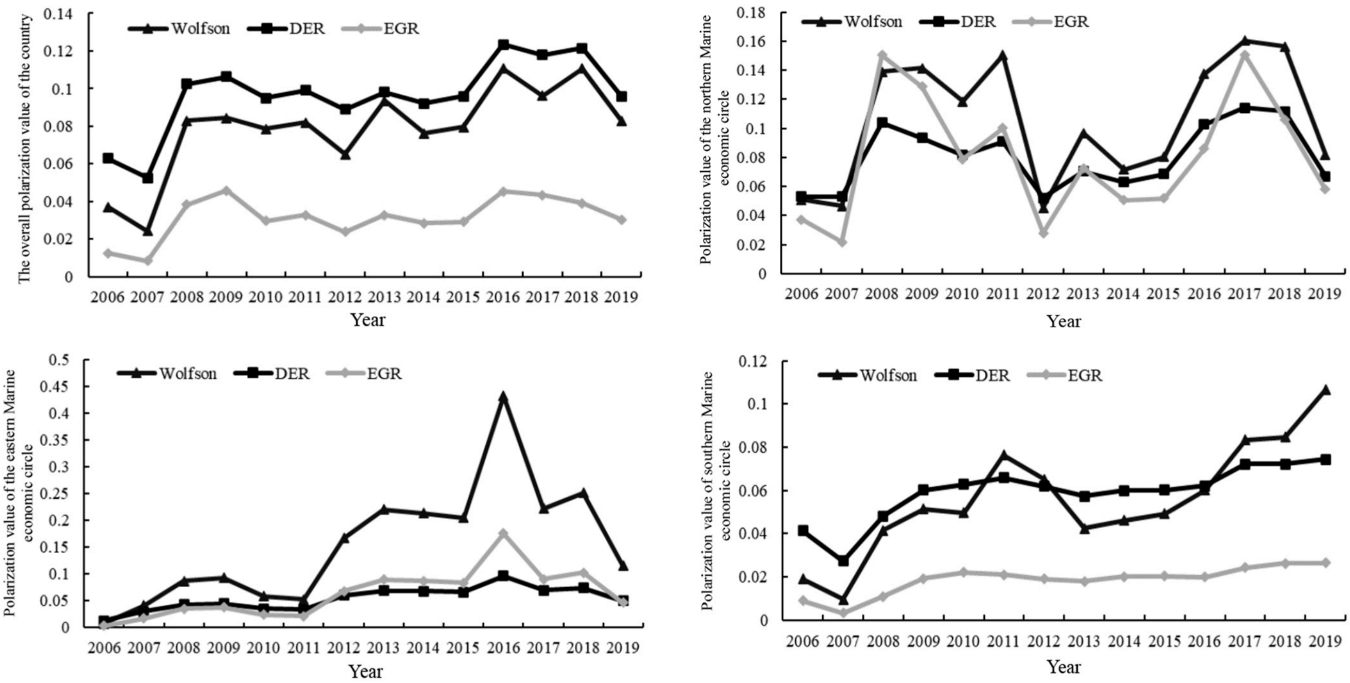

Figure 5. Changes in overall and sub-regional polarization index of seawater green aquaculture efficiency in China.

As can be seen from Figure 5, the three major polarization indices for the northern marine economic circle, as a whole, presented a fluctuating upward trend of first rising and then decreasing. The eastern marine economic circle presented an inverted "U"-shaped fluctuating upward trend of first rising and then decreasing, and the southern marine economic circle presented an overall upward trend. Therefore, over time, the spatial polarization degree of the efficiency of marine green aquaculture in the three marine economic circles was continuously improving. In terms of fluctuation amplitude, the eastern marine economic circle had the largest fluctuation degree, and the fluctuation ranges of the Wolfson index, DER index and EGR index were [0.008, 0.432], [0.013, 0.097] and [0.003, 0.176], respectively. The fluctuation ranges of the Wolfson index, DER index and EGR index were [0.045, 0.160], [0.052, 0.114] and [0.022, 0.151], respectively. The southern marine economic circle had the smallest fluctuation degree, and the fluctuation ranges of the Wolfson index, DER index and EGR index were [0.010, 0.107], [0.027, 0.074] and [0.003, 0.026], respectively. There was obvious heterogeneity in the spatial polarization degree of marine green aquaculture efficiency in the three marine economic circles. From 2006 to 2019, the average values of the Wolfson index, DER index and EGR index for the northern marine economic circle were 0.105, 0.098 and 0.079, respectively. The mean values of the Wolfson index, DER index and EGR index were 0.155, 0.065 and 0.077, respectively. The mean values of the Wolfson index, DER index and EGR index in the southern marine economic circle were 0.056, 0.058 and 0.028, respectively, which means that compared with the northern and eastern marine economic circle, the spatial polarization degree of marine green aquaculture efficiency in the southern marine economic circle was the lowest. The reasons for the increased spatial polarization of green aquaculture efficiency in China may be as follows: first, due to the differences in the development level of marine aquaculture fisheries, the innovation ability of marine aquaculture green technology, the soundness of relevant institutions and mechanisms, and the level of marine aquaculture production and ecological environment monitoring among the three major marine economic circles, the growth rate of marine green aquaculture efficiency is different, resulting in the spatial polarization of marine green aquaculture efficiency among the three major marine economic circles [48,63]; secondly, the growth rate of marine green aquaculture efficiency in coastal provinces within the same marine economic circle is different, resulting in the spatial polarization of marine green aquaculture efficiency within the same marine economic circle [11,48].

The DER index ($\alpha = 0.25$) is decomposed based on the "identity-alienation" framework, and the decomposition results are shown in Table 7. As can be seen from Table 7, the overall results of the samples from 2006 to 2019 showed a downward trend, from 1.2482 in 2006 to 1.0206 in 2019, indicating that the change of marine green aquaculture efficiency in each coastal province did not cluster into minority groups. The degree of alienation increased from 0.0398 in 2006 to 0.0959 in 2019, indicating that the spatial polarization of marine green aquaculture efficiency was caused by the large gap in marine green aquaculture efficiency among coastal provinces.

4. Conclusions

4.1. Discussion

The possible innovations and contributions of this research are as follows. (1) The existing research mainly analyzes the regional heterogeneity of China's marine green aquaculture efficiency through the analysis of its spatial and temporal characteristics. Based on the analysis of the spatial and temporal evolution characteristics of China's marine green aquaculture efficiency using three-dimensional kernel density estimation, this research used the Gini coefficient, MLD index and Theil index to analyze the degree of spatial imbalance of China's marine green aquaculture efficiency and also used a Markov chain to analyze its dynamic evolution trend to generate a beneficial supplement to relevant research. (2) Most of the existing studies analyze the influencing factors on the efficiency of green marine aquaculture based on the spatial spillover effect and the loss model of technical efficiency, but few studies explore the causes of the spatial imbalance of the efficiency of green marine aquaculture. (3) There is a lack of research content on the spatial polarization of the efficiency of green marine aquaculture in China.

4.2. Research Conclusions

The research conclusions are as follows:

(1) The results of the Super-SBM model showed that the efficiency values of China's marine green aquaculture 2006 to 2019 were all above 1, which is a relatively effective state on the whole, but there is still room for improvement. Compared with the northern and eastern marine economic circles, the efficiency of the marine green aquaculture in the southern marine economic circles was higher. The results of the three-dimensional kernel density non-parametric estimation showed that the absolute difference in marine green aquaculture efficiency in the whole country and the three marine economic circles had an expanding trend. The results of the Gini coefficient, Theil index and MLD index showed that the coastal provinces with a medium level of green seawater cultivation efficiency had a large degree of spatial imbalance, while the coastal provinces with low and high levels of green seawater cultivation efficiency had a small regional gap and a small degree of spatial imbalance. The coastal provinces with a medium level of efficiency had the smallest variation in regional disparity. The results of the Markov chain analysis showed that breaking the "self-locking trap" of a low-level state is the key to achieving the spatially balanced development of marine green aquaculture efficiency in China. The efficiency of seawater green aquaculture in China will be stable at a high level.

(2) The QAP regression results showed that the regression coefficients between the differences in mariculture output, the number of professional mariculture employees, the number of fishermen technical training programs, and regional differences in mariculture area, per capita disposable income of fishermen and the efficiency of green mariculture among coastal provinces were all positive. The regression results of the influencing factors of the efficiency of green mariculture in China are relatively robust. The regional differences in mariculture area and fishermen's per capita disposable income have significant effects on the spatial imbalance of green mariculture efficiency in China, but the degree of influence was weak.

(3) The Wolfson index, DER index and EGR index for China's marine green aquaculture efficiency show that the three polarization indexes had an upward trend, and the polarization degree of China's marine green aquaculture efficiency was expanding. There was obvious heterogeneity in the spatial polarization degree of the efficiency of green seawater cultivation in the three marine economic circles. The three polarization indexes in the northern marine economic circle showed a fluctuating upward trend of first rising, then falling, then rising and falling again. The eastern marine economic circle showed an inverted "U"-shaped fluctuating upward trend of first rising and then falling, and the southern marine economic circle showed an overall upward trend. In addition, compared with the northern and eastern marine economic circles, the southern marine economic circle had the lowest spatial polarization degree in terms of the efficiency of green marine culture. Based on the "identification-alienation" framework, the DER multi-level differentiation index was decomposed, and the results showed that the change in marine green cultivation efficiency in each coastal province did not converge into minority groups.

4.3. Policy Suggestions

In view of the above conclusions, in order to further improve the efficiency of marine green aquaculture in China, promote its development towards a spatial equilibrium, and alleviate the problem of spatial polarization, we put forward the following policy implications:

(1) Multiple measures should be taken simultaneously to comprehensively boost the development of marine green aquaculture efficiency from a spatial disequilibrium to spatial equilibrium. First, the financial expenditure and policy subsidies for mariculture should be increased to promote the formation and accumulation of fixed assets for farmers and aquaculture enterprises. This includes the comprehensive development and utilization of sea area resources and improvement in the production efficiency per unit area of sea area. We should accelerate the cultivation and promotion of improved varieties, promote the establishment of high-quality aquatic germplasm resources and protection zones, improve the treatment of mariculture professionals, create a good working atmosphere, and actively explore the cultivation of professional fishermen. Second, we should promote the coordinated development of the three marine economic circles and give full play to the demonstration effect of coastal provinces with a high green seawater aquaculture efficiency and promote a typical experience in all coastal provinces. We should strengthen technological exchanges and cooperation among coastal provinces, accelerate the construction of interconnected capital, talent and technology markets, build and improve resource- and information-sharing platforms, improve the cooperation ability of the three marine economic circles, and promote the "catch-up effect" of coastal provinces with a low seawater green aquaculture efficiency. Finally, it is necessary to prevent the impact of international political and economic crises and alleviate the spatial imbalance of seawater green aquaculture efficiency. Based on the large domestic market, we should make full use of domestic and foreign resources and markets, improve the industrial resilience of marine aquaculture fisheries in coastal provinces, and effectively prevent and resolve the impact and risks brought by international political and economic events.

(2) We should pay attention to the development of mariculture products in the direction of diversification, providing high nutrition, meeting high standards and domestic demands, exploring the international market, promoting coastal provinces to improve the aquaculture structure, and cultivating a famous brand for Chinese mariculture products. We should improve the training system for professional fishermen, including building education and training schools, in order to provide high-level and high-quality personnel for marine aquaculture fisheries. Efforts should be made to popularize fishery technology, and the technical level and practical ability of aquaculture and fishing households should be improved. We should comprehensively develop and utilize marine resources, promote and apply intensive farming models, and promote the efficient use of resources. We should improve fishery policy subsidies, enrich various types of marine aquaculture fishery insurance and build high-level fishery cooperatives to boost farmers' production and income.

(3) In view of the spatial polarization trend of the efficiency of marine green aquaculture in China and the three major marine economic circles, on the one hand, it is not only necessary to analyze the degree of spatial disequilibrium from a series of inequality indicators but also to analyze the causes of the spatial disequilibrium from a series of polarization indicators, so as to provide a path to more effectively solve the disequilibrium. On the other hand, to alleviate spatial polarization, it is not only necessary to reduce the regional gap caused by the alienation of the efficiency of marine green aquaculture in China but also to prevent the intra-group homogeneity caused by identity.

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