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Research Article

Evolutionary Path and Influences on Marine Ecological Farming: Dual Perspective of Government Intervention and Enterprise Participation

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Marine ecological aquaculture is considered a robust scientific farming model, but it has not been widely promoted in China. Although some studies have examined stakeholders' interests in ecological transformation, few studies to date have analyzed the interaction mechanism of the stakeholders in ecological transformation. Therefore, drawing on evolutionary game theory, this study analyzed the different behavioral strategies and evolutionary mechanisms of the government, marine aquaculture farmers, and aquatic enterprises engaged in marine farming processes. Furthermore, a numerical simulation was conducted to evaluate the rationality of the theoretical model. The results show that several factors affected the ecological transformation of mariculture. Government subsidies reduced farmers' and aquatic enterprises' costs of adopting ecological farming. The government's increasing fines for aquaculture pollution slowed down the speed of the system to a stable point. The cost of adopting ecological farming by farmers and aquatic enterprises will affect their decision to adopt or invest in it. The increase in the market price of eco-aquatic products helped accelerate the ecological transformation of mariculture. The brand effect obtained by aquatic enterprises by investing in ecological farming helped increase participation to further improve this practice. In terms of policy implications, we recommend the promotion and guidance of marine aquaculture technology, government support and investment, environmental control of the aquaculture industry, and brand building of eco-aquatic products to transform and upgrade marine aquaculture farming.

1. Introduction

The marine aquaculture industry in China has witnessed steady growth and increased production capacity in recent years. The development has relied on aquaculture factors (i.e., the input) to increase outputs but has neglected environmental protection. Therefore, issues, such as resource constraints and environmental pollution, have restricted the sustainable development of marine aquaculture in China. The Chinese government has vigorously advocated for the development of ecological fisheries [1]. Ecological development that pursues the maximization of production, energy conservation, emission reduction, and environmental protection will become an important solution for marine aquaculture. Marine ecological aquaculture refers to the semiartificial or artificial simulation of an ecosystem using sustainable resources, stable circulation, and safe and efficient methods [2–4]. However, marine ecological aquaculture has not been widely promoted, and its popularity is relatively low [5, 6]. It is widely recognized that paying attention to relevant stakeholders in mariculture represents an important breakthrough in studying the ecological transformation of mariculture [7, 8]. For example, Yu and Yin [8] elaborated on the current situation and development potential of mariculture in China. They pointed out that further development requires the participation of all stakeholders to solve the problems of the difficult transformation, insufficient technical support, and high risk of the industry. Therefore, this study analyzed the transformation mechanism of marine ecological aquaculture from the perspective of the participants and deduced and elaborated the evolutionary path of the ecological transformation.

Farmers are the core subject of ecological transformation in mariculture. Farmers who adopt ecological farming may gain a competitive advantage, enabling them to obtain high profits and leading other farmers to choose ecological aquaculture. However, farmers are reluctant to adopt marine ecological aquaculture because of the high-tech farming system, high initial input cost, technical risks, and difficulty in realizing short-term profits. Some reports have explained that aquatic enterprises connect the consumer and farmers and play an important role in ecological transformation [9, 10]. For example, Lin and Tong [10] found that a supply chain using middlemen, referring to the use of a wholesaler, acquirer, and retailer to achieve aquaculture from farmers to consumers, was more conducive to the promotion of ecological aquaculture farming. In contrast, most existing research has focused on the two main subjects of enterprises and farmers of marine ecological aquaculture, while there has been little research on the government. However, the government is always an important participant in ecological development [11–13]. For example, Siddiki and Goel [14] found that balancing the multi-interests of government organizations and nongovernmental organizations could ensure the implementation of marine farming policies [14]. Although some coastal provinces and cities in China have begun to promote ecological mariculture, it is still relatively local. Therefore, the government adopts corresponding regulation policies on mariculture, which forces mariculture farmers to choose ecological aquaculture. Meanwhile, to improve the enthusiasm of mariculture farmers and aquatic enterprises to adopt ecological mode, the government has an important impact on the ecological transformation of mariculture through effective supervision, policy support, and financial subsidies [15, 16]. For example, in 2016, China adopted the "Reform Plan for Establishing a Green Ecology-Oriented Agricultural Subsidy System", which pointed out that agricultural subsidies should be carried out with green ecology as the guidance, so as to achieve the development goal of equal attention to the quantity, quality, and ecological development of agricultural production.

Although the existing research has discussed the stakeholder, there have been limited studies on the interaction mechanism of stakeholders in the ecological transformation of mariculture. The stakeholders, including the government, aquatic enterprises, and farmers, affect the promotion of marine ecological aquaculture. These stakeholders play games in the aspects of financial subsidies for ecological aquaculture, sales of aquaculture products, seafood prices, seafood quality, rewards, and punishments. Considering that eco-aquatic products are mainly sold through aquatic enterprises, while farmers sell eco-aquatic products to aquatic enterprises, this study only analyzed the evolutionary game relationship between farmers, aquatic enterprises, and the government to make the research objects more targeted. Therefore, the primary purpose of this study was to identify the interaction mechanism and decision-making behavior of mariculture farmers, aquatic enterprises, and the government in the transformation of ecological aquaculture farming. To analyze the decision-making interaction mechanisms of the main bodies in the transformation of ecological aquaculture farming, we applied the evolutionary game theory [17]. The evolutionary game theory is different from the traditional classical game theory, which assumes that the game subjects show bounded rationality. The bounded rationality hypothesis of evolutionary game theory and the adjustment mechanism of decision-making are in line with the actual situation of decision-makers in the transformation process being studied [18–21]. It is more reasonable to study the ecological transformation of mariculture, although few relevant studies have been performed on the subject.

The main contributions of this study were as follows: First, this study added to the small body of studies that have discussed the mechanism of transformation of ecological aquaculture farming. Compared with the previous studies focusing on the stakeholders' attitude and satisfaction [22, 23], this study discussed the interaction between the government, aquaculture enterprises, and farmers around the price of aquatic products, aquaculture costs, adoption of aquaculture technologies, quality and safety of aquatic products, government supervision, and other issues and the different strategies for ecological transformation. A new perspective was provided for studying the promotion mechanism of ecological aquaculture farming. Second, based on the assumption of bounded rationality, the study constructed an evolutionary game model on the transformation of ecological aquaculture farming, which is different from the assumption of complete rationality in classical game theory. Third, in contrast with previous research considering two parties [10], this study extracted three main agents in the transformation of ecological aquaculture farming, more clearly reflecting the actual case.

The remainder of this study is structured as follows: In Section 2, we analyze the different behavioral strategies and evolutionary mechanisms of the government, aquatic enterprises, and farmers in the process of the transformation of mariculture mode, based on the evolutionary game theory. Section 3 describes the numerical simulation, and Section 4 provides our conclusions and policy recommendations.

2. The Model

2.1. Assumptions. The assumptions and parameters of the evolutionary game model, based on the three groups of the government, aquatic enterprises, and marine aquaculture farmers, were set as follows.

Hypothesis 1. There are three groups in the system: the government, aquatic enterprise, and marine aquaculture farmer. The government can either regulate ecological farming or choose not to do so; aquatic enterprises can either invest in ecological farming management or choose not to do so, and farmers can either adopt ecological farming or choose not to adopt it. We assume that the probability that the government regulates ecological farming is x and the probability that it does not is $1-x$; the probability that aquatic enterprises support investment in ecological farming is y and it is $1-y$ otherwise; and the probability that farmers will adopt ecological farming is z and it is $1-z$ otherwise.

Hypothesis 2. The cost of ecological aquaculture products differs from that of their ordinary counterparts [24]. When marine farmers adopt ecological farming, they incur additional costs. Assume that S_0 represents the cost incurred by marine aquaculture farmers who do not adopt ecological farming and S_1 represents the costs incurred by farmers who adopt ecological farming. This hypothesis predicts that $S_1 > S_0 > 0$. Irrespective of the strategic choices adopted by farmers or aquatic companies, their choices affect the other party's benefits or costs. When farmers who adopt ecological farming and aquatic enterprises do not invest in ecological farming, they need to pay higher cost S_2; therefore, $S_2 > S_1 > S_0$.

Hypothesis 3. The payment function of marine aquaculture farmers is determined by product sales revenue and total cost, and the payment function of aquatic enterprises is also determined by their income and cost. Assume that in ordinary farming, the unit purchase price of marine aquaculture products is W_0 and the income generated by farmers not adopting ecological farming is R_0. After the implementation of ecological aquaculture farming, product quality improves because of progress in farming technology, improved management methods, and the ecological environment. The unit purchase price of aquatic products is W_1 and the income generated by the farmers adopting ecological farming is R_1. We assume that $W_1 > W_0 > 0$ and $R_1 > R_0 > 0$. In the scenario where the government participates in ecological management, if the mariculture farmers adopt ecological farming, the mariculture farmers receive subsidies from the government, assuming that the total amount of subsidies is denoted as R_θ.

Hypothesis 4. When aquatic enterprises support and invest in ecological farming, they also generate additional investment costs. These costs include building technical teams, investing in technology research and development, and building ecological farming bases. Assume that C_0 represents the cost incurred by aquatic enterprises that do not invest in ecological farming and C_1 represents the costs incurred by the enterprises that invest in ecological farming. Then, we predict that $C_1 > C_0 > 0$.

Hypothesis 5. The market price of eco-aquatic products is higher than that of ordinary products [25]. Based on the supply chain system of aquatic enterprises as intermediaries, the market price of ordinary aquaculture products is P_0. In the scenario where aquatic enterprises do not invest in ecological farming, we find that their total income is I_0. Assume that farmers who implement ecological farming and aquatic enterprises invest in ecological aquaculture management. After a series of technical and managerial improvements, aquatic products gain value in the consumer market and the aquatic enterprises that invest in ecological farming improve their reputation, which helps raise the brand value. When both parties participate in the development of ecological aquaculture, the unit price of aquatic products is P_1 and the total income of the aquatic enterprise is I_1. If we assumed that (1) Farmers adopt ecological farming, (2) the aquatic enterprise does not support or invest in ecological farming, and (3) there is no corresponding green processing, then the added value of the aquatic products before they enter the consumer market is low. Here, the market sales price for this kind of aquatic products is P_2, and the total income of the aquatic enterprise is I_2; as a consequence, $P_1 > P_2 > P_0 > 0$ is assumed. Therefore, $I_1 > I_2 > I_0 > 0$ is assumed.

Hypothesis 6. In the case that both parties participate in ecological farming, the good reputation obtained by the enterprise is denoted as R_β. In the scenario where the government participates in ecological management, aquatic enterprises receive subsidies and the total amount of subsidies is denoted as R_α.

Hypothesis 7. It is assumed that mariculture pollution caused by ordinary aquaculture must be investigated by relevant departments and that the environmental regulation of mariculture is completely effective. The regulatory cost of government monitoring the adoption or investment of ecological farming is C (e.g., environmental supervision and safety monitoring). Mariculturists adopt the ecological farming mode, and the government provides subsidies denoted as R_θ (e.g., difference subsidy and priority loan). The aquatic enterprise invests in ecology to breed, and the government gives subsidyR_α. The government then implements effective supervision. If the farmers do not adopt ecological farming and cause pollution, a fine (F) is imposed (e.g., sewage fees and fines). The government needs to pay the treatment cost of T to solve the pollution problem. Because of the implementation of ecological mariculture, the social welfare generated is represented by K. Concomitantly, the government gains a good reputation by implementing regulations to improve the environment, denoted as U.

Based on the above assumptions, the payment matrix of the tripartite evolutionary game among the government, aquatic enterprises, and mariculturists can be obtained, as shown in Tables 1 and 2.

2.2. Replicated Dynamic Equations. Combined with the above payment matrix, the expected returns and replicated dynamic equations of each subject under different behavior strategies can be obtained. The replicated dynamic equation refers to the dynamic differential equation of the frequency of a specified strategy used in a group. Similarly, it is also the most basic dynamic model of evolutionary game theory, which can reasonably and correctly reflect the action behavior and change the trend of rational people among a limited group of individuals.

The expected benefits of the government's active supervision strategy are as follows:

Table 1: Payment matrix of the tripartite evolutionary game with government participation.

		Marine aquaculture farmers	
		Adopting (Z)	Not adopting $(1-Z)$
Aquatic enterprises	Investing (y)	$U+K-C-R_\theta-R_\alpha$ $I_1-R_1-C_1+R_\alpha+R_\beta$ $R_1-S_1+R_\theta$	$U-T-C-R_\alpha+F$ $I_0-R_0-C_1+R_\alpha+R_\beta$ R_0-S_0-F
	Not investing $(1-y)$	$U+K-C-R_\theta$ $I_2-R_1-C_0$ $R_1-S_2+R_\theta$	$U+F-C-T$ $I_0-R_0-C_0$ R_0-S_0-F

Table 2: Payment matrix of the tripartite evolutionary game without government participation.

		Marine aquaculture farmers	
		Adopting (z)	Not adopting $(1-Z)$
Aquatic enterprises	Investing (y)	K $I_1-R_1-C_1+R_\beta$ R_1-S_1	$-T$ $I_0-R_0-C_1+R_\beta$ R_0-S_0
	Not investing $(1-y)$	K $I_2-R_1-C_0$ R_1-S_2	$-T$ $I_0-R_0-C_0$ R_0-S_0

$$\begin{aligned}U_{1x} = {} & yz\left(U+K-C-R_\theta-R_\alpha\right)+y(1-z)\left(U-T-C-R_\alpha+F\right)\\ & +(1-y)z\left(U+K-C-R_\theta\right)+(1-y)(1-z)(U+F-C-T).\end{aligned} \tag{1}$$

The expected benefits of the government's nonregulatory strategy are as follows:

$$U_{2x} = yzK + y(1-z)(-T) + (1-y)zK + (1-y)(1-z)(-T). \tag{2}$$

The evolutionary replicated dynamic equation is as follows:

$$F(x) = \frac{dx}{dt} = x(1-x)\left[z\left(-R_\theta - F\right) - yR_\alpha + (U+F-C)\right]. \tag{3}$$

For aquatic enterprises, the respective benefits of investing in ecological and nonecological farming are as follows:

$$\begin{aligned}U_{1y} = {} & xz\left(I_1-R_1-C_1+R_\alpha+R_\beta\right)+x(1-z)\left(I_0-R_0-C_1+R_\alpha+R_\beta\right)+(1-x)z\left(I_1-R_1-C_1+R_\beta\right)\\ & +(1-x)(1-z)\left(I_0-R_0-C_1+R_\beta\right),\end{aligned} \tag{4}$$

$$\begin{aligned}U_{2y} = {} & xz\left(I_2-R_1-C_0\right)+x(1-z)\left(I_0-R_0-C_0\right)+(1-x)z\left(I_2-R_1-C_0\right)\\ & +(1-x)(1-z)\left(I_0-R_0-C_0\right).\end{aligned} \tag{5}$$

The evolutionary replicated dynamic equation is as follows:

$$F(y) = \frac{dy}{dt} = y(1-y)\left[xR_\alpha + z\left(I_1-I_2\right) + \left(C_0 - C_1 + R_\beta\right)\right]. \tag{6}$$

For the farmers, the respective benefits of adopting ecological and nonecological farming are as follows:

$$U_{1z} = xy(R_1 - S_1 + R_\theta) + x(1-y)(R_1 - S_2 + R_\theta) + (1-x)y(R_1 - S_1) + (1-x)(1-y)(R_1 - S_2), \tag{7}$$

$$U_{2z} = xy(R_0 - S_0 - F) + x(1-y)(R_0 - S_0 - F) + (1-x)y(R_0 - S_0) + (1-x)(1-y)(R_1 - S_0). \tag{8}$$

The evolutionary replicated dynamic equation is as follows:

$$\begin{aligned} F(z) = \frac{dz}{dt} &= z(1-z)\left[x(R_\theta + F) + y(S_2 - S_1)\right. \\ &\quad \left. + (R_1 - S_2) - (R_0 - S_0)\right]. \end{aligned} \tag{9}$$

2.3. Evolutionary Stable Strategies. We merge replicated dynamic equations (3), (6), and (9), let $F(x) = F(y) = F(z) = 0$, and then obtain eight partial equilibrium points: $E_1(0,0,0), E_2(0,0,1)$, $E_3(0,1,0)$, $E_4(0,1,1), E_5(1,0,0), E_6(1,0,1), E_7(1,1,0)$, and $E_8(1,1,1)$.

The evolutionary stable strategy (ESS) must be an asymptotically stable state in the replicating dynamic system of a multipopulation evolutionary game, and vice versa. According to Friedman's method, the ESS of the differential equation system can be obtained from the local stability analysis of the Jacobian matrix of the system [26]. Referring to the Lyapunov stability theory, if a strategy set is asymptotically stable, then the eigenvalues of the Jacobian matrix corresponding to this strategy set must be less than 0. If this condition is not met, then the strategy is an unstable point or saddle point of the system [27]. The Jacobian matrix of the system is calculated as follows:

$$J = \begin{bmatrix} (1-2x)\left[z(-R_\theta - F) - yR_\alpha + (U + F - C)\right] & x(1-x)(-R_\alpha) & x(1-x)(-R_\theta - F) \\ y(1-y)R_\alpha & (1-2y)\left[xR_\alpha + z(I_1 - I_2) + \left(C_0 - C_1 + R_\beta\right)\right] & y(1-y)(I_1 - I_2) \\ z(1-z)x(R_\theta + F) & z(1-z)(S_2 - S_1) & (1-2z)x\left[(R_\theta + F) + y(S_2 - S_1) + (R_1 - S_2) - (R_0 - S_0)\right] \end{bmatrix}. \tag{10}$$

When $E_1(0,0,0)$, the three eigenvalues of the Jacobian matrix J are $\lambda_1(U + F - C)$, $\lambda_2(C_0 - C_1 + R_\beta)$, and $\lambda_3[(R_1 - S_2) - (R_0 - S_0)]$. If the three eigenvalues are successively less than 0 and the system is in an asymptotically stable state, $E_1(0,0,0)$ is an evolutionary stability point. By analogy, the eigenvalues of the Jacobian matrix corresponding to the equilibrium point can be obtained individually, as shown in Table 3, from which the asymptotically stable condition of the equilibrium point can be calculated.

2.4. Discussion. The results enable local stability analysis of the evolutionary game system and make it possible to identify the evolutionary path of the transformation of the ecological aquaculture farming model. If the government does not participate in regulation, $(R_1 - S_1) - (R_0 - S_0)$ indicates the super profit obtained by marine aquaculture farmers adopting ecological aquaculture when aquaculture enterprises invest in ecological farming. $(R_1 - S_2) - (R_0 - S_0)$ indicates the super profit obtained by the farmers adopting ecological aquaculture when aquaculture enterprises do not invest in ecological farming. $I_1 - R_1 - C_1 - (I_2 - R_1 - C_0) + R_\beta = (I_1 - C_1) - (I_2 - C_0) +$ indicates the super profit obtained by aquatic enterprises that invest in ecological farming when marine aquaculture farmers choose to adopt ecological farming. $I_0 - R_0 - C_1 - (I_0 - R_0 - C_0) +$ $R_\beta = (I_1 - C_1) + (C_0 - C_1) + R_\beta$ indicates the super profit obtained by aquatic enterprises that invest in ecological farming when farmers choose not to adopt ecological farming.

In the context of government supervision, $(R_1 - S_1 + R_\theta) - (R_0 - S_0 - F)$ indicates the super profit obtained by marine aquaculture farmers adopting ecological farming when aquaculture enterprises invest in ecological farming. $(R_1 - S_2 + R_\theta) - (R_0 - S_0 - F)$ indicates the super profit obtained by farmers adopting ecological aquaculture when aquaculture enterprises do not invest in ecological farming. $I_1 - R_1 - C_1 + R_\alpha - (I_2 - R_1 - C_0) + R_\beta = (I_1 - C_1) + R_\alpha - (I_2 - C_0) + R_\beta$ indicates the super profit obtained by aquatic enterprises that invest in ecological farming when marine aquaculture farmers choose to adopt ecological farming. $I_0 - R_0 - C_1 + R_\alpha \quad - (I_0 - R_0 - C_0) + R_\beta = (C_0 - C_1 + R_\alpha + R_\beta)$ indicates the super profit obtained by aquatic enterprises that invest in ecological farming when farmers choose not to adopt ecological farming:

(1) When the system satisfies $(U + F - C) < 0$, $(C_0 - C_1 + R_\beta) < 0$, $(R_1 - S_2) - (R_0 - S_0) < 0$, then $E_1(0,0,0)$ is the evolutionary stability point. This stable state is not conducive to the adoption of ecological farming technology. When aquatic enterprises find that super profits obtained from investment in ecological aquaculture farming are negative, they discontinue investment in ecological

Table 3: Equilibrium points and eigenvalues of the evolutionary game.

Equilibrium point	Eigenvalue λ_1	λ_2	λ_3
$E_1\,(0,0,0)$	$(U+F-C)$	$(C_0-C_1+R_\beta)$	$(R_1-S_2)-(R_0-S_0)$
$E_2\,(0,0,1)$	$(U-C-R_\theta)$	$(I_1-C_1)-(I_2-C_0)+R_\beta$	$-[(R_1-S_2)-(R_0-S_0)]$
$E_3\,(0,1,0)$	$(U+F-C-R_\alpha)$	$-(C_0-C_1+R_\beta)$	$(R_1-S_1)-(R_0-S_0)$
$E_4\,(0,1,1)$	$(U-C-R_\alpha-R_\theta)$	$-[(I_1-C_1)-(I_2-C_0)+R_\beta]$	$-[(R_1-S_1)-(R_0-S_0)]$
$E_5\,(1,0,0)$	$-(U+F-C)$	$(C_0-C_1+R_\alpha+R_\beta)$	$(R_1-S_2+R_\theta)-(R_0-S_0-F)$
$E_6\,(1,0,1)$	$(U-C-R_\theta)$	$-(C_0-C_1+R_\alpha+R_\beta)$	$-[(R_1-S_2+R_\theta)-(R_0-S_0-F)]$
$E_7\,(1,1,0)$	$-(U+F-C-R_\alpha)$	$-(C_0-C_1+R_\alpha+R_\beta)$	$[(R_1-S_1+R_\theta)-(R_0-S_0-F)]$
$E_8\,(1,1,1)$	$-(U-C-R_\alpha-R_\theta)$	$-[(I_1-C_1)+R_\alpha-(I_2-C_0)+R_\beta]$	$-[(R_1-S_1+R_\theta)-(R_0-S_0-F)]$

farming. If the farmers continue to adopt ecological farming, they bear higher input-costs. If the cost is too high, farmers lose profits and give up ecological farming, instead of choosing the ordinary farming system. If the improvement in the government's reputation and the total amount of fines are not enough to offset the supervision cost, the government also tends not to supervise.

In a slightly disturbing scenario, when the super profits aquatic enterprises obtain from investment in ecological aquaculture farming are positive, they continue to invest in marine ecological aquaculture. In this situation, aquaculture farmers also realize that there are fewer benefits of adopting ecological farming than those in the ordinary farming mode. They will then abandon the former and switch to the latter. Considering that improvements in the government's reputation through supervision and the total amount of fines are not enough to offset the sum of supervision costs and subsidies to aquatic enterprises, the government also tends not to supervise. The system evolution eventually converges on $E_3\,(0,1,0)$.

Now, although aquatic enterprises invest in ecological farming, the farmers do not adopt ecological farming. This means that the ecological technology invested in by aquatic enterprises has no market demand, and the aquatic products purchased are not eco-aquatic products. When the product quality is not high, higher market prices cannot be set. Now, the government tends not to regulate, which means that it is difficult for aquatic enterprises to obtain government subsidies. Therefore, even if there is a certain cost advantage at the beginning, aquatic enterprises eventually give up investing in ecological farming in the long run, and the system evolution converges on $E_1\,(0,0,0)$.

(2) When the system satisfies $(U-C-R_\alpha-R_\theta)<0$, $(I_1-C_1)-(I_2-C_0)+R_\beta>0$, $(R_1-S_1)-(R_0-S_0)>0$, $E_4\,(0,1,1)$ is the evolutionary stability point. In this stable state, there is no government supervision, and thus, there is no consumption of government financial resources. Aquatic enterprises and mariculturists actively invest in or adopt ecological aquaculture farming, which is an ideal stable state. In this system, there is no subsidy. If farmers realize that the benefits of adopting ecological farming are higher than those offered by the ordinary system, they choose the former and abandon the latter. In addition, the profits of aquatic enterprises that invest in ecological farming are higher than those that do not invest in ecological farming. In this case, the enterprises eventually choose to invest in the strategy. If the government implements supervision, the improvements to the government's reputation are not enough to offset the sum of supervision costs and subsidies to enterprises and farmers. Thus, the government will abandon regulation. The system evolution then converges on $E_4\,(0,1,1)$. This is the ideal result under the effective action of the market mechanism.

If the situation is slightly disturbed, when farmers adopt ecological farming, aquatic enterprises find that super profits obtained from investment in ecological aquaculture farming are negative and the enterprises abandon investment. Considering that the improvement in reputation obtained by government supervision is not enough to offset the sum of supervision costs and subsidies to farmers, the government also tends not to supervise. Then, the stable equilibrium point of the system changes from $E_4\,(0,1,1)$ to $E_2\,(0,0,1)$.

In the system of $E_2\,(0,0,1)$, farmers adopt ecological farming, while aquatic enterprises do not invest in ecological aquaculture farming, so the government does not supervise. This means that the farmers lack technical support and guidance for developing ecological farming and also do not have subsidy support from the government. With the small scale, dispersion, and low quality of farmers, it is difficult to implement and set up ecological farming technology and equipment by themselves and the cost of adopting ecological farming is relatively high. In this situation, unless the market price of eco-aquatic products continues to rise, the net income of farmers adopting ecological farming probably shows a downward trend and farmers eventually abandon ecological farming. The system evolution converges on $E_1\,(0,1,1)$.

(3) When the system satisfies $(U+F-C)>0$, $(C_1-C_0-R_\beta-R_\alpha)>0$, $(R_1-S_2+R_0)-(R_0-S_0-F)<0$, E_5

$(1, 0, 0)$ is the evolutionary stability point. This is an unsatisfactory state. This stable state is not conducive to the adoption of ecological farming technology. The government's regulation is ineffective and wasteful. In the context of government supervision, aquatic enterprises find that super profits obtained from investment in ecological aquaculture farming are negative and they discontinue investment in ecological farming. Aquaculture farmers realize that the benefits of adopting ecological farming are fewer than those of the ordinary farming mode, and the farmers will abandon the former and switch to the latter. If the sum of the improvement in the government's credibility and fines obtained in supervision is more than the supervision cost, the government tends to implement supervision. In this case, the government's regulatory resources are wasted and the subsidy input is invalid.

If the situation is slightly disturbed, the possible profit obtained by aquatic enterprises that invest in ecological farming when farmers choose not to adopt ecological farming is positive and then aquatic enterprises invest in ecological farming. If the super profit obtained by marine aquaculture farmers adopting ecological farming when aquatic enterprises invest in ecological farming is negative, the farmers abandon ecological farming. If the government carries out supervision, improves the credibility of the government and obtains fines, and deducts the supervision cost and subsidies to aquatic enterprises, the result is still positive. Then, the government implements active supervision. Therefore, the stable equilibrium point of the system changes from $E_5(1, 0, 0)$ to $E_7(1, 1, 0)$. Under the supervision of the government, aquatic enterprises actively invest in ecological farming technology, but farmers still do not adopt ecological farming, similar to $E_3(0, 1, 0)$. Therefore, $E_7(1, 1, 0)$ is the unstable equilibrium point of the system.

Assume that a small disturbance occurs among farmers and $(R_1 - S_2 + R_\theta) - (R_0 - S_0 - F) > 0$. This indicates that the super profit obtained by the farmers adopting ecological aquaculture when aquaculture enterprises do not invest in ecological farming is positive. In this scenario, the farmers will actively adopt ecological farming. If there is an improvement in the government's credibility achieved through supervision, and the supervision cost and subsidies to farmers are thus reduced, the result is still positive. In this case, the government tends to implement supervision. The stable equilibrium point of the system changes from $E_5(1, 0, 0)$ to $E_6(1, 0, 1)$. The equilibrium state $E_6(1, 0, 1)$ shows that farmers actively adopt ecological farming, but aquatic enterprises do not invest in ecological farming under supervision, which is similar to $E_2(0, 0, 1)$. The system eventually converges to the stable equilibrium point $E_5(1, 0, 0)$.

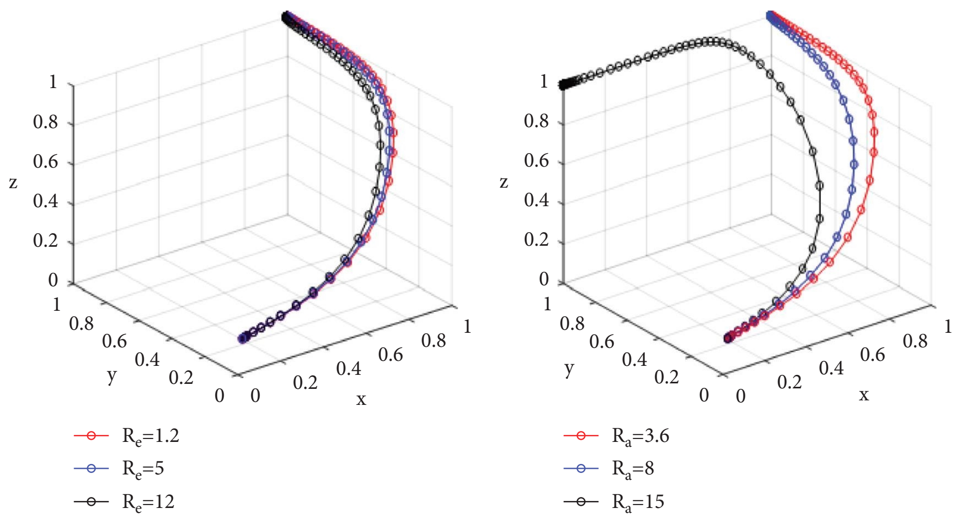
(4) When the system satisfies $(U - C - R_\alpha - R_\theta) > 0$, $(I_1 - C_1) + R_\alpha - (I_2 - C_0) + R_\beta > 0$, $(R_1, S_1 + R_0) - (R_0 - S_0 - F) > 0$, $E_2(1, 1, 1)$ is the evolutionary stability point. In this stable state, the government, aquatic enterprises, and farmers all adopt positive ecological strategies, which is an ideal stable state under the government supervision mechanism.

In this situation, if the government obtains positive profits, it also takes active supervision measures. If farmers realize the benefits of adopting ecological farming are higher than those offered by the ordinary system, they choose the former and abandon the latter. In addition, the profits of aquatic enterprises that invest in ecological farming are higher than those that do not invest in ecological farming, which result in the system evolution finally converging on $E_8(1, 1, 1)$. In certain areas where aquaculture farming is highly developed, farmers have a strong appreciation of the importance of environmental protection and a deeper understanding of ecological aquaculture farming. The scale of farming may be large as well, and a large sum of money may have been invested. In this instance, these farmers may be more willing to adopt ecological farming and reap the positive benefits. When this occurs, the aquatic enterprises that invest in ecological farming will obtain profits higher than those that do not invest in ecological farming. The aquatic enterprises eventually choose to invest in the strategy, and the system evolution converges on $E_8(1, 1, 1)$.

3. Numerical Simulation

Based on the above theoretical derivation, a numerical simulation was used to depict the strategy evolutionary process and observe the parameters' influence more intuitively. It is feasible to assign the variables as price and cost based on research, as similar studies have been carried out [15]. To make the results more reasonable, this study assigns values to variables within a certain range to make them as close to the actual situation as possible. We assumed that $R_1 = 20, R_0 = 12, S_0 = 3, S_1 = 6, S_2 = 8, I_1 = 40, I_2 = 30, C_0 = 10, C_1 = 18, U = 28, C = 8, F = 4, R_\beta = 10, R_0 = 2$, and $R_\alpha = 3$. The above parameters were assumed to meet the conditions: $(U - C - R_\alpha - R_\theta) > 0$, $(I_1 - C_1) + R_\alpha - (I_2 - C_0) + R_\beta > 0$, and $(R_1 - S_1 + R_0) - (R_0 - S_0 - F) > 0$, with a unified unit of US\$10,000.

3.1. Effect of Government Subsidies on Evolution Results. First, we assumed that the other parameter values were constant, $R_\theta = 1.2, 5, 12$, and the evolutionary path and probability would begin to change when the initial position was (0.1, 0.1, 0.1). Figure 1(a) shows that, as the value of R_θ continued to increase, the evolution rate gradually accelerated. An increase in government subsidies to farmers reduced the costs of adopting ecological farming. The government's subsidies to farmers were of significance in realizing the transformation of the ecological aquaculture farming model and promoting the system's converges to the equilibrium point $E_8(1, 1, 1)$.



(a) (b)

Figure 1: Effect of government subsidies on evolution results. (a) R_e refers to the subsidies received by mariculturists on the results of system evolution; (b) R_a refers to the subsidies obtained by aquatic enterprises.

Second, we assumed that the other parameter values were constant, $R_\alpha = 3.6, 8$, or 15, and the evolutionary path and probability began to change when the initial position was (0.1, 0.1, 0.1). Figure 1(b) shows that as the value of R_α continued to increase, the evolution rate gradually accelerated first. When R_α reached a certain value, the system deviated from the evolutionary equalization point $E_8\,(1, 1, 1)$. An increase in government subsidies to aquatic enterprises reduced the costs of investing in ecological farming. However, when government subsidy was fixed, the subsidy given to the farmers was relatively small, which failed to encourage farmers to choose ecological farming.

3.2. Effect of Government Fines on Evolution Results. We assumed that the other parameter values were constant, $F = 4, 20, 80$, and the evolutionary path and probability began to change when the initial position was (0.1, 0.1, 0.1). Figure 2 shows that, as the value of F continued to increase, the evolution rate gradually slowed, although the final result converged on the system equilibrium point $E_8\,(1, 1, 1)$. This means that we should not rely too much on government supervision; instead, we should combine the forces of aquaculture enterprises and cooperation organizations to promote the transformation of the ecological aquaculture farming model.

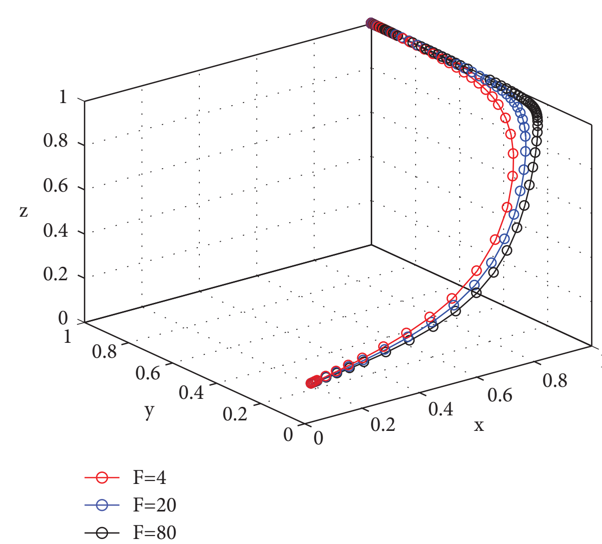
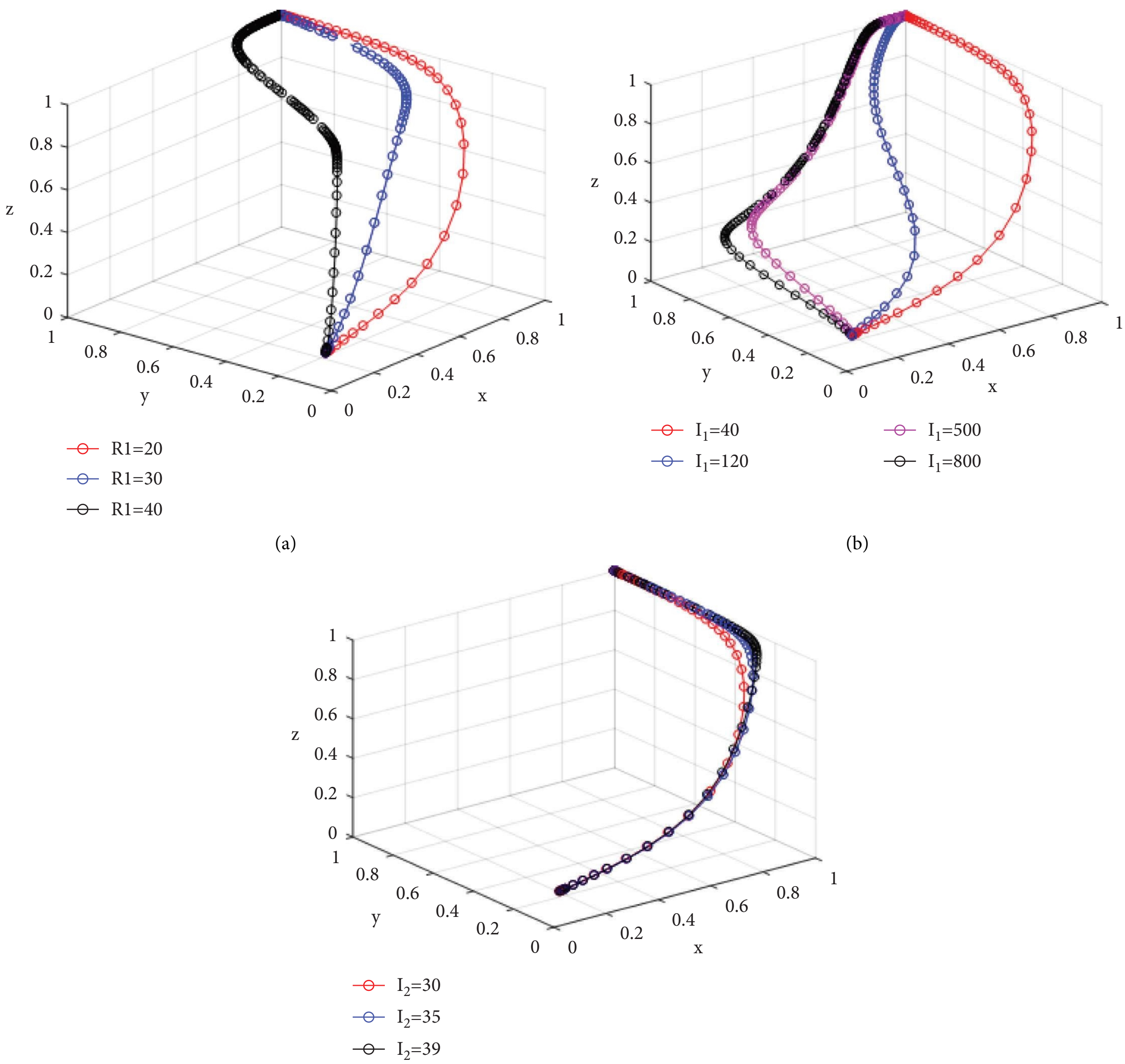


Figure 2: Effect of government fines on evolution results.

3.3. Effect of Market Factors on Evolution Results. First, we assumed that the other parameter values were constant, $R_1 = 20, 30, 40$, and the evolutionary path and probability began to change at the initial position (0.1, 0.1, 0.1). We assumed that the output quantity is stable, the purchase price of eco-aquatic products is high, and the income is high. Figure 3(a) shows that as the value of R_1 continued to increase (mainly because of the increase in acquisition price), the evolution rate gradually accelerated. This indicates that, if the farmers can receive a large profit from the sale of eco-aquatic products, they are likelier to engage in more activities to adopt ecological farming.

Second, we assumed that the other parameter values were constant, $I_1 = 40, 120, 500, 800$, and the evolutionary path and probability began to change at the initial position (0.1, 0.1, 0.1). Generally, it was assumed that the price of eco-aquatic products in the market was relatively high. Assuming that the sales quantity was fixed, the increase in sales revenue I_1 mainly comes from the increase in price. Figure 3(b) shows that, as the value of I_1 continued to increase, the evolution rate accelerated first and then slowed. This indicates that appropriately increasing the price of the products within a certain range can promote the upgrading



(c)

FIGURE 3: Effect of market factors on evolution results. (a) R_1 refers to sales revenue generated by mariculturists adopting the ecological aquaculture model; (b) I_1 refers to the market sales income of aquatic enterprises and mariculturists adopting the ecological aquaculture model; (c) I_2 refers to the sales income of aquatic enterprises, when aquatic enterprises do not invest in ecological aquaculture and mariculturists adopt the ecological aquaculture model.

of ecological aquaculture farming. However, if the market price of eco-aquatic products is too high, consumers buy fewer products.

Third, we assumed that the other parameter values were constant, $I_2 = 30, 35, 39$, and the evolutionary path and probability began to change at the initial position (0.1, 0.1, 0.1). Figure 3(c) shows that, as the value of I_2 continued to increase, the evolution rate gradually slowed. Thus, even if aquatic enterprises did not invest in ecological farming, they could also obtain large benefits as long as they can purchase eco-aquatic products from farmers. This indicates that if the benefits are substantial enough, aquatic enterprises do not choose to invest in ecological farming, which affects the speed of the system converging on the stable equilibrium point $E_8(1, 1, 1)$.

3.4. Effect of Costs on Evolution Results. First, we assumed that the other parameter values were constant, $S_1 = 6, 40, 80$, and the evolutionary path and probability began to change at the initial position $(0.1, 0.1, 0.1)$. Figure 4(a) shows that as the value of S_1 continued to increase, the evolution rate gradually slowed. When the cost reached a certain degree, the evolution result deviated from the system equilibrium point $E_8(1, 1, 1)$. This indicates that if the cost of adopting ecological farming is too high, farmers' activity for ecological transformation is inhibited.

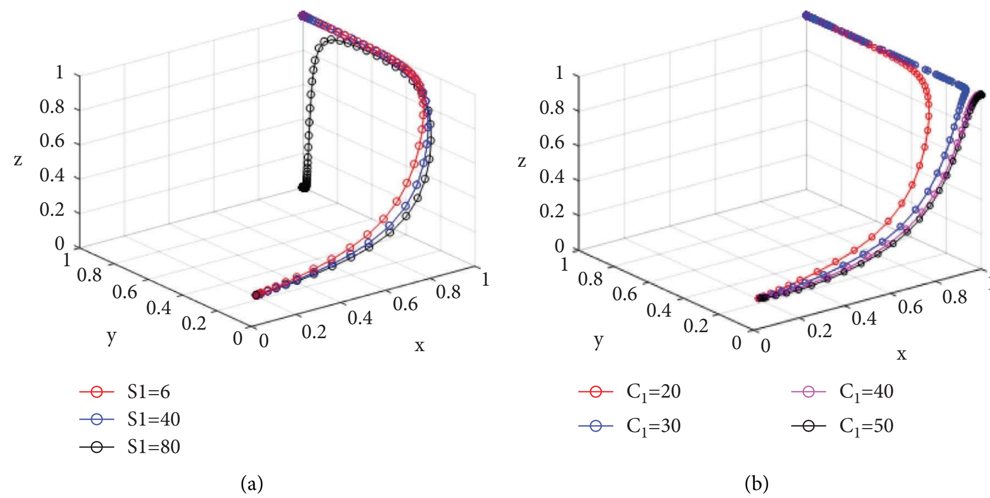


Figure 4: Effect of costs on evolution results. (a) Costs incurred by mariculturists adopting the ecological aquaculture mode; (b) costs (C_1) incurred by aquatic enterprises in investing in the ecological aquaculture mode.

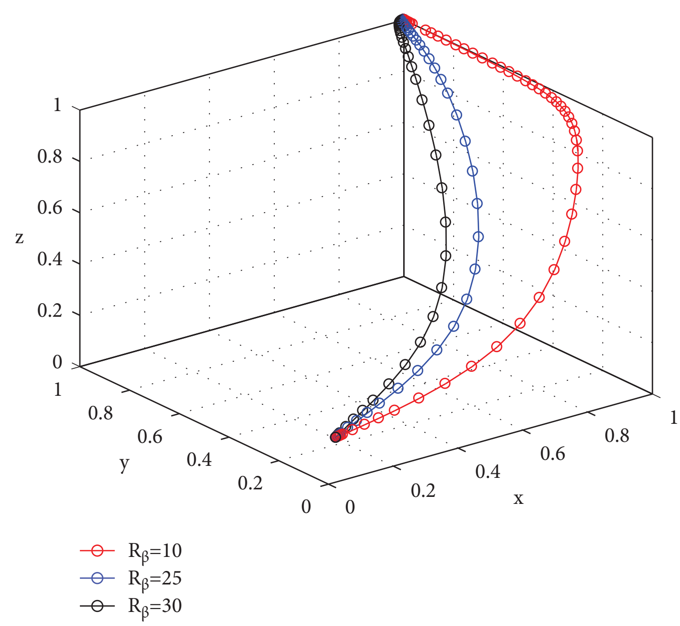


Figure 5: Effect of the brand value of aquatic enterprises on evolution results.

Second, we assumed that the other parameter values were constant, $C_1 = 20, 30, 40, 50$, and the evolutionary path and probability began to change at the initial position (0.1, 0.1, 0.1). Figure 4(b) shows that as the value of C_1 continued to increase, the evolution rate gradually slowed. When the cost reached a certain value, the evolution result deviated from the system equilibrium point $E_8(1, 1, 1)$. The results indicate that cost is an important factor affecting investment by aquatic enterprises in ecological aquaculture. These enterprises only have sufficient incentive to participate in the investment and management of ecological aquaculture when the costs of investment by aquatic enterprises are minimized.

3.5. Effect of Brand Value of Aquatic Enterprises on Evolution Results. We assumed that the other parameter values were constant ($R_\beta = 10, 25, 30$), and the evolutionary path and probability began to change at the initial position (0.1, 0.1, 0.1). Figure 5 shows that as the value of R_β continued to increase, the evolution rate gradually accelerated. This indicates that the brand value is an important factor affecting aquatic enterprises' investment in ecological aquaculture. When these enterprises can obtain greater benefits from investing in ecological aquaculture, they are more enthusiastic to invest in ecological farming. Subject to this outcome, the system accelerates to the point of evolutionary stability $E_8(1, 1, 1)$.

4. Conclusions and Policy Recommendations

The existing research has paid attention to the relevant stakeholders in the ecological transformation of mariculture. However, little empirical evidence has been provided on the micromechanism of the ecological transformation of mariculture from the perspective of the dynamic game. On the premise of bounded rationality, this study formulated an ecological transformation evolution strategy of indicators in mariculture by constructing a dynamic game model of the evolution in three parties and analyzing the important factors that affect the ecological transformation of mariculture. A numerical simulation was conducted to evaluate the rationality of the theoretical model. The conclusions and policy recommendations of this paper are as follows:

(1) In terms of conclusions, the dynamic game model demonstrates how five factors (government subsidies, government fines, the cost of adopting ecological farming by farmers and aquaculture enterprises, the price of eco-aquatic products, and the eco-brand) affect the decision-making of the three parties in the ecological transformation of mariculture. First, government subsidies reduce the cost of adopting and investing in ecological aquaculture technology for farmers and aquatic enterprises. When the system converges to the ideal stable point, $E_8(1,1,1)$, the greater the government subsidy investment, the faster the system converges.

Second, when the government increases fines for aquaculture pollution, the speed at which the system converges at the stable point slows down. Although this punishment is an important way for the government to supervise, it may yield a negative policy effect.

Third, the cost of adopting ecological farming by farmers and aquaculture enterprises will affect their decision to adopt or invest in the practice. The technical implementation cost for farmers is especially high when aquatic enterprises resist investing in ecological aquaculture, and this forces farmers to dismiss ecological farming as a viable alternative.

Fourth, higher market prices (including the purchase and sales price) of eco-aquatic products hasten the ecological transformation of mariculture. Such price increases can make aquatic enterprises and farmers obtain greater benefits, thereby encouraging both parties to actively promote the ecological transformation of mariculture. Although eco-aquatic products should have wide price elasticity, measures should be taken to reduce overly too high prices, which may reduce consumption.

Fifth, aquatic enterprises investing in ecological farming may also be subject to the brand effect. This brand effect is likely to heighten their activities to participate in improving ecological farming.

(2) Several policy implications can be drawn from the above conclusions. First, we suggest that the government can reduce the cost of ecological farming by implementing support measures, including subsidies and preferential loan policies. In the early stages of ecological farming, it is especially vital to expand investments to promote the renovation of aquaculture facilities. Accordingly, the government must provide subsidies and corresponding tax reductions at this stage.

Second, the government should appropriately punish aquaculture pollution and increase the cost of nonecological farming to trigger a shift to ecological aquaculture. However, the government should also increase the awareness of ecological farming. It must guide farmers toward ecological farming rather than advise them to withdraw from aquaculture altogether.

Third, the government should unite enterprises and research institutions to provide training and guidance focused on marine aquaculture technology, especially on-site guidance. It is necessary to accelerate improvements in infrastructure. Moreover, these changes must be implemented at the earliest possible stage.

Fourth, it is necessary to strengthen the public awareness of aquatic enterprises actively investing in ecological farming, so that enterprises can benefit from the brand appreciation brought by good reputation. This ultimately makes them more willing to invest in R&D and the promotion of ecological aquaculture technology and thus more willing to build the "brand" of eco-aquatic products.

This study used the evolutionary game theory to analyze the interactive mechanism of the three parties (the government, aquatic enterprises, and farmers) in the ecological transformation of mariculture. However, there were some limitations to this study. The study was limited to abstracting three main agents in the game system, while more agents may need to be considered in the real world. Moreover, if objective data become more precise, future studies can validate our findings through the numerical simulation approach.

5. Disclosure

Qun Zhang is the first author in this study. Yuanzhu Wei is the corresponding author in this study.

Data Availability

The data generated and analyzed in this manuscript are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

All authors have read and approved the final manuscript.

Acknowledgments

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