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An evolutionary game study of environmental regulation strategies for marine ecological governance in China

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The choice of environmental regulation strategies for marine ecological pollution governance is vital for China's promotion of collaborative marine ecological management. First, based on the assumption of limited rationality, we established a three-party evolutionary game model of China's central government, local governments, and marine enterprises from the perspective of environmental policy to explore the dynamic evolution process of the game strategies of the three participants and the stability of the system equilibrium point. Second, we used numerical simulations to investigate how the incentive- and penalty-based policies of central and local governments have different effects on local governments and marine enterprises, respectively. Finally, we introduced a reputation loss model of public participation to explore the game strategy choices of the three parties under public participation. The finding reveal that (1) Local governments are more sensitive to the central government's punishment policies than marine enterprises are. (2) Increasing the punishment of local governments on enterprises can simultaneously enhance the willingness of enterprises to govern and the willingness of local governments to implement. Moreover, the local governments policy of punishing enterprises was more direct and effective than that of the central government. (3) Although local governments subsidies for marine enterprises can increase their probability of governing marine ecology, they can also decrease local governments' willingness to implement. Finally, (4) Public participation can quickly promote the active governance of marine enterprises. Accordingly, the suggestions are proposed to maintain China's marine ecological security, e.g., the central government should focus on urging local governments to strictly implement marine environmental protection policies; local governments should take the lead in supervising and guiding marine enterprises; and all levels of government need to take measures to promote public participation in marine ecological governance.

KEYWORDS

marine ecological governance, environmental regulation strategy, evolutionary game, numerical simulation, public participation

1 Introduction

At the end of the 20th century, China planned to vigorously develop its marine economy and incorporate the development and utilization of marine resources into its national development strategy (Mallory, 2015; Winther and Su, 2020; Li et al., 2020; An et al., 2022). However, China's marine ecology problems have become more acute as marine resource consumption and the acceleration of urbanization and industrialization have increased in coastal areas, resulting in highly adverse consequences for human survival (Manzoor et al., 2018; Kelly et al., 2019; Chen and Zheng, 2020; Haas et al., 2022). To reverse this crisis, the Chinese government has gradually adjusted its strategic policy from vigorously developing the marine economy to constructing a marine ecological civilization, including measures for combating marine pollution, restoring marine ecosystems, and protecting marine biodiversity. Overall, China's marine ecological management system has achieved positive results. The information disclosed in the 2018 and 2019 China Marine Ecological Environment Status Bulletins indicates that China's marine ecological quality is generally stable. However, some areas still have problems, such as increased marine ecological pollution (Gao et al., 2022b), reduced biodiversity (Xu et al., 2012), declining fishery resources (Yuan et al., 2022), and frequent natural disasters and emergencies (Chen et al., 2017). Ecological fragility and high resource loads have become the norm. Environmental regulation plays a vital role in promoting marine ecological protection (Wright, 2014; Kelly et al., 2019; Chen and Qian, 2020; Liu and Chen, 2022). China's environmental regulatory policies are often formulated by the central government and implemented by local governments. However, local governments often neglect central government policies and tweak enterprise supervision due to high implementation costs or to pursue local economies (Rosenberg, 2009; Chang et al., 2013; Li et al., 2020). Local governments thus form non-cooperative game relationships with the central government. Therefore, choosing a reasonable environmental regulation policy and forming an idealized cooperative game model of "central government guidance, local government promotion, and marine enterprise implementation" has become a key issue in China's marine ecological governance.

As an important element of government social regulation (Niu et al., 2017; Nielsen et al., 2019; Eghbali et al., 2022), the implementation of environmental regulation inevitably involves the interests and strategic choices of multiple co-regulatory actors. The behavioral strategies of subjects with limited rational co-regulation are optimized chiefly through repeated trial and error and learning imitation to reach a stable state (Weibull, 1997; Sotomayor et al., 2020; Wang et al., 2022). This indicates that environmental regulation issues are suitable for evolutionary game analysis. Through the continuous efforts of scholars, many research results have been achieved regarding the evolutionary games of environmental co-regulation subjects. These can be divided into the following four types.

(1) The game of environmental behavior between central and local governments.

Marine ecological management is closely related to government structure. China's central government gives local governments the authority to manage the environment, which constitutes a typical principal–agent relationship. Nevertheless, local governments often neglect to protect the ecological environment in order to win promotional tournaments based on GDP assessments. Yu and Wang (2013) created a Stackelberg model to simulate central and local government solutions regarding afforestation projects and showed that, while the central government tries to maximize eco-efficiency, local governments tend to reduce their administrative budgets due to budget constraints. Kolk and Tsang (2017) explored the strategic choices of central and local governments regarding automotive companies and their sustainability using a mathematical model. The results showed that the central government favored small cars for the sake of environmental development sustainability, whereas local governments focused more on large cars to pursue municipal development. Teichmann et al. (2020) took the environmental game as their starting point and analyzed central government measures taken to combat corruption in local governments. The results showed that excessive government subsidies increased the risk of public official misappropriation and that compliance bonuses may be an effective way to eliminate corruption. Sun et al. (2021) analyzed the key factors in environmental strategy choice between central and local governments based on evolutionary game theory. They pointed out that the choice of environmental behavior for central and local governments depends on a comparison between costs and benefits in governance. Zhu et al. (2022) explored the influence of relevant factors on environmental strategies between central and local governments, finding that there is no evolutionary equilibrium strategy for China but that incentive policies can help the central government guide local governments in choosing environmental strategies in the short term.

(2) The game of environmental behavior among local governments

To develop the local economy, compete for mobile resources, and obtain public support, local governments will launch a political game, which will ultimately affect regional environmental development. In research on Vietnam, Clausen et al. (2011) found that local governments focusing on the game of economic growth would ignore environmental problems, which would ultimately affect the sustainable development of the whole country. Driscoll (2018) proposed that the fierce political game is an antidote for obtaining social sponsorships but also aggravates social tension and instability because, when the two major political parties compete closely for local elections, local governments pay more attention to environmental development in order to win the trust of the people. Meckling and Nahm (2019) affirmed the positive impact of the British political game on green development. They found that local governments use political signals to promote green technology change and enable states to communicate green policies to producers and consumers. In other words, when a local government issues green policies, other local governments may follow closely to seize a competitive advantage. Some scholars argue that games among local governments may cause environmental damage. Jin et al. (2020) analyzed the impact of environmental gaming behavior between governments across regions on local green total factor productivity based on a panel dataset of 278 prefecture-level cities in China.

(3) The game of environmental behavior between local governments and enterprises

Enterprises are key players in pollution emissions and are the main drivers of local economic growth. Therefore, it is important to study the strategic interaction behavior between the government and enterprises in ecological governance. Fairchild (2008) studied the game between governments and enterprises in environmental pollution regulation, using mathematical modeling to analyze the strategic interactions of the participating actors. The results show that enterprises' motivations for ecological governance are closely related to investment costs. By applying cooperative game theory, Meibodi et al. (2015) analyzed how the Iranian and Iraqi governments combat enterprises that generate dust. The results show that cooperation between governments can effectively reduce government supervision costs and improve the government's net revenue. Cai et al. (2016) studied the behavior of the government and two competing firms using an evolutionary game and performed a simulation analysis. The results indicate that the standard penalty strategy has the best suppression effect on environmental pollution, whereas the dynamic penalty strategy can stabilize the fluctuation of the evolutionary game process. Nielsen et al. (2019) studied how government policies affect the strategic choices of enterprises. The results show that, under government incentive measures, it is beneficial for enterprises to establish sustainable development as a goal, increase green investment, and foster environmental improvement. Eghbali et al. (2022) argue that government intervention affects green behavior among enterprises. They find that the government's static intervention reduces the maturity of green startups and improves their innovation level, ultimately reducing their willingness to cooperate with technological enterprises. When the government intervenes dynamically, cooperation between technology companies and green startups is more desirable.

(4) The behavioral game of multiple interests of multiple subjects in environmental governance

Realistic environmental regulation is a complex system of interactions among multiple subjects. Studying the game between only two parties will lead to incomplete research results. Studying the game between multiple subjects can effectively address current research gaps. Based on game theory, Barari et al. (2012) discuss how to establish coordination among manufacturers, retailers, and customers to evaluate their strategies for triggering green practices. The results show that manufacturers can invest in green activities and pass on the cost of greening to customers; retailers then have to invest the maximum marketing cost to emphasize the green dimension to offset the price increase. Bašič et al. (2015) analyzed the environmental behavior game of governments, enterprises, and other subjects to mitigate climate change. They argued that the uncertainty of environmental governance will make all subjects inclined to win-win cooperation. At the same time, they also found that only coordinated actions by multiple participants could effectively reduce greenhouse gas emissions. Xiao et al. (2019) developed an evolutionary game model of collaborative innovation involving multiple actors, including governments, enterprises, financial institutions, and research institutions. They found that complementarity in the resources and capabilities of multiple actors is a crucial factor in forming collaborative innovation alliances and an essential source of additional benefits for innovation actors. Gao et al. (2022b) analyzed the tripartite game mechanism comprising government, marine enterprises, and the public under a new media background. The results showed that a fair new media environment would positively affect marine ecological governance.

In summary, the literature offers many interesting research results regarding the strategic evolution game of environmental co-regulation subjects, but it has several shortcomings. First, the literature describes the regulatory strategies of the central government as either supervision or non-supervision. However, due to China's strong emphasis on marine ecological governance, the central government ignores the fact that marine ecology is inconsistent with reality. Second, most scholars study only the central government, local governments, or the public as the game's leading players. Few scholars have put the central government, local governments, and enterprises into the same game framework and simultaneously considered the impact of public participation on the evolutionary game. Third, most studies only examine whether the regulatory policy has a positive or negative impact on each governance subject in environmental regulation, and ignore whether there are differences between each impact. As China's marine ecological protection policy is improving, studying the effects of different regulatory policies on the same subject and those of the same regulatory policy on different subjects can provide a theoretical basis for using environmental regulatory policies more reasonably.

This study makes several important contributions to the literature. First, considering that the central government's regulatory behavior may range between full supervision and no supervision, this study introduces a degree variable into the strategic choice of the central government. Second, we construct a dynamic evolutionary game model for the central government, local governments, and marine enterprises. We then introduce the reputation loss model of public participation to explore its impact on the players' strategy. Finally, we set the game variables according to the environmental regulation policies implemented in China. We also use MATLAB to change the parameters to explore the differences between punitive-based and incentive-based environmental regulation policies. Finally, this study provides a theoretical basis and policy reference for the efficient management of marine ecology.

The remainder of this paper is organized as follows. Section 2 constructs and solves the evolutionary game model of marine ecological governance and analyzes the evolutionary stable point (ESS) based on the life cycle theory of circular economy. Section 3 introduces the influence of the parameter changes in the relevant policy variables on the ESS through numerical simulation. Finally, Section 4 summarizes and concludes the study.

2 Methodology

2.1 Model assumptions

Given the actual situation of China's marine ecological governance regulation policy, this study proposes the following seven model hypotheses (model parameters and descriptions are expressed as shown in Table 1).

Hypothesis 1: The central government (CG) is participant 1, local governments (LGs) are participant 2, and marine enterprises (MEs) are participant 3. All three parties are finite rational participants, and the strategy choice is stabilized over time using the optimal strategy.

Hypothesis 2: Some scholars divide the central government's strategy simply into supervision and non-supervision (Eghbali et al., 2022). However, the central government, as the main leader of the country's development, cannot completely ignore the pollution behavior of enterprises (Chen et al., 2021). Therefore, we improved the strategy space selection for the central government and set the strategy space of CG as "strict supervision" and "weak supervision"; the proportion of strict supervision is x, and the proportion of weak supervision is 1 - x, $x \in [0,1]$. The strategy space of the LGs is "positive implementation" and "negative implementation"; the proportion of those who choose positive implementation is y, and the proportion of those who choose negative implementation is 1 - y, $y \in [0,1]$. The strategy space of MEs is "positive governance" and "negative governance"; the proportion of those who choose positive governance is z, and the proportion of those who choose negative governance is1 - z, $z \in [0,1]$.

Hypothesis 3: The cost of central government regulation is affected by regulation intensity (Sun et al., 2021; Gao et al., 2022a). However, some scholars simply set the regulatory cost as a fixed value (Du et al., 2022) and do not consider the dynamic effect on cost of regulatory intensity. Therefore, we use r to

TABLE 1 Model parameters and expression meanings.

Players	Parameter	Description
Central government	r	CG's supervision efforts
	C_1	Cost of strict supervision by CG
	S	CG subsidies to LGs and MEs
	m	Influence coefficient of local marine ecological governance level on national marine ecological governance level
Local governments	q	Rate of subsidies transferred from CG to MEs by LGs
	C_2	Costs incurred by LGs when positively implementing marine ecological governance policies
	E	Net environmental benefits generated by LGs when MEs are positively governed (compared to negatively governed)
	P_1	Penalties suffered by CG when LGs do not implement marine ecological management policies, but also the benefits of CG
	i	Share of LGs in CG's and LGs' taxes
Marine enterprises	R	Additional benefits of positive governance (compared to negative governance) for MEs
	C_3	Costs paid by MEs when positively governing marine ecology
	P_2	Penalties of LGs for MEs' negative governance
	P_3	Penalties of CG for MEs' negative governance
	α	Probability of negative ME governance being discovered by CG
	T_1	Lower environmental taxes levied when MEs govern actively
	T_2	Higher environmental taxes levied when MEs govern negatively

denote the CG's supervision intensity, $r \in (0,1]$. When the CG chooses the strict supervision strategy $r = 1$, the supervision cost is C_1. When the CG chooses the weak supervision strategy, $0< r< 1$ will generate a supervision cost rC_1. The introduction of r considers the CG's strategic choice more comprehensively and improves the assumptions of previous scholars regarding the cost of setting up CG supervision.

Hypothesis 4: When LGs choose a positive implementation strategy, it incurs an enforcement planning cost C_2. Moreover, strict enforcement by LGs will force MEs to choose active governance and improve the LGs' environmental performance (Fan et al., 2021). E is the net environmental benefit generated by LGs when the MEs are positively governed compared to when they are negatively governed; when LGs choose negative implementation strategies, they are penalized by the CG, including *via* economic and political penalties, denoted as P_1 ; and the level of local marine ecological governance indirectly affects the governance effectiveness of CG, with m denoting the influence coefficient of local marine ecological governance level on the national marine ecological governance level, $0< m< 1$.

Hypothesis 5: The enhanced benefits of positive ME governance (compared to negative ME governance) are R, and the additional cost of management is C_3; when MEs choose negative governance, they are penalized by LGs, expressed as P_2. According to China's Marine Inspection Regulations, the CG has established a National Marine Inspection Committee to guide, coordinate, and monitor the national marine ecological situation. We thus assume that there is an α $(0 \le \alpha \le 1)$ probability that the pollution behavior of MEs will be discovered and punished by the CG; the penalty amount is denoted as P_3. While Jiang and Li (2021) assume that MEs will definitely be punished by the CG when they display pollution behavior, this study considers a certain probability of being penalized given China's actual policy, which improves upon the previous assumptions in the literature.

Hypothesis 6: To better promote marine ecological governance, the government (including the CG and LGs) will adopt a series of incentive and penalty policies, including financial subsidies, fund allocation, environmental taxation, and tax sharing policies. (a) Regarding the financial subsidy policy, the "Marine Ecological Protection and Restoration Funds Management Measures" issued by the Chinese Ministry of Finance state that the CG will provide, through general public budget arrangements, a dedicated transfer fund to support marine ecological governance and protection, which is important for ecological security and has a wide range of ecological benefits. We assume that S is the transfer payment amount of the CG, which can effectively reduce the implementation costs of LGs and the governance costs of MEs. (b) Regarding fund allocation policy, this concerns the proportion of LGs that have the right to decide on the allocation of funds to MEs. Reiling et al. (2021) stated that LGs may transfer all or part of their funds to enterprises. Therefore, the distribution ratio in this study is q $0 \le q \le 1$. (c) Regarding environmental protection tax policy, the "Marine Engineering Environmental Protection Tax" issued by the State Administration of Taxation of China and the State Oceanic Administration of China mandates that the government shall determine the taxable amount of an enterprise by multiplying the number of its pollution equivalents by the specific tax amount, and the amount of pollution generated when the enterprise is positively governed must be smaller than that when it is negatively governed. Therefore, T_1 and T_2 represent the environmental taxes levied on the positive and negative governance of MEs, respectively; thus $T_1< T_2$. (d) The tax-sharing policy addresses the CG's and LGs' financial rights, and the core is the division of tax revenues (Buettner et al., 2011). We assume that i represents the share of LGs in the taxes; thus $0 \le i \le 1$. When the CG raises the share of LGs in environmental taxes, it can encourage LGs to take the initiative to implement policies related to marine ecological governance and strengthen marine ecological regulation.

2.2 Payment matrix construction

According to the above conditional assumptions of the evolutionary game and the reality of marine ecological governance, we constructed the payment matrix of the tripartite evolutionary game among the CG, LGs, and MEs, as shown in Table 2.

2.3 Evolutionary stabilization strategy solution based on replicated dynamic equations

In marine ecological governance, the CG, LGs, and MEs influence each other and jointly determine the evolution of the game. According to the "economic man" assumption, the strategy choice of all types of subjects is based on the maximization of their own interests. Therefore, the expected benefits of participating subjects are analyzed with the help of a payment matrix, and then the system's single-population evolutionary stabilization strategy is formed by solving the replicated dynamic equation.

2.3.1 Replication dynamic equation of CG's "strict supervision" behavior and its equilibrium point

Suppose that U_1^1 represents the expected payoff of the CG if they are strictly supervised, and U_1^2 represents the expected payoff of the CG if they are weakly supervised. $\overline{U_1}$ represents the average expected payoff of the CG. U_1^1, U_1^2, and $\overline{U_1}$ can be written as

TABLE 2 Three-party subject game payment matrix.

		Local governments	Marine enterprises	
			positive governance (z)	negative governance (1-z)
Central government				
	Strict supervision (x)	positive implementation (y)	$-C_1$-S+mE+(1-i)T_1, $-C_2$+iT_1+(1-q)S+E, $-C_3$+qS+R-T_1	(1-i)T_2-S-C_1, $-C_2$+iT_2-S+P_2 $-T_2$-P_2
		negative implementation (1-y)	$-qS$-C_1+mE+T_1+P_1, E-P_1, $-C_3$+R+qS-T_1	$-C_1$+P_1+αP_3+T_2, $-P_1$, $-T_2$-αP_3
	weak supervision (1-x)	positive implementation (y)	$-rC_1$+mE-S+(1-i)T_1, $-C_2$+E+(1-q)S+iT_1 $-C_3$+R+qs-T_1	$-rC_1$+(1-i)T_2-S, $-C_2$+iT_2+S+P_2 $-T_2$-P_2
		negative implementation (1-y)	$-rC_1$+mE+rT_1+rP_1-(1+rq-r)S, E-rP_1+(1-q)(1-r)S $-C_3$+R+qS-rT_1	$-rC_1$+rP_1+raP_3+rT_2-(1-r)S (1-r)(1-q)S-rP_1 $-raP_3$+(1-r)qS-rT_2

$$\begin{cases} U_1^1 = yz[-S - C_1 + mE + (1-i)T_1] + y(1-z)[(1-i)T_2 - S - C_1] + (1-y)z(-qS - C_1 + mE + T_1 + P_1) + \\ \quad (1-y)(1-z)(-C_1 + P_1 + \alpha P_3 + T_2) \\ U_1^2 = yz[-rC_1 + mE - S + (1-i)T_1] + y(1-z)[-rC_1 + (1-i)T_2 - S] + (1-y)z[-rC_1 + mE + rT_1 + rP_1 - \\ \quad (1 + rq - r)S] + (1-y)(1-z)[-rC_1 + rP_1 + r\alpha P_3 + rT_2 - (1-r)S] \\ \overline{U_1} = xU_1^1 + (1-x)U_1^2 \end{cases}$$

Then, according to evolutionary game theory, the replicator dynamics of the CG adopting the "strict supervision" strategy can be written as

$$F(x) = x(1-x)[(1-r)(-C_1 + T_2 + S + P_1 + \alpha P_3) - y(1-r)(S + P_1 + \alpha P_3 + T_2) - z(1-y)(1-r)(qS + T_2 - T_1 + \alpha P_3)]$$

Make $F(x) = \frac{dx}{dt} = 0$; the obtained solution may be the equilibrium point of the evolution process.

When $z \neq z^* = \frac{(1-r)(-C_1+T_2+S+P_1+\alpha P_3)-y(1-r)(S+P_1+\alpha P_3+T_2)}{(1-y)(1-r)(qS+T_2-T_1+\alpha P_3)}$, we obtain x=0 and x=1 as the two possible equilibria of $F(x)$. According to the stability theory of the replica dynamic equation, it can be concluded that, when $\frac{dF(x)}{dx} < 0$, this point is ESS.

We can obtain the following formula by taking the derivative of $F(x)$:

$$\frac{dF(x)}{dx} = (1-2x)[(1-r)(-C_1 + T_2 + S + P_1 + \alpha P_3) - y(1-r)(S + P_1 + \alpha P_3 + T_2) - z(1-y)(1-r)(qS + T_2 - T_1 + \alpha P_3)]$$

When $z = z^* = \frac{(1-r)(-C_1+T_2+S+P_1+\alpha P_3)-y(1-r)(S+P_1+\alpha P_3+T_2)}{(1-y)(1-r)(qS+T_2-T_1+\alpha P_3)}$, then $F(x)\equiv 0$, indicating that all points on the x-axis are in a steady state, and implying that the CG's strategy choice does not change with time at this point.

When $0<z<\frac{(1-r)(-C_1+T_2+S+P_1+\alpha P_3)-y(1-r)(S+P_1+\alpha P_3+T_2)}{(1-y)(1-r)(qS+T_2-T_1+\alpha P_3)}$, then $\frac{dF(x)}{dx}_{x=1} < 0$, $\frac{dF(x)}{dx}_{x=0} > 0$, Therefore, x=1 is the equilibrium point for the evolution of the CG's behavior. That means that, if MEs tend to opt for negative governance, then the probability of the CG's "strict supervision" strategy will approach 1.

When $\frac{(1-r)(-C_1+T_2+S+P_1+\alpha P_3)-y(1-r)(S+P_1+\alpha P_3+T_2)}{(1-y)(1-r)(qS+T_2-T_1+\alpha P_3)} < z < 1$, then $\frac{dF(x)}{dx}_{x=0} < 0$, $\frac{dF(x)}{dx}_{x=1} > 0$, Therefore, x=0 is the equilibrium point for the evolution of the CG's behavior. That is to say, if MEs tend to opt for positive governance, then the probability of the CG's "strict supervision" strategy will approach 0.

2.3.2 Replication dynamic equation of LGs' "positive implementation" behavior and its equilibrium point

Suppose that U_2^1 represents the expected payoff of the LGs if they are positively implemented and U_2^2 represents the expected payoff of the LGs if they are negatively implemented. $\overline{U_2}$ represents the average expected payoff of the LGs. U_2^1, U_2^2, and $\overline{U_2}$ can be written as

$$\begin{cases} U_2^1 = xz[-C_2 + iT_1 + (1-q)S + E] + x(1-z)(-C_2 + iT_2 + S + P_2) + (1-x)z[-C_2 + E + (1-q)S + iT_1] \\ \quad +(1-x)(1-z)(-C_2 + iT_2 + S + P_2) \\ U_2^2 = xz(E - P_1) + x(1-z)(-P_1) + (1-x)z[E - rP_1 + (1-q)(1-r)S] + (1-x)(1-z) \\ \quad [(1-r)(1-q)S - rP_1] \\ \overline{U_2} = yU_2^1 + (1-y)U_2^2 \end{cases}$$

Then, according to evolutionary game theory, the replicator dynamics of the LGs that adopt the "positive implementation" strategy can be written as

$$F(y) = y(1-y)\{-C_2 + iT_2 + P_2 + rP_1 + (r + q - rq)S + z[i(T_1 - T_2) - qS - P_2] + x(1-r)[P_1 + (1-q)S]\}$$

Make $F(y) = \frac{dy}{dt} = 0$; the obtained solution may be the equilibrium point of the evolution process.

When $x \neq x^* = \frac{C_2-iT_2-P_2-rP_1-(r+q-rq)S-z[i(T_1-T_2)-qS-P_2]}{(1-r)[P_1+(1-q)S]}$, we obtain y=0 and y=1 as the two possible equilibria of $F(y)$. According to the stability theory of the replica dynamic equation it can be concluded that, when $\frac{dF(y)}{dy} < 0$, this point is ESS.

We can obtain the following formula by taking the derivative of $F(y)$:

$$\frac{dF(y)}{dy} = (1-2y)\{-C_2 + iT_2 + P_2 + rP_1 + (r + q - rq)S + z[i(T_1 - T_2) - qS - P_2] + x(1-r)[P_1 + (1-q)S]\}$$

When $x = x^* = \frac{C_2-iT_2-P_2-rP_1-(r+q-rq)S-z[i(T_1-T_2)-qS-P_2]}{(1-r)[P_1+(1-q)S]}$, then $F(y)\equiv 0$, indicating that all points on the y-axis are in a steady state, and implying that the LGs' strategy choice does not change with time at this point.

When $0<x<\frac{C_2-iT_2-P_2-rP_1-(r+q-rq)S-z[i(T_1-T_2)-qS-P_2]}{(1-r)[P_1+(1-q)S]}$, then $\left.\frac{dF(y)}{dy}\right|_{y=0}<0$, $\left.\frac{dF(y)}{dy}\right|_{y=1}>0$, Therefore, y=0 is the equilibrium point for the evolution of LGs' behavior. This indicates that, if the CG tends to select the "lax supervision" strategy, the probability of the LGs choosing the "positive implement" strategy will approach 0.

When $\frac{C_2-iT_2-P_2-rP_1-(r+q-rq)()-z[i(T_1-T_2)-qS-P_2]}{(1-r)[P_1+(1-q)S]}<x<1$, then $\left.\frac{dF(y)}{dy}\right|_{y=1}<0$, $\left.\frac{dF(y)}{dy}\right|_{y=0}>0$, Therefore, y=1 is the equilibrium point for the evolution of LGs' behavior. This implies that, if the CG tends to select the "strict supervision" strategy, the probability of the LGs choosing the "positive implement" strategy will approach 1.

2.3.3 Replication dynamic equation of MEs' "positive governance" behavior and its equilibrium point

Suppose that U_3^1 represents the expected payoff of the MEs if they govern positively and U_3^2 represents the expected payoff of the MEs if they govern negatively. $\overline{U_3}$ represents the average expected payoff of the MEs. U_3^1, U_3^2, and $\overline{U_3}$ can be written as

$$\begin{cases} U_3^1 = xy(-C_3+qS+R-T_1)+x(1-y)(-C_3+R+qS-T_1)+(1-x)y(-C_3+R+qS-T_1) \\ \quad +(1-x)(1-y)[-C_3+R+qS-rT_1] \\ U_3^2 = xy(-T_2-P_2)+x(1-y)(-T_2-\alpha P_3)+(1-x)y(-T_2-P_2)+(1-x)(1-y)\ [-r\alpha P_3+(1-r)qS-rT_2] \\ \overline{U_3} = zU_2^1+(1-z)U_2^2 \end{cases}$$

Then, according to evolutionary game theory, the replicator dynamics of the MEs adopting the "positive governance" strategy can be written as

$$\begin{aligned} F(z) = z(1-z)\ &-C_3+R+r(qS-T_1+T_2+\alpha P_3) \\ &+y[(1-r)(T_2-T_1+qS)+P_2-r\alpha P_3] \\ &+x(1-r)(qS+T_2-T_1+\alpha P_3)-xy(1-r)(qS+T_2-T_1+\alpha P_3)\} \end{aligned}$$

Make $F(z)=\frac{dz}{dt}=0$; the obtained solution may be the equilibrium point of the evolution process.

When $x=x^*=\frac{C_3-R-r(qS-T_1+T_2+\alpha P_3)-y[(1-r)(T_2-T_1+qS)+P_2-r\alpha P_3]}{(1-r)(qS+T_2-T_1+\alpha P_3)-y(1-r)(qS+T_2-T_1+\alpha P_3)}$, then $F(z)\equiv 0$, indicating that all points on the z-axis are in a steady state, and implying that the MEs' strategy choice does not change with time at this point.

When $x\neq\frac{C_3-R-r(qS-T_1+T_2+\alpha P_3)-y[(1-r)(T_2-T_1+qS)+P_2-r\alpha P_3]}{(1-r)(qS+T_2-T_1+\alpha P_3)-y(1-r)(qS+T_2-T_1+\alpha P_3)}$, we obtain z=0 and z=1 as the two possible equilibria of $F(z)$. According to the stability theory of the replica dynamic equation it can be concluded that, when $\frac{dF(z)}{dz}<0$, this point is ESS.

We can obtain the following formula by taking the derivative of $F(z)$:

$$\begin{aligned} \frac{dF(z)}{dz} = (1-2z)\ &-C_3+R+r(qS-T_1+T_2+\alpha P_3)+y[(1-r)(T_2-T_1+qS)+P_2-r\alpha P_3]+ \\ &x(1-r)(qS+T_2-T_1+\alpha P_3)-xy(1-r)(qS+T_2-T_1+\alpha P_3)\} \end{aligned}$$

When $0<x<\frac{C_3-R-r(qS-T_1+T_2+\alpha P_3)-y[(1-r)(T_2-T_1+qS)+P_2-r\alpha P_3]}{(1-r)(qS+T_2-T_1+\alpha P_3)-y(1-r)(qS+T_2-T_1+\alpha P_3)}$, then $\left.\frac{dF(z)}{dz}\right|_{z=0}<0$, $\left.\frac{dF(z)}{dz}\right|_{z=1}>0$; therefore, z=0 is the equilibrium point for the evolution of MEs' behavior. This indicates that, if the CG tends to select the "lax supervision" strategy, then the probability of the MEs choosing the positive governance strategy approaches 0.

When $\frac{C_3-R-r(qS-T_1+T_2+\alpha P_3)-y[(1-r)(T_2-T_1+qS)+P_2-r\alpha P_3]}{(1-r)(qS+T_2-T_1+\alpha P_3)-y(1-r)(qS+T_2-T_1+\alpha P_3)}<x<1$, then $\left.\frac{dF(z)}{dz}\right|_{z=1}<0$, $\left.\frac{dF(z)}{dz}\right|_{z=0}>0$; therefore, z=1 is the equilibrium point for the evolution of MEs' behavior. This implies that, if the CG tends to select the "strict supervision" strategy, then the probability of the MEs choosing the positive governance strategy approaches 1.

2.4 Stability analysis of ESS in tripartite evolutionary game

Based on the above analysis, the three-dimensional dynamical system of the evolutionary game can be written as

$$\begin{cases} F(x) = x(1-x)[(1-r)(-C_1+T_2+S+P_1+\alpha P_3)-y(1-r)(S+P_1+\alpha P_3+T_2) \\ F(y) = y(1-y)\{-C_2+iT+P_2+rP_1+\alpha P_3)+(r+q-rq)S+z[i(T_1-T_2)-qs-P_2] \\ \quad +x(1-r)[P_1+(1-q)S]\} \\ F(z) = z(1-z)\{-C_3+R+r(qS-T_1+T_2+\alpha P_3)+y[(1-r)(T_2-T_1+qS)+P_2-r\alpha P_3] \\ \quad +x(1-r)(qS+T_2-T_1+\alpha P_3)-xy(1-r)(qS+T_2-T_1+\alpha P_3) \end{cases}$$

The ESSs of the system can be obtained as $F(x)$=$F(y)$=$F(z)$=0 . In the three-party evolutionary game, we need only discuss the following ESSs: E_1(0,0,0) , E_2 (1,0,0), E_3(0,1,0) , E_4 (0,0,1), E_5(1,1,0) , E_6 (1,0,1), E_7(0,1,1) and E_8 (1,1,1) (Bjornerstedt and Weibull, 1994). According to Lyapunov stability theory, the asymptotic stability of a system at the equilibrium point can be determined using the eigenvalue of the Jacobian matrix. When the eigenvalue is less than zero, the equilibrium point is the ESS. Thus, we can obtain the eigenvalue expression of the corresponding Jacobian matrix by replacing the aforementioned eight points in the Jacobian matrix (see Table 3). Because $(1-r)C_2>0$ always holds, E_5 (1,1,0) and E_8 (1,1,1) can only be unstable points. Therefore, we only need to discuss the remaining six equilibrium points. The stability conditions for the remaining six points are listed in Table 4.

From the stability conditions of the above six equilibrium points, it can be seen that the difference between the benefits and costs determines the strategy choice of the three subjects. Based on the life cycle theory of the circular economy (Piila et al., 2022), the marine ecological governance process is divided into three stages: the initial, development, and maturity stages. The equilibrium points of different stages are then analyzed.

In the initial stage, the CG neglected marine ecological protection because it paid more attention to the marine economic dividends generated by the use of marine resources, resulting in a lack of systematic and relevant marine ecological governance policies (Xu, 2018). LGs tend to implement marine environmental policies negatively because they lack the constraints of relevant laws and policies, wish to avoid the high cost of implementation, and attach more importance to

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TABLE 3 ESS and eigenvalues of the dynamic system.

ESS	Eigenvalue		
	λ_1	λ_2	λ_3
(0, 0, 0)	$(1-r)(-C_1+T_2+S+P_1+\alpha P_3)$	$-C_2+iT_2+P_2+rP_1+(r+q-rq)S$	$-C_3+R+r(qS-T_1+T_2+\alpha P_3)$
(0, 0, 1)	$(1-r)(-C_1+P_1+T_1+S-qS)$	$-C_2+iT_1+r(P_1+S-qS)$	$C_3-R-r(qS-T_1+T_2+\alpha P_3)$
(0, 1, 0)	$-(1-r)C_1$	$C_2-iT_2-P_2-rP_1-(r+q-rq)S$	$-C_3+R+P_2+T_2-T_1+qS$
(1, 0, 0)	$-(1-r)(-C_1+T_2+S+P_1+\alpha P_3)$	$-C_2+iT_2+P_1+P_2+S$	$-C_3+R+qS+T_2-T_1+\alpha P_3$
(1, 0, 1)	$-(1-r)(-C_1+T_1+S+P_1-qS)$	$-C_2+iT_1+P_1+(1-q)S$	$C_3-R-qS-T_2+T_1-\alpha P_3$
(1, 1, 0)	$(1-r)C_1$	$C_2-iT_2-P_1-P_2-S$	$-C_3+R+T_2-T_1+qS+P_2$
(0, 1, 1)	$-(1-r)C_1$	$C_2-iT_1-r(P_1+S-qS)$	$C_3-R-P_2-T_2+T_1-qS$
(1, 1, 1)	$(1-r)C_1$	$C_2-iT_1-P_1-(1-q)S$	$C_3-R-T_2+T_1-qS-P_2$

TABLE 4 Stability conditions of equilibrium points in the evolutionary game.

ESS	Stability condition
(0, 0, 0)	$(1-r)(-C_1+T_2+S+P_1+\alpha P_3)<0$; $-C_2+iT_2+P_2+rP_1+(r+q-rq)S<0$; $-C_3+R+r(qS-T_1+T_2+\alpha P_3)<0$
(0, 0, 1)	$(1-r)(-C_1+P_1+T_1+S-qS)<0$; $-C_2+iT_1+r(P+S-qS)<0$; $C_3-R-r(qS-T_1+T_2+\alpha P_3)<0$
(0, 1, 0)	$C_2-iT_2-P_2-rP_1-(r+q-rq)S<0$ $-C_3+R+P_2+T_2-T_1+qS<0$
(1, 0, 0)	$-(1-r)(-C_1+T_2+S+P_1+\alpha P_3)<0$; $-C_2+iT_2+P_1+P_2+S<0$; $-C_3+R+qS+T_2-T_1+\alpha P_3<0$
(1, 0, 1)	$-(1-r)(-C_1+T_1+S+P_1-qS)<0$; $-C_2+iT_1+P_1+(1-q)S<0$;$C_3-R-qS-T_2+T_1-\alpha P_3<0$
(0, 1, 1)	$C_2-iT_1-r(P_1+S-qS)<0$; $C_3-R-P_2-T_2+T_1-qS<0$

the economic development of their territories. MEs consider economic interest as their primary goal and lack government constraints, so they continue to expand the scale of production for short-term gain, ignoring the discharge of pollutants into the sea and using marine resources crudely (Saldaña-Ruiz et al., 2022). Therefore, this phase corresponds to the equilibrium point $E_1(0,0,0)$. From Table 4, the following three conditions must be met for the point to be stable: ① $(1-r)(-C_1+T_2+S+P_1+\alpha P_3)<0$;② $-C_2+iT_2+P_2+rP_1+(r+q-rq)S<0$;③ $-C_3+R+r(qS-T_1+T_2+\alpha P_3)<0$. The following array 1 is assigned to satisfy the stability condition in the initial stage: $C_1=21,C_2=18,C_3=20,r=q=m=i=0.5,S=5,T_1=1,T_2=2,P_1=10,P_2=5,P_3=6,R=10,\alpha=0.1,E=6$. Array 1 was randomly started from different initial policy combinations in the range [0,1] and evolved 50 times over time, as shown in Figure 1.

In the development stage, Marine ecological governance is becoming more complex (Brodie Rudolph et al., 2020). As the LGs' and MEs' consumption of marine resources progresses, marine ecological problems are slowly increasing and becoming more complex and challenging to solve. Therefore, marine ecological problems have become an important policy issue for the CG. The CG's focus has shifted from marine economic development to a moderate development of marine resources and marine ecological protection. Relevant policies and regulations have gradually been improved to address the contradiction between marine economic development and marine ecological protection. As the policies and regulations are still being perfected, the constraints on LGs are limited, and they still choose to ignore marine ecological management for the sake of territorial economic development and performance assessment, while indulging the marine pollution of the MEs. Meanwhile, the MEs still disregard marine ecology to maximize profits. Therefore, this stage corresponds to the equilibrium point $E_2(1,0,0)$. From Table 4, the following three conditions must be met for the point to be stable: ① $-(1-r)(-C_1+T_2+S+P_1+\alpha P_3)<0$;② $-C_2+iT_2+P_1+P_2+S<0$;③ $-C_3+R+qS+T_2-T_1+\alpha P_3<0$. The following array 2 is assigned to satisfy the stability condition in the initial stage: $C_1=18,C_2=24,C_3=19,r=q=m=i=0.5,S=6,T_1=2,T_2=3,P_1=10,P_2=5,P_3=6,R=10,\alpha=0.1,E=6$. The systematic evolution path of Array 2 is shown in Figure 2.

In the mature stage, the CG is paying increasing attention to marine ecological issues to ensure the sustainable development of marine ecology. Therefore, marine ecological regulation policies have been deepened and improved in order to induce LGs to perform their duties; these improvements include the CG's environmental tax, fiscal subsidy, fund allocation, and environmental tax sharing policies. The LGs, as "proxy regime operators," will gradually respond to the CG's initiative by adjusting and strengthening their supervision from a political perspective to restrain the marine ecological hazards of the MEs. When the LGs are actively implementing and the MEs are actively governed, the CG will gradually withdraw from supervision to reduce unnecessary financial expenditures. Therefore, the equilibrium point corresponding to this stage is

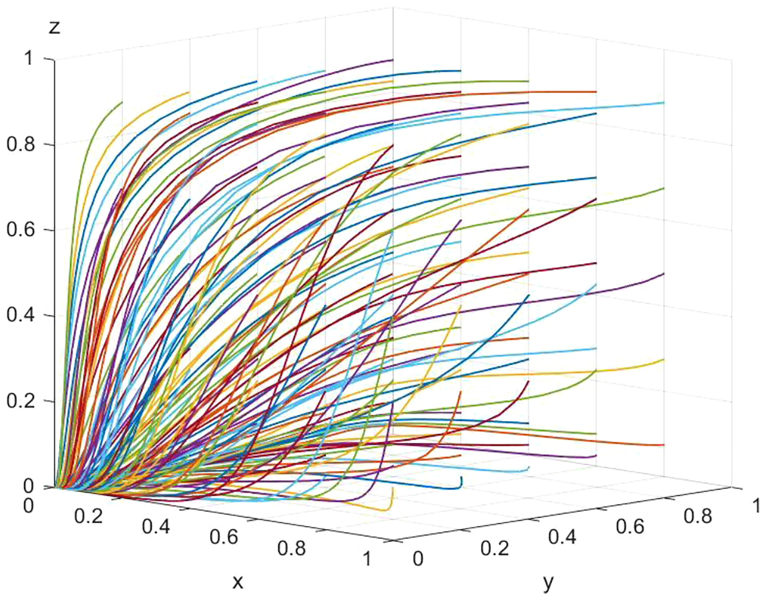

FIGURE 1
Initial stage evolutionary path.

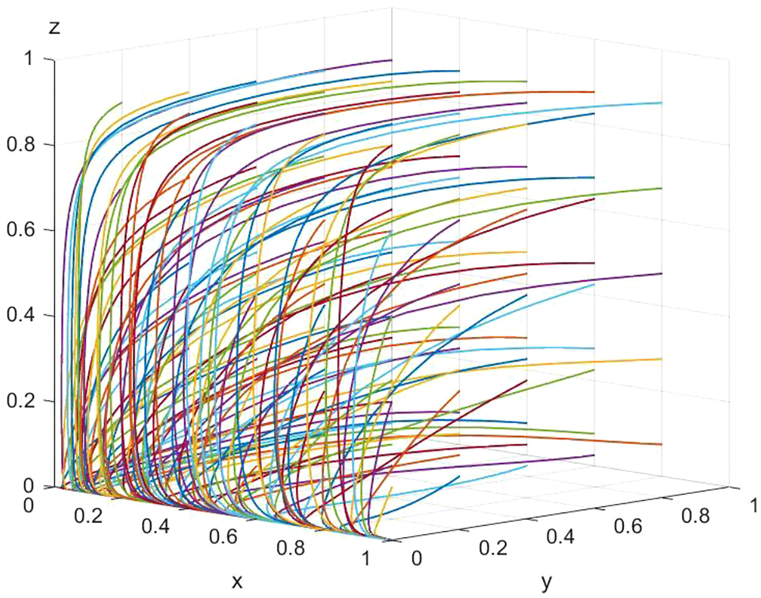

FIGURE 2
Development stage evolutionary path.

$E_7(0,1,1)$, which is the ideal stage for a marine ecological management strategy. From Table 4, the following three conditions must be met for the point to be stable: ① $C_2-iT_1-r(P_1+S-qS)<0$; ② $C_3-R-P_2-T_2+T_1-qS<0$. Assignment of Array 3 to satisfy the stability condition of the maturity stage: $C_1=12$, $C_2=8$,$C_3=10$,$r=q=m=i=0.5$,$S=8$,$T_1=2$,$T_2=4$,$P_1=14$,$P_2=7$,$P_3=8$, $R=5$,$\alpha=0.1$,$E=6$ .The systematic evolutionary path of Array 3 is shown in Figure 3.

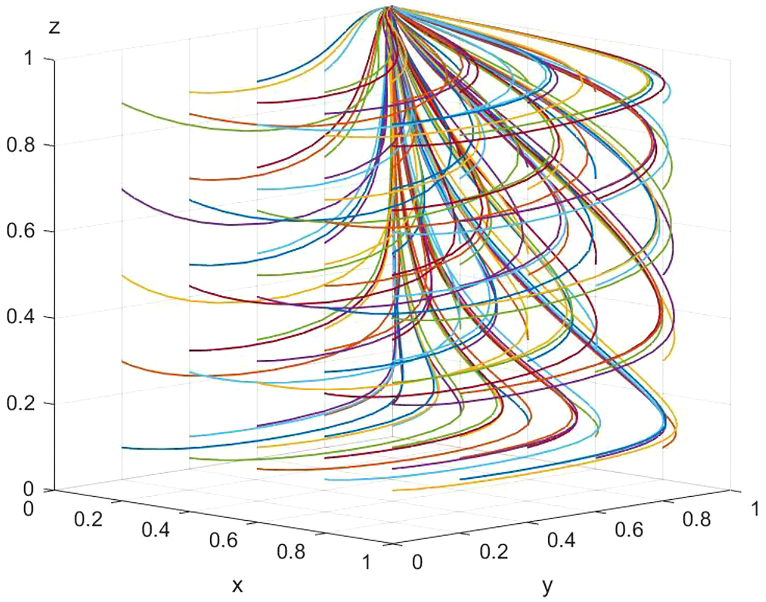

FIGURE 3
Mature stage evolutionary path.

3 Simulation analysis

3.1 Initial strategy simulation analysis

To reflect how these policy changes affect the game players, we use MATLAB to simulate the ideal stage, $E_7(0,1,1)$. As LGs have a geographical advantage (Adewumi, 2021), their governance cost is lower than the CG's supervision cost. By contrast, MEs, as the main subject of marine ecological governance, have governance costs that are higher than the LGs' costs of policy implementation. Once the MEs' violations are discovered by the CG, the CG's penalties become heavier than the LGs'. Therefore, Array 3 satisfied this condition. The willingness to govern marine ecology increased for the MEs, LGs, and the CG, in that order. Drawing on Fan et al. (2022), this study sets the initial probabilities of marine ecology governance by MEs, active implementation by LGs, and strict supervision by CG at 0.3, 0.5, and 0.8, respectively. The results obtained from the initial simulations are shown in Figure 4.

3.2 Simulation analysis of parameter changes

The choices of the three game players may be influenced by many regulatory strategies, including fiscal subsidy policies, environmental tax policies, fund allocation policies, penalty policies, and ecological tax-sharing policies. Therefore, this section examines the impact of various regulatory strategies on the evolutionary game of the tripartite subject. To facilitate the analysis, the CG's incentive is to generate higher financial subsidies, higher fines, and a reduced LG share of tax revenue as a punitive measure. For LGs, reducing their share in the allocation of government and corporate funds is an incentive for MEs, while imposing higher environmental taxes and increasing fines on MEs are penalties.

3.2.1 Impact of CG's incentives on evolution

When the remaining parameters are unchanged, we increase the CG's financial subsidies. This study changes the value of S, fluctuating upward by 50% (S is assigned to 12 and 16, respectively), and the evolutionary path is shown in (2) and (3) in Figure 5. Comparing (1), (2), and (3) in Figure 5, we see that the evolutionary trend of LGs changes very little as subsidies increase, while MEs converge faster. This happens because MEs seek to maximize their economic interests. The MEs are more sensitive to the CG's incentives than the LGs are. Specifically, MEs can use CG subsidies for green technology innovation, shift from old to new dynamics, reduce the cost of marine ecological governance, improve economic efficiency, gain social prestige, and create an endogenous incentive to govern marine ecology. Therefore, the more subsidies MEs receive, the faster they evolve to govern marine ecology, and the stronger their willingness to do so.

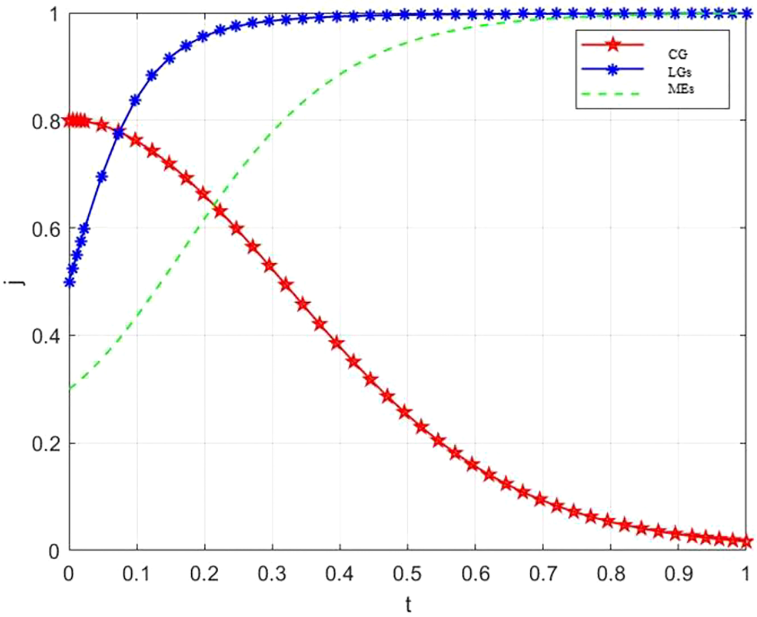

FIGURE 4
Three-way evolution with initial parameters.

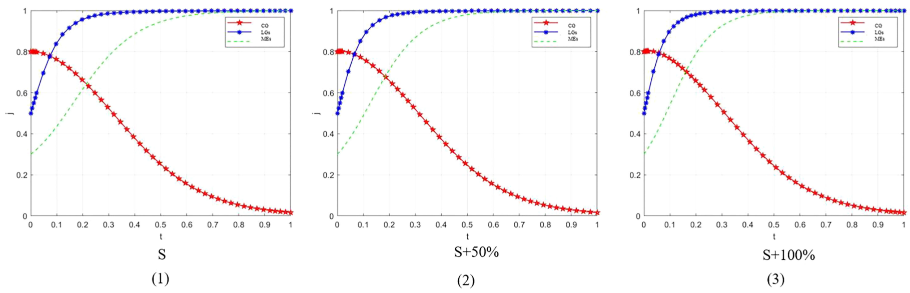

FIGURE 5
The impact of CG' incentives on the evolution.

3.2.2 Impact of CG's penalties on evolution

With the remaining parameters unchanged, when the CG inspects more frequently, sets higher fines, and reduces the tax share of LGs, we obtain P_1 , P_3 , and α , which fluctuate upwards by 50% (P_1 is assigned 21 and 28 respectively; P_3 is assigned 12 and 16 respectively; α is assigned 0.15 and 0.2 respectively), while i fluctuates downward by 50% (i) is assigned 0.25 and 0). The evolutionary path is shown in (2) and (3) in Figure 6. Comparing (1), (2), and (3) in Figure 6 reveals that, as the CG imposes stricter penalties, LGs can quickly reach a steady state of a strict implementation of marine environmental policies; however, this has not been effective in driving MEs to a state of active governance more quickly. The root cause of this fact is that the long-standing pressure-based system in China has made the behavioral logic of LGs fall more in line with the will of the CG. When the CG raises penalties for marine ecological governance, it conveys more precise political intentions to LGs, leading them to actively implement the CG's decisions. In addition, the CG, as the macro-control authority, always has limited human, material, and financial resources to invest in the direct supervision of regional ecological governance. Thus, MEs are more likely to evade accountability and punishment by the CG. As a result, LGs are more sensitive to penalties imposed by the CG than MEs are. The higher the penalties imposed by the CG and the greater the pressure exerted, the faster the LGs evolve towards an active implementation strategy.

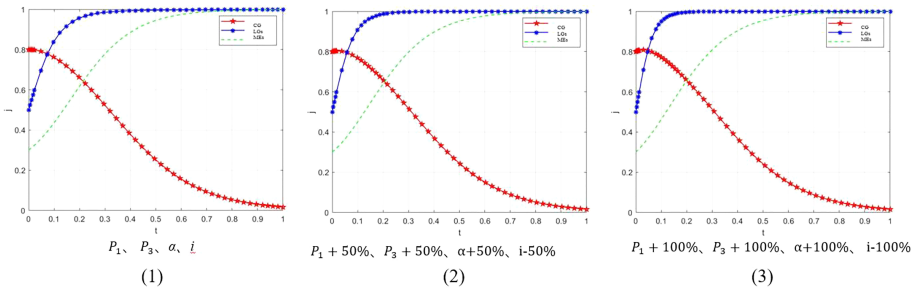

FIGURE 6
The impact of CG' penalties on the evolution.

3.2.3 Impact of LGs' incentives on evolution

When the remaining parameters remain unchanged, we increase the LGs' subsidies to MEs. q is the range of subsidies allocated to MEs by the CG as a percentage of LGs. The LGs can flexibly adjust q to encourage MEs to take responsibility for marine ecology management. When the number of subsidies allocated by the CG is determined, the subsidies that MEs can receive from the LGs are affected only by the allocation ratio q. In this section, we change the value of q fluctuating upward by 50% (assigned to 0.75 and 1), and the evolutionary path is shown in Figure 7. Comparing this to the results shown in Figure 5, we see that the more the proportion of subsidies allocated to MEs increases, the more active MEs will be in governing marine ecology, and the more the rate of "positive governance" will decrease. This happens because LGs have increased their subsidies to MEs, and the internal funding of LGs will decrease. The high supervision cost has led to a small decrease in the frequency of LGs' supervision. By contrast, MEs are the direct beneficiaries of the increased subsidies from LGs. Adequate subsidies incentivize MEs to improve production techniques, implement lean management, transform production methods, optimize business processes, and achieve an intensive use of marine resources. Therefore, when LGs' subsidies to MEs increase, the willingness to apply "positive governance" increases, but the "strict supervision" willingness of LGs decreases.

3.2.4 Impact of LGs' penalties on evolution

When the remaining parameters remain unchanged, we assume that LGs adopt a stricter environmental tax policy with a heavier ecological tax and higher penalty amount. The values of T_1 and P_2 fluctuate upward by 50% (T_1 is assigned to 10.5 and 14, respectively; P_2 is assigned to 3 and 4, respectively), and its evolutionary path is shown in (2) and (3) in Figure 8. Comparing this to the results shown in Figure 5, we see that, as the penalties increase, the curve trend of CG changes little, whereas both LGs and MEs can reach a steady state more quickly. Compared with the results shown in Figure 6 (regarding how the CG's penalties affect the evolution), the LGs' penalties are more likely to force MEs to govern marine ecology than the CG's. The LGs, as the implementers of marine environmental governance policies, have geographical and information advantages over the CG in their jurisdictions. Thus, LGs are more sensitive to marine resource waste, direct discharge into the sea, and negative governance by MEs seeking to maximize profits. MEs are more likely to be negligent about marine ecology, and the opportunity cost of "negative governance" becomes higher. The fines paid by MEs also cover the cost of LG supervision. Therefore, when faced with LG supervision, MEs are more willing to engage in positive governance. At the same time, the fines paid by MEs increase the LGs' willingness to supervise strictly. In summary, LGs are more effective than the CG

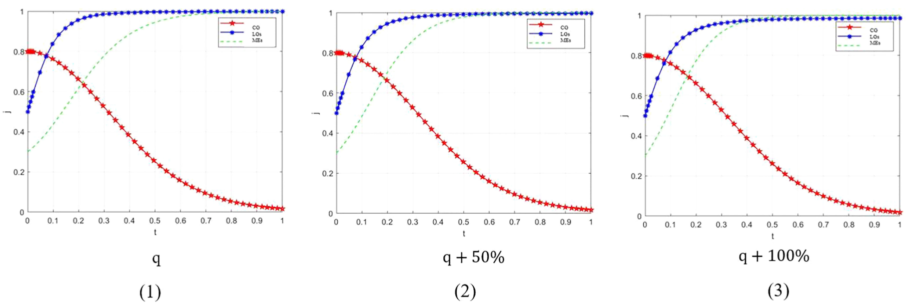

FIGURE 7
The impact of LGs' incentives on the evolution.

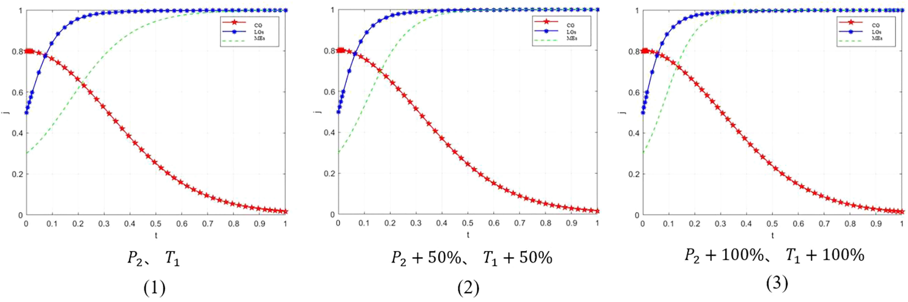

FIGURE 8
The impact of LGs' penalties on the evolution.

in restraining the negative governance of MEs. The stronger the penalties imposed by the CG, the higher the probability that sea-related enterprises and local governments will be inclined to actively govern marine ecology.

3.3 Impact of public participation on evolution

In the protection and governance of marine ecology, public participation can compensate for the lack of government supervision, which is an essential factor influencing ecological governance and the efficiency of pollution control (Gao et al., 2022b). Many countries have adopted public participation to complement their environmental governance. In Japan, the Basic Law for the Environment, enacted in the 1990s, clearly stipulates that citizens have the right to participate in marine ecological governance and the disposal of marine litter, which implies the rights to information, supervision, and consultation. The public's right to ecological information disclosure is guaranteed by law. Denmark was the first country in the world to establish an environmental protection department and enact the Environmental Protection Act, under which the Ministry of Energy and the Environmental Protection Agency were given authority to develop a series of explicit and detailed environmental regulations setting out how the public can participate in marine ecological governance. The United States passed the Freedom of Information Act in 1967, which gave citizens the right to access government information and provided institutional safeguards for public participation in environmental governance. The US National Environmental Policy Act Implementation Regulations, promulgated under the National Environmental Policy Act, stipulate that the public must be fully consulted and supervised throughout the preparation of an environmental impact statement. The Environmental Protection Law of the People's Republic of China was officially implemented in 2015. It not only established a system that allowed the public to access ecological information and participate in ecological protection, but also affirmed the importance of public participation in ecological protection. Therefore, it is necessary to consider the impact of public involvement in marine ecological governance. First, for MEs, negative governance can bring negative externalities to the coastal public. This would lead the public to give the ME a poor rating, resulting in a loss of reputation and operating earnings. This loss is denoted as L_1. Second, for LGs, amid improvements in information disclosure, inaction will cause dissatisfaction among the coastal public, leading to a decline in their credibility; this is denoted as L_2. Finally, for the CG, the public will also have a poor impression of its lax supervision, causing the CG to suffer a loss of credibility; this is denoted as $(1-r)L_3$.

The dynamic replication equation for the tripartite subject was adjusted after the introduction of public participation. The changed replication dynamic equations are as follows:

$$\begin{cases} F(x)_1 = x(1-x)[(1-r)(-C_1+T_2+S+P_1+\alpha P_3+L_3)-y(1-r)(S+P_1+\alpha P_3+T_2+L_3)+ \\ \quad z(1-y)(1-r)(qS+T_2-T_1+\alpha P_3+L_3) \\ F(y)_1 = y(1-y)\{-C_2+iT_2+P_2+rP_1+L_2+(r+q-rq)S+z[i(T_1-T_2)-qs-P_2-L_2]+ \\ \quad x(1-r)[P_1+(1-q)S] \\ F(z)_1 = z(1-z)\{-C_3+R+L_1+r(qS-T_1+T_2+\alpha P_3)+y[(1-r)(T_2-T_1+qS)+P_2-r\alpha P_3]+ \\ \quad x(1-r)(qS+T_2-T_1+\alpha P_3)-xy(1-r)(qS+T_2-T_1+\alpha P_3) \end{cases}$$

In the stability analysis of equilibrium points in a three-party evolutionary game, we must discuss eight particular equilibrium points and one mixed-strategy equilibrium point (Bjornerstedt and Weibull, 1994). The characteristic expressions of the Jacobian matrix are then obtained by substituting each of the eight special equilibrium points into the Jacobian matrix. Because $(1-r)C_2>0$ is constant, only the stability of the six equilibria in Table 5 must be discussed under the stability conditions. In particular, this study focuses on the ideal evolutionary equilibrium point $E_7(0,1,1)$, with no public participation, and the ideal evolutionary equilibrium point $E_7^{'}(0,1,1)$, with public participation. From $E_7^{'}(0,1,1)$ in Table 5, it can be seen that, in the presence of public participation, the MEs' governance strategies are influenced by public evaluations, in addition to the cost of governance, benefits of positive governance, government subsidies, penalties for negative governance, and environmental taxes. |In Figure 9, the MEs in (2)

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TABLE 5 Stability conditions for the equilibrium point under public participation.

equilibrium point	Stability conditions
(0, 0, 0)	$(1-r)(-C_1+T_2+S+P_1+\alpha P_3+L_3)<0$; $-C_2+iT_2+P_2+rP_1+L_2+(r+q-rq)S<0$; $-C_3+R+L_1+r(qS-T_1+T_2+\alpha P_3)<0$
(0, 0, 1)	$(1-r)(-C_1+P_1+T_1+S-qS)<0$; $-C_2+iT_1+r(P+S-qS)<0$; $C_3-R-L_1-r(qS-T_1+T_2+\alpha P_3)<0$
(0, 1, 0)	$C_2-iT_2-P_2-rP_1-L_2-(r+q-rq)S<0$; $-C_3+R+L_1+P_2+T_2-T_1+qS<0$
(1, 0, 0)	$-(1-r)(-C_1+T_2+S+P_1+\alpha P_3+L_3)<0$; $-C_2+iT_2+P_1+P_2+S+L_2<0$; $-C_3+R+L_1+qS+T_2-T_1+\alpha P_3<0$
(1, 0, 1)	$-(1-r)(-C_1+T_1+S+P_1-qS)<0$; $-C_2+iT_1+P_1+(1-q)S<0;C_3-R-qS-T_2-L_1+T_1-\alpha P_3<0$
(0, 1, 1)	$C_2-iT_1-r(P_1+S-qS)<0$; $C_3-R-P_2-T_2-L_1+T_1-qS<0$

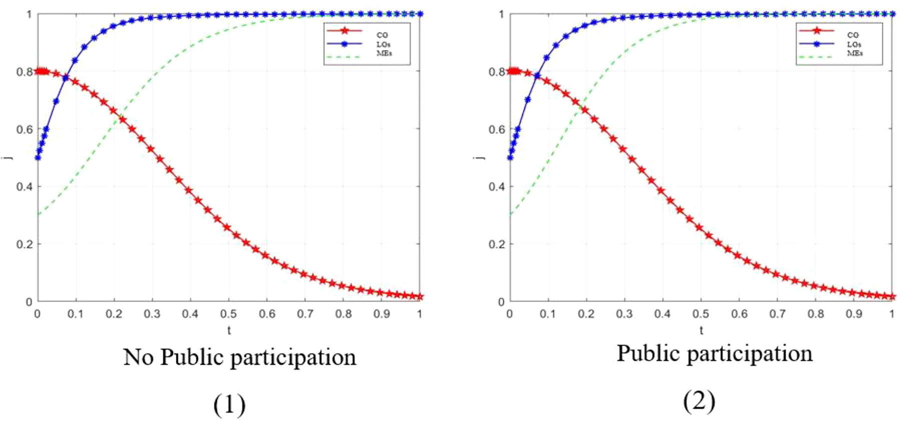

FIGURE 9
The impact of public participation on the evolution.

can evolve to positive governance at a rate much faster than the rate of those in (1). This shows that public participation can accelerate the MEs' adoption of eco-friendly behavior. The ideal situation of strict CG supervision, positive LG implementation, and positive ME governance will soon be realized.

4 Results and discussion

4.1 Results

Based on evolutionary game theory, this study focuses on the problem of marine ecological governance and constructs a three-party evolutionary game model composed of the CG, LGs, and MEs. Moreover, based on the life cycle theory of circular economy, the evolution strategy of the three subjects is sorted out. Then this paper use MATLAB to analyze the influence of policy factors and public participation on the strategic selections of game subjects in the optimal evolutionary stability point. The study draws the following conclusions. (1) CG's penalties have limited effect in pushing MEs to govern marine ecology. In addition, we also find that LGs are more sensitive to CG's penalties. Through policy pressure, CG can effectively guide LGs to strictly implement marine ecological environmental protection policies. (2) Compared with CG, LGs are more direct and effective in punishing MEs to govern marine ecology. In this regard, if the government wants MEs to govern marine ecology positively, LGs need to implement marine ecology policies strictly, increase penalties for non-compliant MEs and enhance the deterrent effect themselves. In reality, many countries have issued a series of environmental laws and regulations to urge subordinate departments to restrict the pollution behavior of enterprises, and have achieved certain results. For example, China's Environmental Protection Inspection Plan and "Environmental Storm" activities, Japan's Environmental Strategy, France's Environmental Charter and the United States' "National Environmental Policy Act", etc. (3) LGs' subsidies are effective in supporting MEs to govern marine ecology, increasing the endogenous motivation for positive governance. However, this crowds out funds for LGs to implement marine ecological policies, leading to a decline in LGs' willingness to do so. (4) With the deterioration of global environment and the improvement of public environmental awareness, polluting enterprises are facing more and more pressure to improve environmental protection (Zhao et al., 2022). Quesnel and Ajami (2017) showed that the public's influence is huge and can directly affect the behavior of the government and enterprises. This paper confirms this view. We find that coastal public participation facilitates the strategy selection of MEs to positively govern marine ecology. Thus, the ideal situation of CG's strict supervision, LGs' positive implementation, and MEs' positive governance will be realized soon.

4.2 Discussion

The research results of this paper may have the following three contributions compared with previous relevant studies: First, previous studies only verified whether the existing marine ecological governance policies have a positive or negative impact on relevant stakeholders (Innes et al., 2015; Song et al., 2020). Few studies compare the differences in impacts. This paper is based on the actual implementation of China's marine ecological governance policies, it compares the effects of different regulatory policies on the same subject and the same regulatory policy on different subjects, which helps the Chinese government to implement marine regulatory policies more efficiently. Second, previous research on marine environmental regulation policies mainly focused on the practice of regulation policies (Matheson, 2019; Roll et al., 2022), lacking relevant theoretical research. This paper explores the actual implementation of China's marine environmental regulation policies using evolutionary game method, which helps to make up for the lack of theoretical research. Third, the previous research subjects of marine environmental regulation policies mainly focused on the CG or LGs (Willis et al., 2018; Song et al., 2022). This paper also considered the CG, LGs, MEs and the public, which is not only helpful to understand the complex relationship between different stakeholders in marine ecological governance, Moreover, it can provide a more comprehensive theoretical basis for the formulation of relevant environmental regulation policies in China.

Based on the above conclusions, this study proposes the following suggestions. (1) The CG should focus its supervision on LGs and gradually establish systems that can ensure the normalization of the supervision process. As a pressure-based accountability mechanism, the CG's ecological willingness can be conveyed to LGs more quickly. Specifically, when marine ecological performance is included in the annual appraisal system of LGs, it can punish government personnel for failing to implement CG policies, urge LGs to implement marine environmental policies strictly, and induce LGs to govern and protect marine ecology. (2) Moreover, LGs should actively take responsibility for marine ecological governance, give full play to their geographical and informational advantages, and strengthen ME supervision and guidance. LGs should provide subsidies to MEs that display positive governance to support them in green technology innovation. In addition to financial subsidies, MEs can seek financial support through equity financing, industrial funds, and bond financing. LGs should also raise the environmental tax rate and increase the penalties on non-compliant MEs to reduce their violations. This will induce enterprises to reduce their emissions, promote intensive production, and ultimately produce a shift from "pollution first and then treatment" to "treatment at source." (3) In addition, the government should establish a system of public participation for marine ecological governance. Although the public is a victim of environmental pollution, they have little awareness of their responsibility to participate in marine ecological governance. First, the government should stimulate the public's awareness of their responsibility to participate in marine ecological governance through awareness raising and training campaigns. Second, the government should improve the incentive mechanism for public complaints and reports about marine ecological problems. Finally, the government could reduce the cost of public participation by establishing public monitoring platforms, hotlines, and litigation channels.

This study resets the central government's strategic choice behavior based on the actual situation in China and makes a breakthrough by integrating multiple marine ecological governance stakeholders into a unified analytical framework. However, it has several limitations. The study is based on relatively idealistic assumptions, wherein the central government, local governments, marine enterprises, and the public are assumed to be independent stakeholders. Moreover, the vertical partners of marine enterprises are not considered. In future studies, we intend to consider a more complex reality by building a more practical model, and thus generate deeper insights.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

LG: conceptualization, writing, review, and editing; AY: conceptualization, writing original draft, methodology, software; QY: writing original draft, methodology, reviewing, and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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