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Original Research

Tripartite Evolutionary Game Analysis of Fishery Carbon Sink Trading in China Based on Prospect Theory

Hailin Mu[1], Peiyao Chen[1], Hongye Wang[2, 3]*, Nan Li[1], Na Xu[4]

[1]Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education,
Dalian University of Technology, Dalian 116024, China
[2]School of Economics and Management, Dalian University of Technology, Dalian 116024, China
[3]Institute of Carbon Peak and Neutrality, Dalian University of Technology, Dalian 116024, China
[4]Dalian Customs Comprehensive Technical Service Center, Dalian 116699, China

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Abstract

The development of fishery carbon sink trading is an important starting point to help China achieve its carbon dioxide emission reduction targets and an inherent requirement for sustainable economic development. However, China's fishery carbon sink trading market is not yet mature, and the influences of multiple factors have blunted stakeholders' enthusiasm for market participation. Therefore, it is important to determine the influencing mechanisms of stakeholders' participation in the fishery carbon sink trading market. In this context, to clarify the factors that affect the enthusiasm of participants, this study establishes a tripartite evolutionary game model of fishery carbon sink trading stakeholders based on the prospect theory. The dynamic evolution trends of the game subjects' strategies are studied, and the effects of unit fishery carbon sink price, government subsidy ratio, psychological effects of the game subjects, and other factors are discussed. With the development of the fishery carbon sink trading market, the development stages can be divided into initial, medium, and mature stages, and the game players choose different strategies at different stages. Different factors affect the choices of the three parties. When psychological factors involve uncertain gains and losses, they are also important in influencing decision-makers' decisions.

Keywords: fishery carbon sink trading, tripartite evolutionary game model, prospect theory, market participation enthusiasm

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*e-mail: wanghongye@dlut.edu.cn;
Tel.: 0411 84708095

Introduction

In September 2020, General Secretary Xi mentioned in his speech that China would adopt more powerful measures to achieve the carbon peaking target by 2030 and achieve the carbon neutrality goal by 2060. The ultimate goal of the dual-carbon target is to achieve a balance between carbon emissions and carbon absorption. Industrial carbon capture and natural carbon sinks are the primary methods of carbon absorption. However, at present, heat and power consumption, and equipment investment in China's CO_2 capture technology are high, leading to a high total cost of industrial carbon capture technology. In contrast, the development of natural carbon sinks has appreciable economic benefits and few detriments. Therefore, making good use of natural carbon sinks will enhance China's realization of its dual-carbon target.

Among the various ecosystems with carbon sink capacities, that of the ocean is significant. By exchanging carbon fluxes with the terrestrial biosphere, nearly 50 % of carbon emissions from human activities can be eliminated [1]. Marine carbon sinks include carbon stored in mangroves, salt marshes, seagrass beds, and fishery carbon sinks. Fishery carbon sinks are closely related to human activities [2-4]. Therefore, carbon sinks in fisheries are economically valuable. Incorporating fishery carbon sinks into carbon trading markets is conducive to achieving the dual-carbon target, and promotes the development of the marine economy and formation of new economic growth factors [5]. In January 2022, Lianjiang County, Fujian Province, relying on the country's first marine carbon sink trading platform, completed a 15,000t fishery carbon sink trading project. This was also the first marine fishery carbon sink trading project in the first trial of local carbon sink construction.

Despite this initiative, China's fishery carbon sink trading market is not yet mature, and stakeholders' enthusiasm for market participation is low due to the influence of multiple factors. Marine carbon sink trading, including fishery carbon sink trading, has not been included in the national carbon emission trading market system, and relevant practices are still mainly piloted locally. China's fishery carbon sink trading market is in its infancy, and the construction of the fishery carbon sink trading market in China is slow. Thus, it is particularly important to improve the market participation enthusiasm of stakeholders and promote the rapid development of the fishery carbon sink trading market. Relatively few studies have addressed carbon sink trading in fisheries. Zheng et al. researched the impact of government subsidies on the evolution of the fishery carbon sink trading market using the evolutionary game method [6]. He et al. constructed a mathematical model including fishery carbon sink producers, research departments, and local governments, and analyzed the stability of the three parties [7]. Prior research on fishery carbon sink transactions has not considered the purchasers of fishery carbon sinks and has not comprehensively analyzed the influencing factors when game players were making decisions, instead only considering government subsidies. This study conducted in-depth research on this basis.

Previous research has mainly focused on blue carbon trading. Few studies have refined research on fishery carbon sink trading. However, because of the particularity of fishery carbon sinks (cultivation of mangroves and seagrass beds do not have the characteristics of a short growth cycle, tradable products, and simple artificial breeding as fishery breeding), previous research on blue carbon trading cannot be fully applied to fishery carbon sink trading.

Furthermore, the actual utility of carbon sink trading has been used as the basis for the analysis of the behavior of game players. However, participation in the construction of a fishery carbon sink trading market has some risks for participants. Therefore, there will be a certain deviation between the psychological perception of utility and the actual utility, which will lead to a difference in the final decisions of the participants. Because in the process of building a fishery carbon sink trading market, participants will face risks. To get the maximum utility, they should use the psychological perception utility rather than the actual utility as a reference. Due to the clear explanation of the decision-making process of human beings in risk situations provided by prospect theory, it is suitable for analyzing the risk decision-making process of each participant involved in the development of the fishery carbon sink trading market.

This study considers local governments (LG), marine ranching (MR), and enterprises in need of fishery carbon sinks (CNFC) as the research objects. The development of the fishery carbon sink requires the joint efforts of producers (MR) and consumers (CNFC). But due to the public good nature of carbon sinks, MR is not highly motivated to develop carbon sink fisheries, and CNFC will not voluntarily carry out fishery carbon sink trading. If LG provides subsidies to MR and CNFC, and supervises the fishery carbon sink trading market, the cost of MR and CNFC to conduct fishery carbon sink trading can be reduced, and LG can ensure that the transaction is fair as a supervisory body; MR sells their fishery carbon sinks to CNFC for ecological and economic benefits; CNFC purchases fishery carbon sinks from MR to meet emission reduction targets. Based on this, LG, MR, and CNFC have formed a fishery carbon sink trading development system, MR can decide whether to breed seafood with carbon sink capacity, CNFC can decide whether to purchase fishery carbon sinks, and LG can decide whether to supervise and provide financial support for the construction of fishery carbon sink trading markets.

Prospect theory and evolutionary game theory are combined to establish a dynamic game model between LG, MR, and CNFC. The main factors influencing decision-making behavior and construction of the fishery carbon sink trading market are studied in depth. For this, a three-party evolutionary game model consisting of LG, MR, and CNFC is constructed, which can effectively describe the interaction mechanism of the behavior strategies of the three stakeholder groups. The influences of the main parameters, including unit fishery carbon sink price, unit carbon tax price, and government subsidy amount, on stakeholder group decision-making are illustrated by numerical simulation. The findings show that the introduction of prospect theory into the three-party evolutionary game model, considering the expected utility of different participants, can effectively improve the scientific nature of the decision-making behavior analysis of the three stakeholder groups.

In the remainder of this paper, the second section reviews the existing literature related to this study. The third section details the construction of a tripartite evolutionary game model of LG, MR, and CNFC. In the fourth section, the evolution process and influencing factors of the fishery carbon sink trading market construction are illustrated through numerical simulation and some corresponding policy recommendations are put forward. Finally, the fifth section presents the research conclusions.

Literature Review

The carbon transaction policy mainly controls CO_2 emissions by reducing the total emissions of enterprises and affecting the cost of enterprise emissions [8]. Carbon emissions and carbon sink trading are two important carbon transaction methods.

Carbon emissions trading is a market mechanism for reducing global greenhouse gas (GHG) emissions [9-11]. Zhang et al. gave a systematic overview of China's ETS pilots from 2013 to 2016, and highlighted some recommendations for the upcoming national systems [12]. A game model was devised to study the decisions of suppliers and consumers under cap-trade regulation [13]. Wang et al. proposed a multi-market syndication transaction process, and proposed a multi-market bidding optimization model based on an evolutionary game [14]. Qi et al. researched the evolution tactics of the carbon market with the goal of dual-carbon with an evolutionary game method [15]. Ma et al. designed a long-term Stackelberg model to study the game of a supply chain with quota and transaction regulation [16]. Pan et al. designed a tripartite game model to analyze the behavioral relationship between commercial sources of emission, third-party verification agencies, and LG [17].

The carbon sink trading mechanism refers to the process by which the ecosystem absorbs CO_2 in the atmosphere and fixes it to reduce its atmospheric concentration [18-21], then entities that exceed their carbon emission quota can purchase units of absorbed CO_2 emissions to offset their emissions. Blue carbon trading and green carbon trading are important components of carbon sink trading. Green trading mainly includes forest and grassland carbon sinks[20]. Blue trading mainly involves carbon stored in coastal ecosystems, such as mangroves, salt marshes, and in fisheries [22-24]. Song et al. comprehensively analyzed the potential of China's forest resources and concluded that the forest carbon sink market should be incorporated into China's carbon emissions transaction market [25, 26]. Forest carbon sinks have great potential. But blue carbon has unique advantages such as a higher carbon sink rate [27]. Fishery carbon sinks are closely associated with human activity. Integrating fishery carbon sinks into the carbon trading market is conducive to achieving the goal of efficient emission reduction and sinks increase, and in promoting economic development. However, research on fishery carbon sinks mainly focused on the natural realm [28-31]. Few studies have focused on the relationship between the strategies of fisheries carbon sequestration stakeholders.

Evolutionary game theory can use mathematical methods to explain the behavior of stakeholders and describe how the interaction of different stakeholders who prioritize their own goals leads to the evolution of a system [32-34]. Evolutionary game theory has a wide range of applications. For example, Chen et al. used evolutionary game theory to evaluate the different hydrogen technologies, providing conditions for all airports and airlines to convert technologies [35]. Duan et al. designed a dynamic game model to analyze the dynamic change and stability of the steel market in China [36, 37]. Xiu et al. designed an evolutionary game model to analyze the relationship among the central government, the local government, and the farmers [38]. Sun et al. studied the evolutionary trends of the tripartite game of waste sorting [39]. Peng et al. combined evolutionary game theory with the pricing model to study the dynamic mechanism in channel selection [40]. Feng et al. studied how the industrial Internet platform guides the sharing of high-quality information in semiconductor manufacturing [41]. As a final example, Zhang et al. designed a four-party evolutionary game model to study the impact of behavioral safety management systems on coal mine safety production [42].

In addition to its past use to study carbon emissions trading, evolutionary game theory can also be used to study the strategic interactions of different stakeholders in the blue carbon trading market. For example, Yu et al. constructed a game model of marine carbon sink trading; and analyzed the impact of management methods on marine carbon sink market trading [43]. Based on the evolutionary game method, a model that includes carbon sink producers, research institutions, and governments was constructed to study how to implement the marine carbon sink fisheries [7]. Wan et al. developed an evolutionary game model of marine ranching, carbon transaction platforms, and governments to study how to promote blue carbon trading [44]. Wan also developed a model consisting of government regulators, carbon trading platforms, and news media to analyze evolutionary equilibrium conditions and evolutionary stability strategies of all parties [45]. Wang et al. designed an evolutionary game model consisting of Chinese government, marine ranching, and companies that need blue carbon. The main parameters were simulated to research the impact of parameter changes on evolution [46]. In another study, the participation probability of stakeholders was improved by evolutionary game theory, and an evolutionary game model of local governments, blue carbon producers and demanders was constructed [47].

Despite these achievements, the evolutionary game model has some limitations. Participants may face risks during the game process. Therefore, there is a certain deviation between the psychological utility of the decision maker and the actual utility, which leads to a difference in the final decisions of the participants. The literature indicates that the prospect theory can effectively solve this problem. Prospect theory has made a significant contribution to human judgment under uncertainty [48]. Many scholars have combined prospect theory with the evolutionary game model to study the influence of the psychological role of the game subject on decision-making and judgment [49-51].

The main contributions of this paper are as follows: This paper discusses the change process and main influencing factors of LG, MR, and CNFC decision-making behavior in the development of the fishery carbon sink market, which can provide an important reference for decision-makers related to the construction of fishery carbon sink trading market; Based on the expected utility of different participants, a tripartite evolutionary game model of LG, MR and CNFC was established based on prospect theory. By introducing psychology and risk into analysis, the scientific analysis of the decision-making behavior of game agents can be effectively improved, and policy suggestions can be provided for LG, MR, and CNFC accordingly.

Material and Methods

In this section, the fundamental hypothesis is proposed and the expected returns of the three stakeholders under different strategic choices are listed. The replication dynamic equation of the three-party evolutionary game model is obtained through calculations. To obtain the evolutionary stable strategy (ESS) of the replication dynamic system, 13 equilibrium points are obtained by calculation, including eight pure-strategy equilibrium points. The Jacobian matrix of the system is calculated, and the asymptotic stability of the equilibrium points is verified by analyzing the eigenvalues of the Jacobian matrix. Finally, the eight ESSs in the system and their eigenvalues are solved.

Cao et al. used evolutionary game theory to improve the probability of stakeholders' participation in building an effective blue carbon transaction market and a mangrove trading in China was used as a case study to validate the game model; The simulation results are consistent with the actual situation, which verifies the accuracy of our model. The instance verification results are consistent with the predicted results, so the example verification shows that the evolutionary game model is effective [47].

However, there may be risks in the evolution of the system, and considering the psychological factors of the game agent will make the research more comprehensive, and the prospect theory can solve this problem well, so this study adds the prospect theory on the basis of the tripartite evolutionary game model, so that the simulation results are more scientific and effective.

Participants and Their Strategy Sets

Stakeholders involved in the establishment of the fishery carbon sink trading market are identified as: LG, MR, and CNFC. LG encourages MR and CNFC to participate in the fishery carbon sink trading market by issuing subsidies. As a regulatory agency, LG can ensure fair trading. MR sells fishery carbon sinks for profit, and CNFC buys the fishery carbon sinks to achieve emission reduction targets.

LG may choose to participate in the construction of the fishery carbon sink trading market to maximize social benefits. However, due to LG's limited financial resources, high subsidies may force it to not support the development of the fishery carbon sink trading market. Therefore, the LG strategy is {participate, not participate}. MR may choose to breed carbon-sink relevant seafood because of LG subsidy and the perspective of social reputation, or may choose not to breed carbon-sink relevant seafood considering the costs and risks of the process. The strategy set for the MR is {breed, not breed}. CNFC may choose to buy fishery carbon sinks from the perspective of social reputation, or may choose to pay a carbon tax to LG because of emission reduction needs or the risk of fishery carbon sink trading. Thus, the CNFC strategy set is {buy, not buy}.

Fundamental Hypotheses

The detailed reason for hypothesis 1 is that the evolutionary game analysis method studies the decision-making of the actor based on the assumption of bounded rationality and learning mechanism, the game party must continuously improve its strategy through a certain period of learning and accumulation to obtain a stable equilibrium result, therefore, it is assumed that the participating subjects, including LG, MR, and CNFC, are the decision-makers of bounded rationality; The detailed reason for hypothesis 2 is that assumptions based on the basic principles of prospect theory; Detailed reasons for hypotheses 3 to hypothesis 6 are that in reality, the behavioral game of LG, MR, and CNFC is quite complex, and it is difficult to take into account every factor and every situation, in order to facilitate the follow-up research, hypotheses 3 to 6 are proposed based on the overall characteristics of the interest game of fishery carbon sink trading.

Based on the above reasons, the following hypotheses are proposed:

Hypothesis 1: The evolutionary game model includes three players: LG, MR, and CNFC. They are not entirely rational and aim to maximize their benefits. In addition, they can learn from each other and change their strategies anytime as the fishery carbon sink trading market develops.

Hypothesis 2: According to prospect theory, when participants are uncertain about profits or losses, there are differences between their perception of profit and loss and their actual value, and the value of the reference point is set to 0.

Hypothesis 3: MR is free to choose whether to participate in the construction of the fishery carbon sink trading market. MR may choose to breed seafood with carbon sink capacity because of LG subsidy incentives or from the perspective of social reputation. Otherwise, MR may choose to breed seafood without carbon sink capacity because of the cost and risks of fishery carbon sink projects.

Hypothesis 4: CNFC carbon emissions have exceeded the specified amount, making it necessary to meet emission reduction requirements by purchasing fishery carbon sinks or paying a carbon tax to LG. If CNFC wants to buy fishery carbon sinks and the local MR does not farm seafood with a carbon sink capacity, CNFC can buy fishery carbon sinks from other regions. CNFC companies trade carbon sinks in fisheries or pay a carbon tax is equivalent to contributing to environmental protection; thus, the company's image will be improved.

Hypothesis 5: The LG may subsidize and supervise MR and CNFC to promote the development of the fishery carbon sink trading market. However, if the subsidy cost is too high, LG may choose not to participate in the fishery carbon sink trading market. The LG department will incur costs in the promotion of the fishery carbon sink trading policy and will also gain image and environmental benefits. If LG does not participate in the fishery carbon sink trading market, it will also gain environmental benefits when fishery carbon sink trading is carried out between MR and CNFC.

Hypothesis 6: The proportion of LG participating in the construction of fishery carbon sink trading market is x ($0 \le x \le 1$), the proportion of MR choosing to breed seafood with carbon sink capacity is y ($0 \le y \le 1$), and the proportion of CNFC choosing to buy fishery carbon sinks is z ($0 \le z \le 1$).

In the process of building a fishery carbon sink trading market, LG, developers, and buyers each have their own strategic choices. The strategies among them influence each other, and different choices have different effects on the development of the fishery carbon sink trading market. To explore the revenue and expenditure of the three players' different behavioral strategies, we set some relevant parameters as shown in Appendix 1.

Expected Return and Replication Dynamic Equation of Each Participant

Based on the above assumptions, the expectations of LG, MR, and CNFC under different strategic choices are explained in Appendix 2, and the benefits are shown in Table 1.

The basic principle of the replication dynamic equation is that a strategy with better results than the average level will gradually be used by more individuals, eventually converging to a stable strategy.

The replication dynamic equation refers to the process in which players in the game can change their original strategies and choose a more advantageous strategy than before on the basis of learning from the behavior strategies of other players.

The formula of the replication dynamic equation formula is $f(x) = dx/dt = x*(A11-A1)$.

Among them, x represents the probability of LG participating in the fishery carbon sink trading market, A1 represents the average return of LG at the current

Table 1. LG, MR, CNFC tripartite game payoff matrix.

Strategy combination	LG gains	MR gains	CNFC gains
A1,B1,C1	V(R2)-V(R1)-w	D*p1+k1*w-Q1*M1+P4*Q1	V(S1)-D*p1+k2*w
A1,B1,C2	V(R2)-V(R1)-k1*w+D*p2	k1*w-Q1*M1+P4*Q1	V(S2)-D*p2
A1,B2,C1	V(R2)-V(R1)-k2*w	-Q2*M2+P3*Q2	V(S1)-D*p1+k2*w
A1,B2,C2	V(R2)-V(R1)+D*p2	-Q2*M2+P3*Q2	V(S2)-D*p2
A2,B1,C1	V(R3)	D*p1-Q1*M1+P4*Q1	V(S1)-D*p1
A2,B1,C2	D*p2	-Q1*M1+P4*Q1	V(S2)-D*p2
A2,B2,C1	0	-Q2*M2+P3*Q2	V(S1)-D*p1
A2,B2,C2	D*p2	-Q2*M2+P3*Q2	V(S2)-D*p2

moment, A11 represents the expected return of LG choosing to participate in the fishery carbon sink trading market at the current moment, $f(x) = dx/dt$ represents the rate of change in the probability that LG chooses to participate in the fishery carbon sink trading market per unit time.

The same is true for $f(y)$ and $f(z)$.

We calculated the expected returns of LG participating or not participating in the fishery carbon sink trading market, which are expressed as A11 and A12 respectively. The average return is expressed as A1.

$$A11 = (V(R2)-V(R1)-w)*y*z+(V(R2)-V(R1)-k1*w+D*p2)*y*(1-z)+(V(R2)-V(R1)-(1-k1)*w)*(1-y)*z+(V(R2)-V(R1)+D*p2)*(1-y)*(1-z); \tag{1}$$

$$A12 = (V(R3))*y*z+(D*p2)*y*(1-z)+(D*p2)*(1-y)*(1-z); \tag{2}$$

$$A1 = x*A11+(1-x)*A12 \tag{3}$$

According to the three equations above, the replication dynamics equation $f(x)$ of the LG can be obtained.

$$F(x) = dx/dt = x*(A11-A1) = x*(x-1)*(V(R1)-V(R2)+k1*w*y+k2*w*z+V(R3)*y*z) \tag{4}$$

The expected returns of MR breeding seafood with carbon sink capacity or ordinary seafood were calculated and expressed as B11 and B12, respectively, and the average return was expressed as B1.

$$B11 = x*z*(D*p1+k1*w-Q1*M1+P4*Q1)+x*(1-z)*(k1*w-Q1*M1+P4*Q1)+(1-x)*z*(D*p1-Q1*M1+P4*Q1)+(1-x)*(1-z)*(-Q1*M1+P4*Q1); \tag{5}$$

$$B12 = x*z*(-Q2*M2+P3*Q2)+x*(1-z)*(-Q2*M2+P3*Q2)+(1-x)*z*(-Q2*M2+P3*Q2)+(1-x)*(1-z)*(-Q2*M2+P3*Q2); \tag{6}$$

$$B1 = y*B11+(1-y)*B12 \tag{7}$$

Based on the three equations above, the replication dynamic equation $f(y)$ of the MR was obtained.

$$F(y) = dy/dt = y*(B11-B1) = -y*(y-1)*(M2*Q2-M1*Q1-P3*Q2+P4*Q1+k1*w*x+p1*D*z) \tag{8}$$

We calculated the expected return of CNFC to buy fishery carbon sinks or pay a carbon tax, which is expressed as C11 and C12, respectively, and the average return is expressed as C1.

$$C11 = x*y*(V(S1)-D*p1+(1-k1)*w)+(1-x)*y*(V(S1)-D*p1)+x*(1-y)*(V(S1)-D*p1+(1-k1)*w)+(1-x)*(1-y)*(V(S1)-D*p1); \tag{9}$$

$$C12 = x*y*(V(S2)-D*p2)+x*(1-y)*(V(S2)-D*p2)+(1-x)*y*(V(S2)-D*p2)+(1-x)*(1-y)*(V(S2)-D*p2); \tag{10}$$

$$C1 = z*C11+(1-z)*C12 \tag{11}$$

Based on the above three equations, the replication dynamic equation $f(z)$ of the CNFC was obtained.

$$F(z) = dz/dt = z*(C11-C1) = -z*(z-1)*(V(S1)-V(S2)-p1*D+p2*D+(1-k1)*w*x) \tag{12}$$

By combining equations $f(x)$, $f(y)$, and $f(z)$, the replication dynamics equation of the three-party evolutionary game model is obtained:

$$f(x) = dx/dt = x*(x-1)*(V(R1)-V(R2)+k1*w*y+k2*w*z+V(R3)*y*z) \tag{13}$$

$$f(y) = dy/dt = -y*(y-1)*(M2*Q2-M1*Q1-P3*Q2+P4*Q1+k1*w*x+p1*D*z) \tag{14}$$

$$f(z) = dz/dt = z*(C11-C1) = -z*(z-1)*(V(S1)-V(S2)-p1*D+p2*D+(1-k1)*w*x) \tag{15}$$

Evolutionary Stability Strategy

Players are not completely rational but have bounded rationality. When a player experiences multiple games and does not change the strategy, the dynamic replication system is stable. The strategy combination for all participants in the stable state is the ESS.

To obtain the stable state and ESS of the system, $f(x) = 0$, $f(y) = 0$, and $f(z) = 0$ are used to obtain 13 equilibrium points by calculation. These 13 points include eight pure strategy equilibrium points, E1[0,0,0], E2[0,0,1], E3[0,1,0], E4[1,0,0], E5[1,1,0], E6[1,0,1], E7[0,1,1], and E8[1,1,1], and five non-pure strategy equilibrium points, E*[x*,y*,z *].

The equilibrium point is not necessarily the ESS. It can become ESS only when the equilibrium point satisfies the pure strategy Nash equilibrium[52]. Since E* is a mixed-strategy Nash equilibrium, it is difficult to express its practical significance. This paper only solved the eigenvalues of eight pure strategy equilibrium points. The magnitude of the eigenvalues of the Jacobian can be used to determine whether the stability point of the system is an ESS. When all eigenvalues are less than zero, the equilibrium point is ESS. When all eigenvalues are greater than zero, the equilibrium point is unstable. When both positive and negative eigenvalues exist, the equilibrium point is a saddle point and remains unstable [53].

Appendix 3 provides a Jacobian matrix description. The eigenvalues of each equilibrium point are obtained by substituting the eight pure-strategy equilibrium points into the Jacobi matrix and calculating the eigenvalues of the matrix. Appendix 4 presents the eigenvalues for each equilibrium point.

Results and Discussion

Using the tripartite evolutionary game model based on the prospect theory established in the previous section, the equilibrium points and their stability conditions at different stages are analyzed. A numerical simulation is carried out, and the behavioral evolution process of the three stakeholders in three stages of the fishery carbon sink trading industry is explained. In the development stage, the sensitivity of stakeholders to parameter changes (market price of unit fishery carbon sink, unit carbon tax price, LG subsidy ratio, LG subsidy amount, and psychological role of game players) is numerically simulated.

Stabilization Strategies at Different Stages

Based on the theory of the market development [54, 55], the development trend of the fishery carbon sink trading market is divided into three stages: initial, development, and mature stages [53, 56]. The stability conditions of the three stages are analyzed. The parameter settings are listed in Table 2.

Table 2. Parameter settings.

Variable	Prophase	Metaphase	Anaphase
p1	1.5	1.5	1.8
p2	0.7	0.7	0.7
P3	5	4	4
P4	2	3	3
Q1	10	11	15
Q2	20	15	10
M1	3	2	2
M2	2	2	2
S1	8	10	20
S2	2	2	2
D	10	10	10
k1	0.7	0.7	0.7
k2	0.3	0.3	0.3
w	10	10	10
R1	2	1.2	1.5
R2	21	26	13
R3	3	3.5	5

Evolution Process of the System in the Initial Stage

The evolution process in the initial stage of the fishery carbon sink trading market is shown in Fig. 1. In the initial stage of the construction of the fishery carbon sink trading market, MR and CNFC usually hesitate due to unknown risks and choose ‘non-cooperation’. At this time, LG should take the lead in adopting an active strategy to promote the fishery carbon sink trading policy.

There are three conditions for the system to reach the stable point [1,0,0]. The first is V(R1)–V(R2)<0. In this condition when the perceived benefits obtained by the LG department responsible for the promotion policy of fishery carbon sink transaction is greater than the perceived cost of LG’s promotion policy of fishery carbon sink transaction and the perceived management cost of a restriction policy to reduce the enterprises paying a carbon tax, LG chooses the ‘participation’ strategy.

The second condition Is M2*Q2-M1*Q1-P3*Q2+P4*Q1+k1*w<0. In this condition, when the profit of fishermen breeding ordinary seafood is greater than the sum of the profit of breeding seafood with carbon sink capacity and the subsidy of LG to MR, MR chooses the strategy of ‘breeding non-carbon sink fishery seafood’.

The third condition is V(S1)-V(S2)+k2*w-p1*D+p2*D<0. In this condition, when the perceived benefit of CNFC paying a carbon tax minus the amount of carbon tax payment is greater than the perceived benefit of conducting fishery carbon sink transactions and LG’s subsidy to CNFC minus the expenditure of conducting fishery carbon sink transactions, CNFC chooses the strategy of ‘paying a carbon tax’.

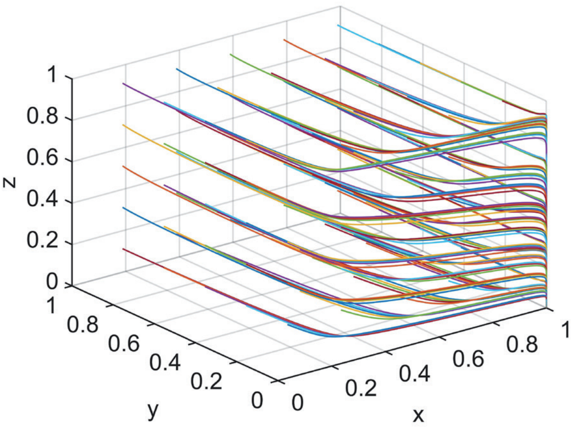

Fig. 1. Evolution process of the system in the initial stage.

Evolution Process of the System in the Development Stage

The evolution process in the development stage of the fishery carbon sink trading market is shown in Fig. 2. With the continuous advancement of policies and regulations, the fishery carbon sink trading market is gradually forming and entering a development stage. MR and CNFC will also choose to participate in fishery carbon sink trading, and these three players will play an indispensable role in the system.

The conditions for the system to reach a stable point [1,1,1] are:

V(R1)-V(R2)+V(R3)+w<0. In this condition, when LG does not participate in the construction of the fishery carbon sink trading market, the benefits perceived by LG are less than the LG sector's perceived benefits from the promotion policy of fishery carbon sink trading minus LG's perceived cost from this promotion policy and the implementation of restrictive policies to limit the enterprises paying a carbon tax, and minus LG's total subsidy to MR and CNFC, LG chooses the 'participation' strategy.

M1*Q1-M2*Q2+P3*Q2-P4*Q1-k1*w-p1*D<0, the profit of fishermen breeding non-carbon sink fishery seafood is less than the profit of fishermen breeding carbon sink fishery seafood and the profit of fishery carbon sink transaction and LG's subsidy to MR, MR chooses the strategy of 'breeding carbon sink fishery seafood'.

V(S2)-V(S1)-k2*w+p1*D-p2*D<0, when CNFC's perceived benefit of paying a carbon tax minus the carbon tax payment is less than the perceived benefit of the fishery carbon sink transaction and LG's subsidy for CNFC minus the expenditure of the fishery carbon sink transaction, CNFC chooses the strategy of 'fishery carbon sink trading'.

Evolution Process of the System in the Mature Stage

The evolution process in the mature stage of the fishery carbon sink trading market is shown in Fig. 3. With the development of the fishery carbon sink trading market, the development of the fishery carbon trading market enters a mature stage. LG gradually withdraw and choose the 'do not participate' strategy. MR and CNFC will become the main body of the fishery carbon sink trading market and choose a 'cooperative' strategy.

Three conditions are required for the system to reach a stable point [0, 1, 1]. The first is when V(R2)-V(R1)-V(R3)-w<0. In this condition, when LG does not participate in the fishery carbon sink trading market, the perceived benefits of LG when MR and CNFC participate are greater than the perceived benefits obtained by LG department's promotion policy of fishery carbon sink trading minus the cost of LG's promotion policy of fishery carbon sink trading, the cost of limiting carbon tax payments by businesses and the total amount of LG subsidies to MR and CNFC, LG chooses the 'do not participation' strategy.

The second condition is M1*Q1-M2*Q2+P3*Q2-P4*Q1-p1*D<0. In this condition, when the profit of fishermen breeding non-carbon sink fishery seafood is less than the sum of the profit of breeding carbon sink fishery seafood and the income from fishery carbon sink trading, the MR chooses the strategy of 'breeding carbon sink fishery seafood'.

The third condition is V(S2)-V(S1)+p1*D-p2*D<0. In this condition, when the CNFC's perceived income from paying a carbon tax minus the amount of carbon taxes paid is less than the perceived income from fishery carbon sink trading minus expenditure on fishery carbon sink trading, CNFC chooses the strategy of 'fishery carbon sink trading'.

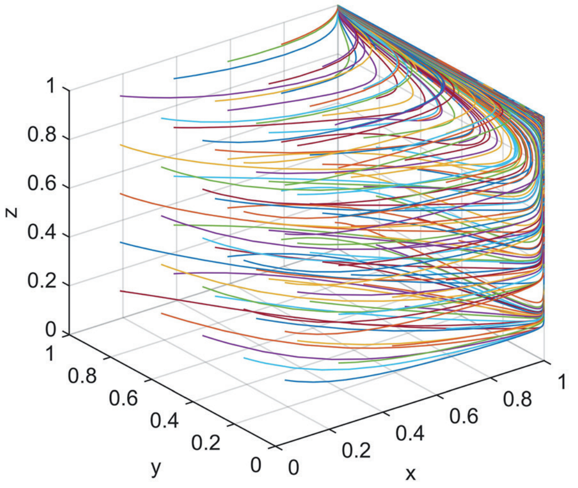

Fig. 2. Evolution process of the system in the development stage.

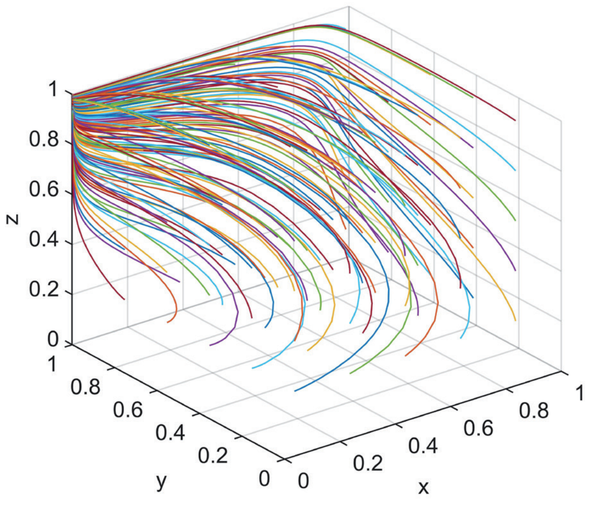

Fig. 3. Evolution process of the system in the mature stage.

Influence of Parameters on Evolutionary Results

The medium-term stage will continue for a long time in China and is in line with China's sustainable development. As China is a socialist country, the construction of the fishery carbon sink trading market is inseparable from the participation of LG. Simultaneously, MR and CNFC can obtain huge economic benefits and beneficial social reputations through carbon sink trading. Therefore, we performed a sensitivity analysis of the six important parameters in the development stage to obtain a more stable game system.

Impact of Unit Fishery Carbon Sink Price

The unit fishery carbon sink price p1 is set to 1, 1.5, 2, 3, and 4 respectively. Based on the three-dimensional dynamic system, the five values of p1 are numerically simulated, and the results are shown in Fig. 4.

In the five cases of p1 = 1, 1.5, 2, 3, and 4, x eventually evolved into the same stabilization strategy (participating in the fishery carbon sink trading market), indicating that the unit fishery carbon sink price has little effect on LG's willingness to regulate and subsidize. This is because LG is eager to build a fishery carbon sink trading market at this time, and external factors have difficulty influencing LG's decision-making. When p1 = 1, CNFC chooses to participate in the fishery carbon sink trading market because the lower price of the fishery carbon sinks makes CNFC choose to purchase the fishery carbon sinks. However, because the price of the fishery carbon sinks is too low, MR tends to choose non-carbon sink fisheries with higher profits. When p1 = 1.5, LG, MR, and CNFC all choose to participate in fishery carbon sink trading. This occurs because at this time, MR and CNFC can profit from participating in fishery carbon sink trading, and all three participants will play an indispensable role in the system. Subsequently, with the increase in p1, MR and CNFC choose not to participate in the construction of the fishery carbon sink trading market because the high price of the fishery carbon sink increased the cost of emission reduction of CNFC. Instead, they choose to pay a carbon tax. The fishery carbon sinks of MR are difficult to sell, so MR does not participate in the construction of the fishery carbon sink trading market. Therefore, LG should assist in planning the price range of the fishery carbon sink market.

Impact of Unit Carbon Tax Price

The unit carbon tax price p2 is set to 0.3, 0.5, 0.7, 1, and 3, respectively. The five values of p2 are numerically simulated, and the results are shown in Fig. 5.

In the five cases of p2 = 0.3, 0.5, 0.7, 1, and 3, x eventually evolved into the same stabilization strategy (i.e., participating in the construction of the fishery carbon sink trading market). This indicates that the appropriate change in the unit carbon tax price has little impact on LG's willingness to regulate and subsidize for the same reason. When p2 = 0.3 and 0.5, both MR and CNFC tend to choose not to participate in the construction of the fishery carbon sink trading market because the lower carbon tax price will greatly reduce the emission reduction cost of CNFC. Instead, they choose to pay a carbon tax. When CNFC tends to pay a carbon tax, the income of MR will decrease, and MR will have to re-examine its strategy and make new choices, such as adjusting the price of the fishery carbon sinks or choosing to farm non-carbon sink fisheries. When the value of p2 increases to 0.7, 1, and 3, the stability strategy of CNFC and MR evolves into the choice to participate in the construction of the fishery carbon sink trading market. This is because, at this time, for CNFC the purchase of fishery carbon sinks is more cost-effective, and MR is also actively involved in the construction of the fishery carbon sink

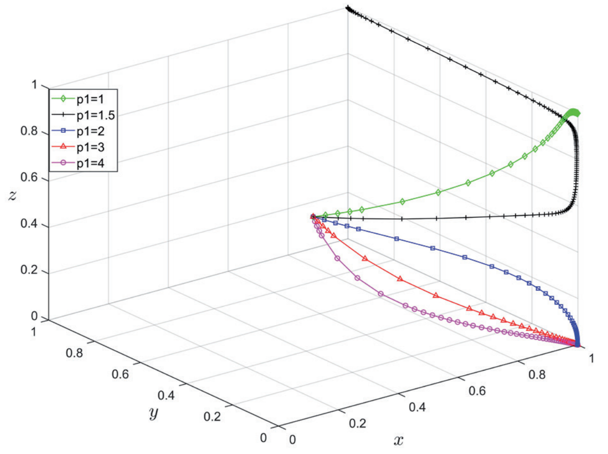

Fig. 4. Impact of p1 on the evolution of the behavior of the three stakeholders.

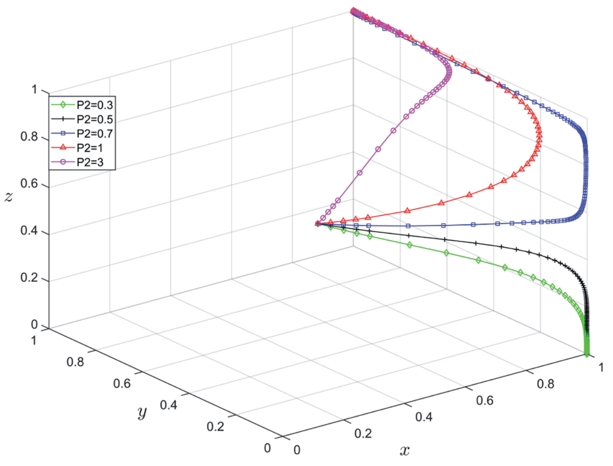

Fig. 5. Influence of p2 on the behavior evolution of three stakeholders.

trading market because of the increase in the number of buyers of fishery carbon sinks. An appropriate increase in carbon tax standards promotes the development of the fishery carbon sink trading market. Therefore, LG should formulate appropriate carbon tax standards after considering various market factors.

Impact of the Subsidy Ratio

The ratio k1 of the LG subsidy MR is set to 0.1, 0.3, 0.5, 0.7, and 0.9, and k2 corresponds to 0.9, 0.7, 0.5, 0.3, and 0.1. The five values of k1 are numerically simulated. The results are shown in Fig. 6.

In the five cases where k1 is 0.1, 0.3, 0.5, 0.7, and 0.9, x eventually evolves into the same stabilization strategy. This indicates that although the proportion of subsidies to MR and CNFC has changed, the total expenditure of LG has not changed, so the change in k1 does not affect LG's willingness to participate in and supervise the fishery carbon trading market. When k1 = 0.1 and 0.3, the subsidy ratio of LG to MR is much smaller than that to CNFC, and the subsidy of LG reduces the emission reduction cost of CNFC. Therefore, these enterprises are encouraged to actively participate in the fishery carbon sink transaction. However, LG's subsidy to MR is too small, resulting in the high cost of MR aquaculture carbon sink fishery. Expenses exceed profit and MR chooses the non-carbon sink fishery with higher breeding profits. When k1 = 0.5 and 0.7, LG, MR, and CNFC all choose to participate in the fishery carbon sink transaction, indicating that the LG subsidy required by MR is the same or higher than that of CNFC. CNFC must pay a carbon tax or participate in fishery carbon sink trading if it wants to achieve emissions reduction targets, while MR's motivation to participate in fishery carbon sink trading is not as strong, MR can choose non-carbon sink fisheries with higher market prices, so LG's subsidy for the MR is particularly important. When k1 = 0.9, the proportion of LG's subsidy to MR is far greater than that to CNFC. CNFC chooses to pay a carbon tax to reduce the cost of emission reduction. Although MR has received a subsidy from LG, because there is no buyer for the fishery carbon sinks, the evolution trend of the system develops in the direction that MR and CNFC do not participate in the fishery carbon sink transaction market over time.

Impact of LG Subsidy Amount

The total amount of the subsidies of LG to MR and CNFC is set to 5, 8, 10, and 12, respectively. The four values are numerically simulated. The results are shown in Fig. 7.

When w = 5, the subsidy of LG is too low to attract MR and CNFC to participate in the construction of the fishery carbon trading market. With the increase in the amount of the subsidy of LG, when w = 8, LG's subsidy attracts CNFC to participate in the fishery carbon sink trading market, because at this time, compared with paying a carbon tax, the cost of carbon emission reduction caused by purchasing fishery carbon sinks is lower. However, at this time, LG's subsidy is too small for MR, and the aquaculture carbon sink fishery will not be profitable for MR. Thus, MR is more inclined to choose the higher-profit non-carbon sink fisheries.

When w = 10 and 12, the stable strategy of CNFC and MR evolves into the choice to participate in the fishery carbon sink trading market. This indicates that appropriate LG subsidies are propitious to the development of the fishery carbon sink trading market.

Influence of Loss Aversion Coefficient

λ represents the loss aversion coefficient. $\lambda > 1$ indicates that the game subject is more sensitive to the loss than the gain. λ is set to 1.15, 1.65, 2.25, and 3.15 respectively. The t during the simulation is the virtual

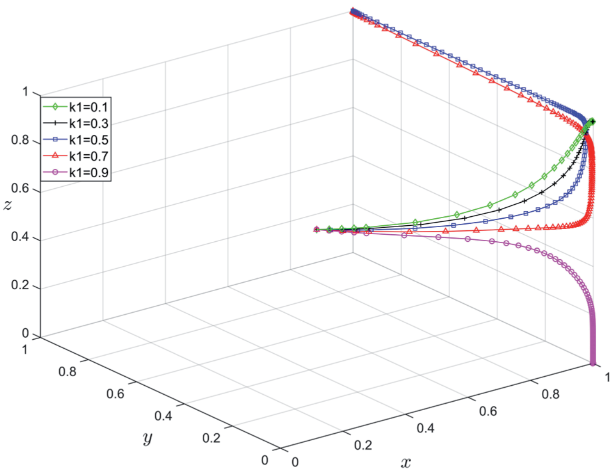

Fig. 6. Influence of k1 and k2 on the behavior evolution of three players.

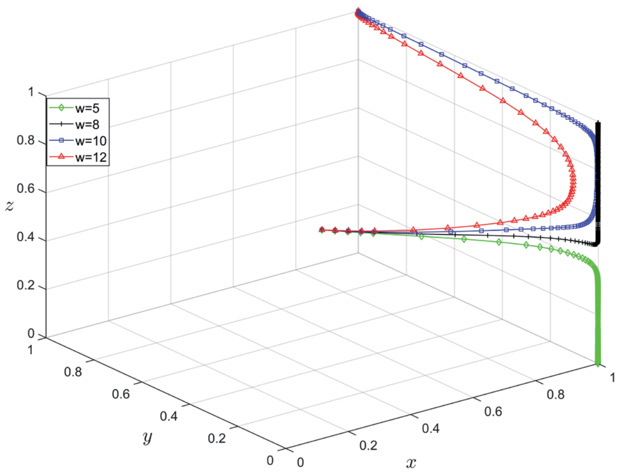

Fig. 7. Influence of w on the behavior evolution of three stakeholders.

time, rather than real time. However, it reflects the relative size. The results are shown in Figs. 8, 8a), 8b), and 8c).

In this paper, λ (loss aversion coefficient) is used to modify R1. Other parameters remain unchanged. Fig. 8 shows that the evolution trend curve of the system is coincident under the four conditions of λ = 1.15, 1.65, 2.25, and 3.15. LG, MR, and CNFC all choose to participate in fishery carbon sink trading, possibly because, among the many parameters, only R1 needs to be corrected with λ, and because correction of one parameter is not sufficient to affect the changing trend of the entire game system. Therefore, as evident in Fig. 8, even if λ is assigned as 1.15, 1.65, 2.25, or 3.15, the corresponding evolution process curves do not change significantly.

Although the final evolution results for x, y, and z are close to 1, the evolution paths are different. As shown in Fig. 8a), with the increase of λ, the time for x to reach stability becomes progressively slower. Therefore, for LG, it is necessary to reduce the loss aversion coefficient to promote the construction of a fishery carbon sink trading market.

As shown in Fig. 8b), over time, the probability of y choosing to participate in the construction of the fishery carbon sink trading market does not increase monotonically but first decreases to close to 0, and then increases to close to 1. The reason may be that MR found a lack of enthusiasm for CNFC participation and there is no buyer for the generated fishery carbon sinks. Even if there is an LG subsidy, there is a high possibility of monetary loss. Therefore, the probability of MR choosing to participate in the fishery carbon sink trading market is significantly reduced. With time, the probability of CNFC participating in the fishery carbon sink trading market greatly increases, and with the subsidy and policy guidance of LG, MR finally tends to breed aquatic products with carbon sink capacity and participate in the fishery carbon sink trading market.

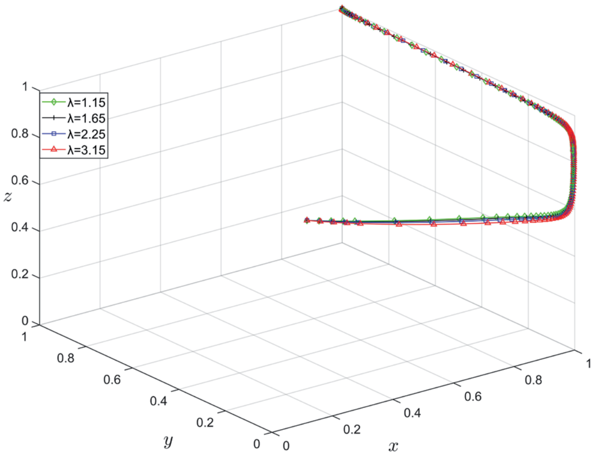

Fig. 8. Influence of λ on the behavior evolution of three stakeholders.

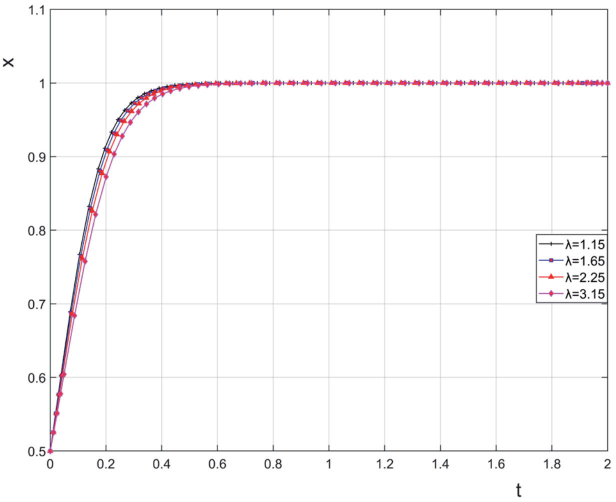

Fig. 8a) Effect of λ on the evolution of x behavior.

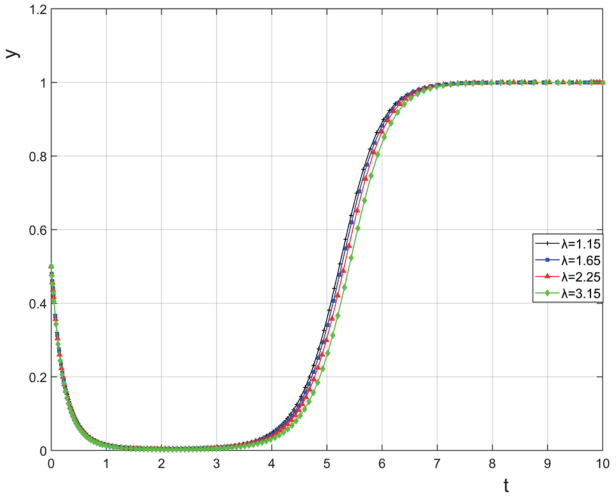

Fig. 8b) Effect of λ on the evolution of y behavior.

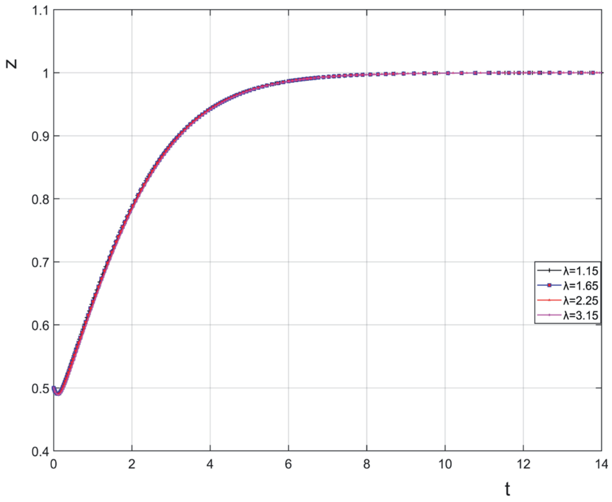

Fig. 8c) Effect of λ on the evolution of z behavior.

As shown in Fig. 8c), the probability that CNFC chooses to participate in the construction of the fishery carbon sink trading market shows an increasing trend until 1 after a slight and rapid reduction. A possible reason for this is that CNFC is in a ‘wait-and-see’ state at the beginning, so it is more secure to choose to pay a carbon tax. With the promotion of LG subsidies and policies, CNFC found that the cost of emission reduction generated by participating in the fishery carbon sink trading market is lower and very beneficial to the reputation of the enterprises. Therefore, the probability that CNFC will participate in the fishery carbon sink trading market increases until 1.

Influence of Risk Preference Coefficient

n represents the risk preference coefficient. Because the risk preference coefficient n ∈ [0, 1], n is set to 0.2, 0.5, 0.88 and 1. Four values of n are numerically simulated. The results are shown in Fig. 9.

When n = 0.2, none of the three parties participate in the construction of the fishery carbon sink trading market, indicating that the three parties choose a conservative strategy under the condition of low-risk appetite and are unwilling to participate in the unknown fishery carbon sink trading market. When n=0.5, LG chooses to participate in the fishery carbon sink trading market, and the other two parties still maintain a wait-and-see attitude, because when the risk appetite is not low, the government, as the pioneer of the construction of the fishery carbon sink trading market, must take the lead in participating in the market construction. When the risk appetite coefficient of MR and CNFC is not high, the benefits of their participation in the construction of the fishery carbon sink trading market will be underestimated, which will lead to misjudgment. At this time, MR and CNFC believe that it is unprofitable to participate in the fishery carbon sink trading market, so they choose a conservative strategy.

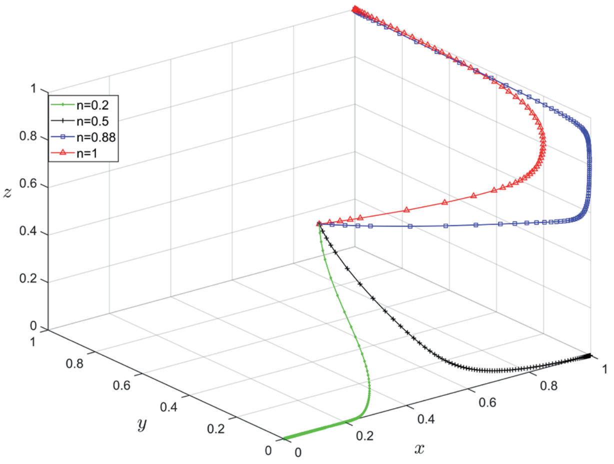

Fig. 9. Impact of n on the evolution of the behavior of the three stakeholders.

When n increases to 0.88 (high-risk preference) and 1 (risk-neutral), All three parties choose to participate in the fishery carbon sink trading market. This indicates that when n is larger, decision-makers’ prediction and judgment of loss and income are closer to the real value. They believe that participating in the fishery carbon sink trading market could benefit significantly. Therefore, if necessary, measures can be taken to amplify the risk preferences of game players to promote the development of a fishery carbon sink trading market.

For the reproducibility of simulation results, all the calculation results and the figures appearing in the article have been recalculated and simulated to ensure the reliability and repeatability of the results. The results are completely consistent across multiple replicates, indicating the reproducibility and reliability of the results.

Policy Recommendations

Based on previous research, the following policy recommendations for LG, MR, and CNFC are proposed to promote the development of China’s fishery carbon sink trading market.

LG

Currently, the main categories of carbon trading projects include renewable energy power generation projects, such as hydropower and wind power, waste heat recovery and utilization of power generation, biogas utilization, and forest and grassland carbon sinks. Although shellfish and algae in the ocean have large carbon sink capacities, the status of fishery carbon sinks in the carbon-trading market is not significant. Therefore, the relevant departments of LG must improve the laws and regulations of fishery carbon sink trading, strengthen the publicity and popularization of fishery carbon sinks, and mobilize the willingness of MR and CNFC to participate in the fishery carbon sink trading market.

LG needs to determine the appropriate price mechanism and subsidy system for fishery carbon sink trading and encourage cooperation between MR and CNFC. When the carbon trading price is unreasonable, the suppliers and demanders eventually choose not to join the carbon sink trading market. At this time, LG is required to macro-control the fishery carbon sink trading price to promote the healthy development of the trading market. To attract more participants, in the initial and middle stages of the development of the fishery carbon sink trading market, LG should increase subsidies within its financial capacity, especially for MR subsidies. This is because the enthusiasm of MR for participating in the fishery carbon sink trading market is not high, and the subsidies of MR are particularly important. LG should develop appropriate carbon tax standards considering various market factors. Increasing the carbon tax standard appropriately can promote the development of the fishery carbon sink trading market.

Because it is predicted that only CNFC and MR will participate in the final development stage of fishery carbon sink trading, and the government will gradually withdraw at this time, both CNFC and MR must strengthen cooperation and exchanges, and a good cooperative relationship between buyers and sellers can ensure that the fishery carbon sink trading market is gradually maturing. For example, CNFC and MR can work together to establish a carbon trading platform to promote information transparency and cooperation.

MR

Marine ranches should not breed seafood blindly. It is necessary to strengthen theoretical studies, understand which seafood has carbon sink capacity and the breeding environment requirements of this seafood, and use scientific breeding methods; Fishery practitioners need to cooperate with the government and establish good links with the government, because the government's overall grasp is indispensable in the process of fishery carbon sink trading; MR can strengthen exchanges with marine pastures that have successfully traded fishery carbon sinks and acquire advanced experience.

For MR, when n is larger, that is, the risk appetite coefficient is larger, their enthusiasm to participate in the fishery carbon sink trading market is higher, which requires fishermen to have the adventurous spirit to participate in new things. For example, when fishermen lose money when they breed or trade carbon sink fisheries, the government can provide appropriate subsidies to improve the risk-taking spirit of fishermen. At the same time, the government can take steps to reduce the risk of fishermen participating in the fishery carbon sink trading, for example, predicting and designing solutions for possible problems in the future. For example, the maintenance of machinery and equipment in the breeding site of carbon sink fishery to ensure the normal progress of aquaculture activities and reduce the risk of aquaculture.

CNFC

Enterprises need to actively cooperate with and implement government policies, operate in good faith, actively assume social responsibilities, adopt energy-saving and emissions-reduction equipment as much as possible in production, learn the latest energy-saving and emissions-reduction technologies to control carbon emissions, and not steal or conceal reports. If carbon emissions exceed the state's allowable range, active measures should be taken (e.g., paying a carbon tax, purchasing carbon emission rights, or conducting carbon sink transactions). Enterprises also need to enhance their spirit of adventure, and the decision to participate in the fishery carbon sink trading market should not be too conservative. The above research shows that participating in the fishery carbon sink trading market is beneficial to the three parties of the game. Thus, enterprises should actively participate.

Conclusions

Research on the behavioral decision-making of fishery carbon sink trading participants is important for improving the carbon trading system and has both theoretical and practical significance. In this study, an evolutionary game model based on prospect theory was constructed, which considered the complex dynamic relationship between LG, MR and CNFC in the transaction process, and simulated the influence of different parameters on the behavior of game agents. There are three conclusions: First, with the development of the fishery carbon sink trading market, the development stage can be divided into initial, middle, and mature stages. Game players have different strategies at different stages. Second, unit fishery carbon sink price, unit carbon tax price, and the proportion and amount of LG subsidies mainly affect the choice of the MR and CNFC, but have little impact on the LG's strategy. Finally, when psychological factors involve uncertain gains and losses, they are also important in influencing decision-makers.

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Conflict of Interest

The authors declare no conflict of interest.

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Appendix

Appendix 1: Description of main parameters

Table 3. Description of main parameters.

Parameter	Implication	Quote
p1	Unit fishery carbon sink price	[7]
p2	Unit carbon tax price	[50]
P3	Unit market price of seafood without carbon sink capacity	[6]
P4	Unit market price of seafood with carbon sink capacity	[6]
Q1	The amount of seafood farmed by fishermen with carbon sink capacity	[6]
Q2	The amount of seafood farmed by fishermen without carbon sink capacity	[6]
M1	The cost to fishermen of raising a unit quantity of seafood with carbon sink capacity	[7]
M2	The cost to fishermen of raising a unit quantity of seafood without carbon sink capacity	[7]
S1	CNFC's corporate reputation and credit utility obtained from fishery carbon sink transactions	[47]
S2	CNFC's corporate reputation and credit utility are obtained by paying a carbon tax	[47]
D	Carbon emissions that CNFC needs to offset	[47]
k1	The proportion of LG subsidies to MR	[46]
k2	The proportion of LG subsidies to CNFC (k1+k2 = 1)	[46]
w	The total amount of LG subsidies to MR and CNFC	[46]
R1	Administrative costs of LG when promoting fishery carbon sink trading policies and restricting CNFC from paying a carbon tax	[57]
R2	The benefits that LG derives from promoting fisheries carbon sink trading policies, such as government reputation, credit utility and environmental benefits	[57]
R3	When LG does not participate in the construction of fishery carbon sink trading market, both MR and CNFC participate in the construction, the benefits obtained by LG	[57]
X	The probability of LG participating in the construction of a fishery carbon sink trading market	
Y	The probability of MR raising seafood with carbon sink capacity	
Z	The probability of CNFC choosing fishery carbon sink trading	

Appendix 2: Event explanation

Table 4. Event explanation.

Event	Implication
A1	LG participates in the construction of fishery carbon sink trading market
A2	LG does not participate in the construction of fishery carbon sink trading market
B1	MR chooses to breed marine products with carbon sink capacity
B2	MR chooses to breed marine products without carbon sink capacity
C1	CNFC chooses to conduct fishery carbon sink trading
C2	CNFC chooses to pay a carbon tax

Appendix 3: Jacobi matrix description of tripartite evolutionary game model:

$$J=\begin{bmatrix}\frac{\partial f(x)}{\partial x} & \frac{\partial f(x)}{\partial y} & \frac{\partial f(x)}{\partial z}\\ \frac{\partial f(y)}{\partial x} & \frac{\partial f(y)}{\partial y} & \frac{\partial f(y)}{\partial z}\\ \frac{\partial f(z)}{\partial x} & \frac{\partial f(z)}{\partial y} & \frac{\partial f(z)}{\partial z}\end{bmatrix}=\begin{bmatrix}J_{11} & J_{12} & J_{13}\\ J_{21} & J_{22} & J_{23}\\ J_{31} & J_{32} & J_{33}\end{bmatrix}$$

= [(x-1)*(V(R1)-V(R2)+k1*w*y+k2*w*z+V(R3)*y*z)+x*(V(R1)
-V(R2)+k1*w*y+k2*w*z+V(R3)*y*z), x*(x-1)*(k1*w+V(R3)*z), x*(x-1)*(k2*w+V(R3)*y)]
[-y*(y-1)*k1*w, -y*(M2*Q2-M1*Q1+P4*Q1-P3*Q2+k1*w*x+p1*D*z)
-(y-1)*(M2*Q2-M1*Q1+P4*Q1-P3*Q2 +k1*w*x+p1*D*z),
-y*(y-1)*p1*D]
[-k2*w*z*(z-1),0,
-(z-1)*(V(S1)-V(S2)-p1*D+p2*D+k2*w*x)-z*(V(S1)-V(S2)-p1*D+p2*D+k2*w*x)]

Appendix 4: Eigenvalues of each pure strategy equilibrium point

Table 5. The eigenvalues of each pure strategy equilibrium point.

Points of equilibrium	Eigenvalue λ1	Eigenvalue λ2	Eigenvalue λ3
[0,0,0]	V(R2)-V(R1)	M2*Q2-M1*Q1-P3*Q2+P4*Q1	V(S1)-V(S2)-p1*D +p2*D
[1,0,0]	V(R1)-V(R2)	M2*Q2-M1*Q1-P3*Q2+P4*Q1+k1*w	V(S1)-V(S2)+k2*w-p1*D+p2*D
[0,1,0]	V(R2)-V(R1)-k1*w	M1*Q1-M2*Q2+P3*Q2-P4*Q1	V(S1)-V(S2)-p1*D +p2*D
[0,0,1]	V(R2)-V(R1)-k2*w	M2*Q2-M1*Q1-P3*Q2+P4*Q1+p1*D	V(S2)-V(S1)+p1*D-p2*D
[1,1,0]	V(R1)-V(R2)+k1*w	M1*Q1-M2*Q2+P3*Q2-P4*Q1-k1*w	V(S1)-V(S2)+k2*w-p1*D+p2*D
[1,0,1]	V(R1)-V(R2)+k2*w	M2*Q2-M1*Q1-P3*Q2+P4*Q1+k1*w+p1*D	V(S2)-V(S1)-k2*w+p1*D-p2*D
[0,1,1]	V(R2)-V(R1)-V(R3)-w	M1*Q1-M2*Q2+P3*Q2-P4*Q1-p1*D	V(S2)-V(S1)+p1*D-p2*D
[1,1,1]	V(R1)-V(R2)+V(R3)+w	M1*Q1-M2*Q2+P3*Q2-P4*Q1-k1*w-p1*D	V(S2)-V(S1)-k2*w+p1*D-p2*D