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Can multi-agent cooperation promote the ecological value realization of blue carbon in marine ranching?

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A R T I C L E I N F O

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A B S T R A C T

Ecological value realization of blue carbon in marine ranching is essential to achieve carbon neutrality. The motivation for conducting the study is to verify whether multi-agent cooperation can promote the ecological value realization of blue carbon in marine ranching. Based on the blue carbon ecological value realization model of marine ranching enterprises, blue carbon demand enterprises, blue carbon trading platforms and government, this paper explores the cooperative governance strategy of marine ranching for each subject using cooperative game and non-cooperative game models. Further, we conduct a comparative analysis to arrive at the optimal strategy. The conclusions are as follows. Multi-agent cooperation is more conducive to the ecological value realization of blue carbon in marine ranching. Compared with non-cooperative governance, the platform's commission and blue carbon price are lower, and the blue carbon output, profit of each market subject, government utility and overall profit are higher in cooperative governance. The strengths of this paper lie in 2 aspects. First, we focuses on the ecological value of blue carbon in marine ranching instead of economic value, providing a new theoretical basis for ecological compensation in marine ranching. Second, we construct a government-led and market-oriented operation of marine ranching's blue carbon ecological value realization mechanism, incorporating blue carbon trading platform and government into the value realization model.

1. Introduction

Blue carbon generated from marine ranching has significant economic and ecological value [1,2]. Conducting blue carbon ecological value realization of marine ranching can not only increase the added value of marine ranching enterprises, but also contribute to protecting the blue carbon ecosystem and promoting carbon neutrality goals [3]. Currently, China's blue carbon ecological value realization is in the critical period of moving from the pilot and pre-construction stage to deepening promotion [4]. From the pre-construction and development perspective, there are still many shortcomings, and it is urgent to open and improve the critical link to realize the equity value of various ecological resources [5]. In 2021, China announced the *Opinions on Establishing a Sound Mechanism for Realizing the Value of Ecological Products*, requiring provinces to explore mechanisms and paths for establishing the value of ecological products. To this end, various provinces have proposed blue carbon first programs or built blue carbon trading market. However, China's blue carbon ecological value multi-agent cooperation model has not yet to be established [6], the blue

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carbon market is not active, and there are problems such as lack of development experience, weak development willingness and concern about market recognition [7]. Theoretically, in the ecological value realization of blue carbon, all subjects have the basis and prospect of cooperation [8]. On the one hand, the ecological value realization of blue carbon in marine ranching is not a zero-sum game [9]. As profit-oriented organizations, marine ranching enterprises and blue carbon demand enterprises can always expect that cooperation will lead to more benefits for themselves, and there is the possibility of synergistic development and mutual benefits [10]. On the other hand, driven by the goal of carbon neutrality, the government and trading platforms are more motivated to promote the realization of the value of ecological products [11]. Therefore, all participants have the possibility to work together and form a grand alliance. Then, can the multi-agent cooperation promote the realization of blue carbon ecological value? This is the central question to be explored in this paper.

Accordingly, this paper aims to verify whether multi-agent cooperation can promote the ecological value realization of blue carbon in marine ranching. Based on the value realization path of ecological products that are government-led, participated by enterprises and the community, market-oriented operation and sustainable, this paper constructs the blue carbon ecological value model of marine ranching enterprises, blue carbon demand enterprises, blue carbon trading platform and government, analyze the optimal blue carbon governance strategies and equilibrium benefits of each subject using the non-cooperative game and cooperative game under the blue carbon ecological value realization mode. Then draws a comparison between the strengths and weaknesses of non-cooperative governance and cooperative governance models for blue carbon in marine ranching. The findings can contribute to guidance and instructions for realizing blue carbon ecological value in marine ranching.

The contributions of this study are as follows. First, this paper focuses on the ecological value of blue carbon in marine ranching instead of economic value, providing a new theoretical basis for ecological compensation. Second, integrates blue carbon trading platform and government into the blue carbon ecological value realization model, making it more consistent with the government-led and market-oriented operation of the blue carbon ecological value realization mechanism. Thirdly, draws a comparison between the strengths and weaknesses of non-cooperative and cooperative governance models for the realization of blue carbon ecological value, and argues the necessity of cooperative governance of blue carbon with multiple subjects.

2. Literature review

2.1. Blue carbon in marine ranching

Marine ranching is different from traditional fishing and aquaculture, and it aims to create a three-dimensional, multi-level natural ecological space through the organic integration of various industries and the use of environmental engineering, biological control of resources, production support and other technologies. It is a marine economic complex that "grazes" in marine waters, islands and specific areas of the mainland coastal zone [12,13]. Marine ranching can solve the problems of improper utilization of marine resources, overfishing, and seawater pollution faced by mariculture [14], and is a critical way to protect the ecological environment of nearshore waters and efficiently produce marine fishery resources [15]. Marine ranching provides essential ecological and economic functions, but at the same time, there are various real problems and risks. For example, microplastics were present in 37.6% of fish in the marine ranching of the Maan Islands [16], generating a series of environmental risks and fish safety risks.

In recent years, One aspect of marine ranching that is gaining attention is the role of blue carbon in ecosystems. Blue carbon refers to the carbon stored in coastal and marine ecosystems, such as seagrasses, mangroves, and salt marshes [17]. Studies have explored the current state of knowledge on blue carbon in marine ranching and its implications for climate change mitigation and adaptation. Seagrasses, mangroves, and salt marshes are all important components of marine ranching ecosystems [18]. These ecosystems are known to be highly productive and support a diverse range of species. They also play a crucial role in carbon sequestration and storage [19]. Seagrasses, for example, are known to sequester carbon at rates up to 35 times higher than terrestrial forests. Mangroves and salt marshes are also highly effective at capturing and storing carbon [20]. These ecosystems are therefore important tools for mitigating climate change. In addition to their role in carbon sequestration, seagrasses, mangroves, and salt marshes provide a range of ecosystem services that are important for marine ranching. Seagrasses, for example, provide habitat for a range of fish and invertebrate species, while mangroves and salt marshes provide important nursery habitats for fish and other aquatic organisms [21]. These habitats also provide protection from storms and erosion, which is important for coastal communities [22].

The role of blue carbon in marine ranching has important implications for climate change mitigation and adaptation. By enhancing and restoring seagrass beds, mangroves, and salt marshes, we can increase carbon sequestration and storage in these ecosystems, thereby reducing the amount of carbon dioxide in the atmosphere [23]. In addition to their role in mitigating climate change, these ecosystems also provide important adaptation benefits [24]. By restoring and enhancing these habitats, we can increase the resilience of coastal communities to the impacts of climate change, such as sea level rise and storm surges. This is particularly important in areas where traditional coastal protection measures, such as sea walls, are not feasible or effective [25].

2.2. Ecological value realization of blue carbon

Blue carbon ecological value realization urgently needs to build a multi-agent cooperation model and realization path led by the government, market operation and social participation. The essence of realizing the value of ecological products is to monetize ecological elements or make ecological benefits visible.

On the one hand, the key to market operation is to establish a blue carbon trading platform. Carbon trading market is an essential environmental policy tool to reduce carbon emissions and realize the value of ecological products [26]. Scholars have conducted numerous studies on the effects of carbon trading [27,28]. First, regarding the economic effects of carbon trading, carbon trading can significantly improve energy efficiency [29]. Second, regarding the ecological impact of carbon trading, carbon trading promotes carbon emission reduction in the region and reduces carbon emissions in the surrounding areas [30]. Third, regarding the ecological economy of carbon trading, carbon trading reduces carbon emissions and carbon intensity [31], but inhibits green technological innovation [32]. In fact, it is more important to focus on the construction of the carbon trading market, such as the auction ratio of carbon emission allowances [33], and the carbon trading price [34], than on the impact of carbon trading. Wang et al. [35] validated an effective market for carbon trading in China.

On the other hand, the key to government-led is to mobilize various market players to participate in blue carbon governance with subsidies. Government subsidies are commonly used as incentives, including green technology investment subsidies and carbon emission reduction subsidies [36]. The study shows that government subsidies have an incentive effect and can significantly promote green technology innovation among Chinese firms [37]. A great deal of research has also been conducted on government carbon emission reduction subsidies. Wang et al. analyzed the supply chain carbon reduction decision under government subsidies [38]. Valkengoed and Werff [39] verified the role of Dutch government subsidies in promoting the development of new energy vehicles. Ma et al. [40] examined the effect of government subsidies on participants' performance in the presence of asymmetric information on carbon emission reduction. Some scholars have also found that carbon reduction subsidies for gasoline vehicles are more effective than cost subsidies for new energy vehicles when the initial carbon emissions are low, and the reduction efficiency is high [41]. Carbon trading subsidies have a better carbon reduction effect than purchase subsidies [42]. Of course, there are preconditions for government subsidies to promote carbon emission reduction. Li et al. [36] pointed out that the range of green investment costs, the reduction rate of green technology and carbon emission intensity play a moderating role in the carbon reduction effect of government subsidies.

2.3. Multi-agent cooperative governance of blue carbon based on game theory

Cooperative game means that the interests of all game subjects increase, or the interests of at least one of them increases, while the interests of other subjects do not decrease [43]. The cooperative game is particularly evident in the multi-actor collaborative governance of environmental problems. Asghari et al. considered the environmental responsibility of supply chain members to improve the environmental impact of products and services through a cooperative game of green manufacturers, retailers and consumers [44]. Zhang et al. used the Cobb-Douglas function with the Shapley value method to study the feasibility of cooperative marine plastic litter governance in the Northwest Pacific. The results show that any country joining the triple alliance would create more excellent value and receive higher benefits. For China, Japan, and South Korea, the co-management to the Northwest Pacific Ocean of marine plastics is a win-win situation [45]. Some studies also showed that the key to the current cooperative marine plastic litter management is to establish a stable and long-term market mechanism, regulating the governance relationship between countries, and promote international cooperation in marine plastic litter management [46].

The allocation of responsibility for carbon emission reduction is a prerequisite for the carbon emissions trading market [47]. Dietzenbacher et al. [48] compared the differences in accounting methods for attributing responsibility for greenhouse gas emissions among 41 countries and regions between 1995 and 2009. The study finds that emission responsibility allotment is the best method for accounting for gas emissions compared to production-based accounting and consumption-based accounting. Qin et al. built a graphically constrained cooperative game model by proposing a new characteristic function to describe the minimum possible carbon emissions [49]. Salcedo et al. investigated the cooperative game strategy for sustainable supply chain design [50]. A three-way game model of carbon emissions in China, the U.S. and the EU suggests that, unlike the prevailing prisoner's dilemma, collective cooperative governance can lead to a unique Nash equilibrium [9]. The cooperative game theory results show that each factory earns an average profit of 12% when sharing its carbon credits. Compared to working independently, plants are 25% more profitable when working in a coalition [51].

In the case of cooperative blue carbon governance, Bednar et al. [52] proposed a two-times-scale dynamical model describing the long and complex negotiation process of the 2015 Paris Agreement on climate change. Wang et al. [53] explored carbon reduction strategies from the perspective of co-benefits across geographic regions, finding that spatially nuanced regional policies are critical to maximizing co-benefits. Liao and Yao [54] suggested that the current design of China's national carbon market ignores regional differences in carbon emission allowance allocation and needs to reflect this heterogeneity. The study further suggests that a more flexible cross-regional cooperation mechanism could help achieve a win-win situation for China's east and west. Allowing both direct carbon emission reductions and offsets from renewable energy production conversions through projects where additional investments can be made, investors could apply for carbon emission allowances from the projects accordingly. Zhao et al. [55] explored the feasibility of blue carbon cooperation in the South China Sea region from an economic perspective and constructed the distribution mechanism of cooperation benefits based on the Shapley value in game theory.

2.4. Literature gaps

First, in a comprehensive view, the existing studies on marine ranching mainly focus on the construction history, ecological and economic effects, problems and response policies. However, few studies have paid attention to the ecological product value of blue carbon in marine ranching, and studies on the ecological value realization of blue carbon in marine ranching need to be enriched.

Second, most existing studies on the value realization of marine carbon sinks regard the value realization as a "black box", mainly focusing on the ecological and economic effects of value realization, but not enough research on the process, mechanism and multi-agent strategy of value realization. Only by clearly knowing the internal elements and operation mechanism of the "black box" can we optimize the “black box” more effectively and give better play to the ecological and economic effects of ocean carbon sinks.

Third, the research on the cooperative game of multiple subjects mainly focus on carbon emission strategies, and there are fewer studies on the blue carbon multiple subject governance strategies of marine ranching. In addition, in terms of cooperative subjects, the existing literature is mainly about supply chain subjects and national subjects, and few studies involve government and platform subjects. These two subjects are indispensable in realizing the ecological value of blue carbon in marine ranching.

3. Model construction

Any market activity is linked to supply and demand and cannot be separated from the market mechanism, and the blue carbon market is no exception. Blue carbon demand enterprises are those who need to offset carbon emissions, mainly those who rely on traditional energy sources. Marine ranching enterprises are the suppliers of blue carbon. Currently, blue carbon trading is focused on three types of blue carbon ecosystems recognized by the Intergovernmental Panel on Climate Change (IPCC), including mangroves, seagrass beds, and salt marshes. The trading platform effectively connects the production and the demand sides of marine ranching blue carbon. It can provide diversified services such as basic research, carbon pool survey, carbon sink accounting, trading rule making, and value transformation. In recent years, provincial governments have positively sought to establish trading platforms to support marine ranching enterprises in carbon sequestration. The subsidy is the most common incentive tool used by the government. In order to promote the ecological value realization of blue carbon, the government can start from the production, trading and demand sides to subsidize each market player. Accordingly, the four-subject cooperation model consisting of government, marine ranching enterprises, trading platform and blue carbon demand enterprises is shown in Fig. 1.

According to the above ecological value realization model of blue carbon in marine ranching, the following assumptions are proposed in this paper.

Assumption 1. Drawing from the research on blue carbon sink trading [56], we assumes that the blue carbon production cost of the marine ranching enterprise as a quadratic function about the blue carbon output, and its cost function is $c_1 = \frac{1}{2}a_1q^2$, where $q(q \geq 0)$ is the blue carbon output and $a_1(0 < a_1 \leq 1)$ is the production cost coefficient. The marine ranching enterprise obtains blue carbon revenue by trading through the platform, and its revenue function is $g_1 = pq$, where $p(p > 0)$ is the blue carbon trading price.

Assumption 2. Drawing from the research of carbon trading platform participation motivating blue carbon trading of marine ranching [56,57], this paper assumes that the blue carbon trading platform charges commissions based on trading volume, and its revenue function is $g_2 = wq$, where $w(0 < w < 1)$ is the commission coefficient of the trading platform. The operating cost of the blue carbon trading platform is a quadratic function about the commission coefficient, and its cost function is $c_2 = \frac{1}{2}a_2w^2$, where $a_2(0 < a_2 \leq 1)$ is the transaction cost coefficient of the platform.

Assumption 3. Blue carbon demand enterprises buy the blue carbon emission rights through trading platform. Drawing on research of non-cooperative game and cooperative game method [58,59], this paper assumes that blue carbon demand enterprise’s cost function is $c_3 = pq$ and the benefit function is $g_3 = mq$, where $m(0 < m \leq 1)$ is the blue carbon utility coefficient of the demand enterprise.

Assumption 4. To enhance environmental performance, the government will adopt incentives to support blue carbon development by subsidizing marine ranching enterprises, trading platforms and demand enterprises. Drawing on research on government subsidy strategies [11,57], we assumes the government’s payment cost function is $c_4 = \theta_1 b + \theta_2 b + \theta_3 b$ where $b(b \geq 0)$ is the total amount of government subsidies. $\theta_1(0 < \theta_1 < 1)$ is the subsidy coefficient for marine ranching enterprises, $\theta_2(0 < \theta_2 < 1)$ is the subsidy coefficient for blue carbon trading platform, $\theta_3(0 < \theta_3 < 1)$ is the coefficient of government subsidy given to the blue carbon demand enterprises, and $\theta_1 + \theta_2 + \theta_3 = 1$. The government’s blue carbon benefit function is $g_4 = nq$, where $n(0 < n \leq 1)$ is the government’s blue carbon utility coefficient.

Based on the multi-agent’s cost and benefit, the marine ranching enterprises’ profit function is shown in equation (1), the trading platform’s profit function is shown in equation (2), the blue carbon demand enterprises’ profit function is shown in equation (3), the government’s utility function is shown in equation (4), and the overall benefit function is shown in equation (5).

$$s_1 = pq - \frac{1}{2}a_1q^2 - wq + \theta_1 b \tag{1}$$

$$s_2 = wq - \frac{1}{2}a_2w^2 + \theta_2 b \tag{2}$$

$$s_3 = mq - pq + \theta_3 b \tag{3}$$

$$s_4 = nq - b \tag{4}$$

$$s = mq + nq - \frac{1}{2}a_1q^2 - \frac{1}{2}a_2w^2 \tag{5}$$

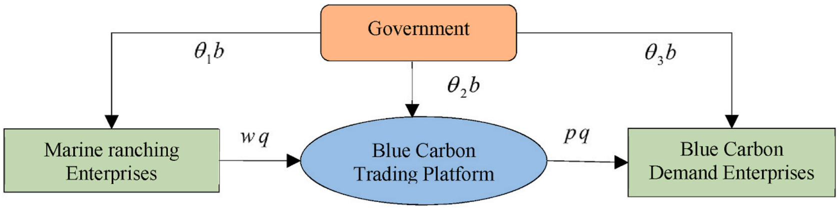

Fig. 1. Blue carbon ecological value realization model of marine ranching.[11] (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Results and analysis

4.1. Non-cooperative game's results

Under the non-cooperative game situation, each subject determines its own optimal decision according to its own profit maximization principle. Marine ranching enterprises determine the optimal blue carbon output according to their own profit maximization principle, so let the partial derivative of equation (1) $\partial s_1/\partial q = 0$, and get the optimal blue carbon production q_N^* , as shown in equation (6). The trading platform determines the optimal transaction cost according to the principle of maximizing its own profit, so let the partial derivative of equation (2) $\partial s_2/\partial w = 0$, and get the optimal commission for the platform w_N^*, as shown in equation (7). Substituting equation (6) into the blue carbon demand function $q = A - p$, the optimal blue carbon trading price p_N^* is obtained in equation (8).

$$q_N^* = \frac{A(a_2 + a_1a_2 - 2)}{(a_1 + 1)(a_2 + a_1a_2 - 1)} \tag{6}$$

$$w_N^* = \frac{A}{a_2 + a_1a_2 - 1} \tag{7}$$

$$p_N^* = \frac{Aa_1(a_2 + a_1a_2 - 1) + A}{(a_1 + 1)(a_2 + a_1a_2 - 1)} \tag{8}$$

From equation (6), it can be seen that in the non-cooperative game situation, q_N^* is positively proportional to A and inversely proportional to a_1, a_2. This indicates that the initial demand for blue carbon positively affects blue carbon output. Marine ranching enterprises' production cost coefficient and the platform transaction cost coefficient negatively affect blue carbon output in marine ranching.

From equation (7), it can be seen that in the non-cooperative game situation, w_N^* is positively proportional to A and inversely proportional to a_1, a_2. This indicates that the initial demand for blue carbon positively affects the platform's optimal commission. Marine ranching enterprises' production cost coefficient and platform transaction cost coefficient negatively affect the platform's optimal commission.

From equation (8), it can be seen that p_N^* is positively proportional to A, a_1 and a_2 in the non-cooperative game situation. This indicates that the initial demand for blue carbon, the production cost coefficient of marine ranching enterprises and the platform transaction cost coefficient positively affect blue carbon trading price.

Further, to explore the optimal outcome for each subject in the non-cooperative situation, by substituting equations (6)–(8) into the revenue functions (1) to (5) of each subject respectively, the profit of the marine ranching enterprise is equation (9), the blue carbon trading platform's profit is equation (10), the blue carbon demand enterprise's profit is equation (11), the maximum utility of the government is equation (12), and the overall profit is equation (13), where $t = a_2 + a_1a_2 - 1$.

$$s_1^{N*} = \theta_1 b - \frac{A^2(t-1)}{(a_1+1)t^2} - \frac{A^2a_1(t-1)}{2(a_1+1)^2t^2} + \frac{A^2(t-1)(a_1t+1)}{(a_1+1)^2t^2} \tag{9}$$

$$s_2^{N*} = \theta_2 b + \frac{A^2(2t - a_2)}{2t^2} - \frac{A^2(a_1t+1)}{(a_1+1)t^2} \tag{10}$$

$$s_3^{N*} = \theta_3 b - \frac{A^2(t-1)(a_1t+1)}{t^2(a_1+1)^2} + \frac{Am(t-1)}{t(a_1+1)} \tag{11}$$

$$s_4^{N*} = An - \frac{An(a_1t+1)}{(a_1+1)t} - b \tag{12}$$

$$s^{N*} = \frac{A(t-1)(m+n)}{(a_1+1)t} - \frac{A^2 a_2}{2t^2} - \frac{A^2 a_1 (t-1)^2}{2t^2 (a_1+1)^2} \tag{13}$$

From equation (9), we can see that s_1^{N*} is positively proportional to θ_1, b, A, and inversely proportional to a_1, a_2. This shows that in the case of multi-agent non-cooperative governance, the subsidy coefficient for marine ranching enterprises, the total government blue carbon subsidy, and the initial demand for blue carbon positively affect the profit of marine ranching enterprises. The blue carbon production cost coefficient and the trading platform transaction cost coefficient of marine ranching enterprises negatively affect the profit of marine ranching enterprises.

From equation (10), we can see that s_2^{N*} is positively proportional to θ_2, b, A, and inversely proportional to a_1, a_2. This indicates that in the case of multi-agent non-cooperative governance, the coefficient of subsidy given to marine ranching enterprises, the total government blue carbon subsidy, and the initial demand for blue carbon positively affect blue carbon trading platform's profit. Blue carbon production cost coefficient of marine ranching enterprises and the transaction cost coefficient of blue carbon trading platform negatively affect blue carbon trading platform's profit.

From equation (11), s_3^{N*} is positively proportional to θ_3, b, m, A, and inversely proportional to a_1, a_2. This indicates that in the case of multi-agent non-cooperative governance, the coefficient of subsidy given to marine ranching enterprises, the total government blue carbon subsidy, the blue carbon utility coefficient of demand enterprises, and the initial demand of blue carbon positively affect the profit of blue carbon demand enterprises, and the blue carbon production cost coefficient of marine ranching enterprises and the transaction cost coefficient of blue carbon trading platform negatively affect the profit of blue carbon demand enterprises.

Equation (12) shows that s_4^{N*} is positively proportional to n, A, and inversely proportional to b, a_1, a_2. This indicates that in the case of multi-agent non-cooperative governance, the government blue carbon utility coefficient and the initial demand for blue carbon positively affect the government profit, and the total government blue carbon subsidy, blue carbon production cost coefficient of marine ranching enterprises and blue carbon trading platform transaction cost coefficient negatively affect the government profit.

From equation (13), s^{N*} is positively proportional to m, n, A, and inversely proportional to a_1, a_2. This indicates that in the case of multi-agent non-cooperative governance, the demand enterprise blue carbon utility coefficient, the government blue carbon utility coefficient, and the initial demand for blue carbon positively affect the overall profit. The marine ranching enterprise' blue carbon production cost coefficient and the trading platform transaction cost coefficient negatively affect the overall profit.

4.2. Results and analysis of cooperative game

In the cooperative game situation, each subject no longer determines the optimal decision according to its own profit maximization principle, but determines the optimal output and price of blue carbon depending on the overall profit maximization principle. Let the partial derivative of equation (5) $\partial s/\partial q = 0$, and get the optimal blue carbon production q_C^*, as shown in equation (14). The optimal transaction cost w_C^* of the trading platform can be determined from the optimal blue carbon output is shown in equation (15). Substituting equation (14) into the blue carbon demand function $q = A - p$, the optimal blue carbon trading price p_C^* is obtained in equation (16).

$$q_C^* = \frac{m+n}{a_1} \tag{14}$$

$$w_C^* = \frac{m+n}{a_1 a_2} \tag{15}$$

$$p_C^* = \frac{Aa_1 - m - n}{a_1} \tag{16}$$

From equation (14), it can be seen that q_C^* is positively proportional to m, n, and inversely proportional to a_1 in the case of multi-agent cooperative governance. This indicates that the demand enterprise blue carbon utility coefficient and the government blue carbon utility coefficient positively affect the blue carbon output of marine ranching, and the marine ranching enterprises production cost coefficient negatively affect the blue carbon output.

From equation (15), w_C^* is positively proportional to m, n, and inversely proportional to a_1, a_2 in the case of multi-agent cooperative governance. This indicates that the demand enterprise blue carbon utility coefficient and the government blue carbon utility coefficient positively affect the platform transaction cost, and the ocean ranch enterprise production cost coefficient and the platform transaction cost coefficient negatively affect the platform transaction cost.

From equation (16), it can be seen that p_C^* is positively proportional to A and inversely proportional to a_1, m, n in the case of multi-agent cooperative governance. This indicates that the initial demand for blue carbon positively affect blue carbon trading price, and marine ranching enterprises production cost coefficient, the demand enterprises blue carbon utility coefficient and the government blue carbon utility coefficient negatively affect the blue carbon trading price.

Further, by substituting equations (14)–(16) into the benefit functions (1) to (5) of each subject respectively, the optimal results can be obtained given the cooperation of each subject. Among them, the profit of the marine ranching enterprise is shown in equation (17),

[1] Blue carbon ecological value realization model of marine ranching is from the author's concept.

the blue carbon trading platform's profit is shown in equation (18), the blue carbon demand enterprise's profit is shown in equation (19), the maximum utility of the government is shown in equation (20), and the profit of the whole is shown in equation (21).

$$s_1^{C*} = \theta_1 b - \frac{(a_1a_2+2)(m+n)^2}{2a_1^2a_2} - \frac{(m+n)(m+n-Aa_1)}{a_1^2} \tag{17}$$

$$s_2^{C*} = \theta_2 b + \frac{(m+n)^2}{2a_1^2a_2} \tag{18}$$

$$s_3^{C*} = \theta_3 b - \frac{(m+n)(m+n-Aa_1)}{a_1^2} - \frac{m(m+n)}{a_1} \tag{19}$$

$$s_4^{C*} = \frac{n(m+n)}{a_1} - b \tag{20}$$

$$s^{C*} = \frac{(a_1a_2-1)(m+n)^2}{2a_1^2a_2} \tag{21}$$

From equation (17), we can see that s_1^{C*} is positively proportional to θ_1, b, A, m, n, and inversely proportional to a_1, a_2. This indicates that, in the case of multi-agent cooperative governance, the subsidy coefficient for marine ranching enterprises, the total government blue carbon subsidy, the initial demand for blue carbon, the demand enterprise blue carbon utility coefficient, and the government blue carbon utility coefficient positively affect the profit of marine ranching enterprises, and the blue carbon production cost coefficient of marine ranching enterprises and the transaction cost coefficient of blue carbon trading platform have a negative The blue carbon production cost coefficient. The blue carbon trading platform cost coefficient negatively affect the profit of marine ranching enterprises.

From equation (18), we can see that s_2^{C*} is positively proportional to θ_2, b, m, n, and inversely proportional to a_1, a_2. This indicates that, in the case of multi-agent cooperative governance, the subsidy coefficient for marine ranching enterprises, the total government blue carbon subsidy, the demand enterprise blue carbon utility coefficient, and the government blue carbon utility coefficient positively affect the profit of blue carbon trading platform. The blue carbon production cost coefficient of marine ranching enterprises and the blue carbon trading platform transaction cost coefficient negatively affect the profit of trading platform.

From equation (19), we can see that s_3^{C*} is positively proportional to θ_3, b, A, m, n, and inversely proportional to a_1. This indicates that, in the case of multi-agent cooperative governance, the subsidy coefficient for marine ranching enterprises, the total government blue carbon subsidy, the initial demand for blue carbon, the blue carbon utility coefficient of demand enterprises, and the government blue carbon utility coefficient has positive effects on the profit of blue carbon demand enterprises. The blue carbon production cost coefficient of marine ranching enterprises has negative effects on the profit of blue carbon demand enterprises.

From equation (20), we can see that s_4^{C*} is positively proportional to m, n, and inversely proportional to b, a_1. This indicates that, in the case of multi-agent cooperative governance, the demand enterprise blue carbon utility coefficient and the government blue carbon utility coefficient positively affect the optimal government profit. The total government blue carbon subsidy and the marine ranching enterprise blue carbon production cost coefficient negatively affect the optimal government profit.

From equation (21), we can see that s^{C*} is positively proportional to m, n, and inversely proportional to a_1, a_2. This indicates that, in the case of multi-agent cooperative governance, the demand enterprise blue carbon utility coefficient and the government blue carbon utility coefficient positively affect the overall profit. The marine ranching enterprise blue carbon production cost coefficient and the blue carbon trading platform transaction cost coefficient negatively affect the overall profit.

4.3. Comparison of non-cooperative game and cooperative game

Further, we calculate the cooperative surplus to determine the strengths and weaknesses of the non-cooperative game and cooperative game for the ecological value realization of blue carbon in marine ranching. The optimal commission, blue carbon price, blue carbon production, and profit in the cooperative game situation are subtracted from those in the non-cooperative game situation, respectively, and the difference between them is shown in equations (22)–(29). Among them, $j = (m+n)(m+ma_1+n-Aa_1)$, and $k = 2Aa_1a_2(m+n) - (m+n)^2(a_1a_2+2a_2+2)$.

$$\Delta w = w_C^* - w_N^* = \frac{m+n}{a_1a_2} - \frac{A}{t} < 0 \tag{22}$$

$$\Delta p = p_C^* - p_N^* = A - \frac{m+n}{a_1} - \frac{A(a_1t+1)}{t(a_1+1)} < 0 \tag{23}$$

$$\Delta q = q_C^* - q_N^* = \frac{m+n}{a_1} + \frac{A(a_1t+1)}{t(a_1+1)} - A > 0 \tag{24}$$

$$\Delta s_1 = s_1^{C*} - s_1^{N*} = \frac{k}{2a_1^2 a_2} - \frac{A^2 a_1 (t-1)^2}{2t^2 (a_1+1)^2} > 0 \tag{25}$$

$$\Delta s_2 = s_2^{C*} - s_2^{N*} = \frac{(m+n)^2}{2a_1^2 a_2} + \frac{A^2 a_2}{2t^2} - \frac{A^2 (t-1)}{t^2 (a_1+1)} > 0 \tag{26}$$

$$\Delta s_3 = s_3^{C*} - s_3^{N*} = \frac{j}{a_1^2} + \frac{(t+1)(Aa_1 t + A - ma_1 t - mt)A^2}{t^2 (a_1+1)^2} > 0 \tag{27}$$

$$\Delta s_4 = s_4^{C*} - s_4^{N*} = \frac{m(m+n)}{a_1} - \frac{An(t-1)}{t(a_1+1)} > 0 \tag{28}$$

$$\Delta s = s^{C*} - s^{N*} = \frac{k}{2a_1^2 a_2} + \frac{A^2 a_2}{2t^2} - \frac{A(t-1)(A-mt-nt)}{t^2(a_1+1)} - \frac{A^2(t-1)(a_1 t+1)}{t^2 (a_1+1)^2} > 0 \tag{29}$$

From equation (22), $\Delta w = w_C^* - w_N^* < 0$, indicating that the commission coefficient of the platform is lower when multiple subjects are governed cooperatively compared to non-cooperative governance. From equation (23), $\Delta p = p_C^* - p_N^* < 0$, indicating that the trading price is lower when multiple subjects are governed cooperatively. From equation (24), $\Delta q = q_C^* - q_N^* > 0$, indicating that the blue carbon production of the marine ranching enterprises is higher in the case of cooperative governance. From equation (25), $\Delta s_1 = s_1^{C*} - s_1^{N*} > 0$, indicating that the profit of the marine ranching enterprise is higher in the case of cooperative governance. From equation (26), $\Delta s_2 = s_2^{C*} - s_2^{N*} > 0$, indicating that the blue carbon trading platform is more profitable in the case of cooperative governance. From equation (27), $\Delta s_3 = s_3^{C*} - s_3^{N*} > 0$, indicating that the profits of blue carbon demand companies are higher in the case of cooperative governance. From equation (28), $\Delta s_4 = s_4^{C*} - s_4^{N*} > 0$, indicating that the government utility is greater in the case of cooperative governance. From equation (29), $\Delta s = s^{C*} - s^{N*} > 0$, indicating that the overall profit is higher in the case of multi-agent cooperation for the blue carbon ecological value realization.

5. Discussion and implications

5.1. Discussion

This paper aims to explore whether multi-agent cooperation governance can promote the realization of blue carbon value in marine ranching. The results show that compared with independent governance, blue carbon's price is lower and blue carbon's output is higher when multiple subjects cooperatively govern marine ranching blue carbon. Moreover, the profits of marine ranching enterprises, blue carbon trading platforms and blue carbon demand enterprises are higher. Therefore, an interest linkage mechanism should be established among the subjects to achieve win-win cooperation.

Regarding the research assumptions, this paper draws on the study of non-cooperative and cooperative game theory method [58, 59] to propose the assumptions. Yu et al. assume that the blue carbon production cost of the ocean ranching enterprise as a quadratic function of the blue carbon output [56], which is the same as this research. Unlike linear function in Wan's research [57], this study assumes the operating cost of blue carbon trading platform is a quadratic function. Zheng et al. distribute the subsidy among all subjects [11]. This paper draws on that approach and assumes that the government subsidy is distributed among marine ranching enterprises, trading platforms and blue carbon demand enterprises.

Zhao et al. [55] explored the economic feasibility of blue carbon cooperation among countries in the South China Sea region. They used the Shapley value in game theory to construct the distribution mechanism of cooperation benefits. It provides a reference for this paper, and the conclusions of this paper are similar. Although the government is crucial in promoting blue carbon cooperation, realizing blue carbon ecological value is also inseparable from the cooperation among market players. This paper not only includes the government in the cooperation framework, but also considers the cooperative governance of blue carbon market players in marine ranching. Wan et al. [60] argued that the government should take on a regulatory function, pointing out that government regulation can restrain the opportunistic behavior of blue carbon trading platforms. However, this is obviously a common-sense conclusion. In contrast, this paper explores the government's blue carbon subsidy strategy. In the early stage when blue carbon trading is not yet fully developed, the incentive is better than the constraint approach to promote its rapid development. Therefore, government blue carbon subsidy for marine ranching is a topic with theoretical significance and practical value. Wang et al. [61] pointed out that the special subsidy for blue carbon in marine ranching can improve the motivation of marine ranching enterprises and blue carbon demand enterprises to trade blue carbon, which is the same as the findings of this paper. Zheng et al. [11] proposed that subsidy is not the more, the better. It tends to the production side can obtain the best effect. In contrast, this paper does not find a boundary for government subsidy. In addition to government subsidies, market transactions are also an essential means of realizing the ecological value of blue carbon in marine ranching. Wan et al. [57] proposed that the blue carbon transaction cost should be reduced and the blue carbon transaction price should be increased in ocean pastures' blue carbon market trading. The conclusion of reducing blue carbon transaction costs is similar to the findings of this paper. However, different from it, this paper finds that the blue carbon trading price can be reduced by multi-agent cooperation. In addition, unlike existing studies, this paper further explores the advantages of multi-agent cooperation in realizing blue carbon ecological value in marine ranching.

Blue carbon has positive spatial spillover effects. Yu et al. [56] analyzed the blue carbon cooperative governance between neighboring regions using game theory. They concluded that the effect of blue carbon cooperative governance in neighboring regions is greater than that of independent governance. This area is not considered in this study and provides an empirical reference for this paper. In addition, this paper's cooperative versus non-cooperative game research method is a static mathematical model study that does not allow for dynamic trend analysis like the evolutionary game approach [62]. It does not allow for statistically significant results on large samples like the econometric approach [63,64]. This is due to the fact that the current blue carbon in marine ranching is in the initial exploration stage, and the cooperation of multi-subject governance has not yet been reached, so that dynamic evolutionary analysis and regression analysis based on large samples cannot be conducted. Its advantage is that it allows cross-sectional comparisons to obtain the advantages and disadvantages of cooperative or independent governance of multiple subjects by comparing the results of cooperative and non-cooperative game models.

5.2. Policy implications

Firstly, make full use of the market mechanism's decisive role in realizing the value of blue carbon ecological products of marine ranching, and gradually incorporate blue carbon of marine ranching, blue carbon of mangroves and blue carbon of seagrass beds into the blue carbon trading system. Accelerate the construction of the blue carbon trading platform of ocean pasture, improve the trading mechanism of the platform from the trading side, reduce the transaction cost, improve the price formation mechanism, and then promote the realization of the ecological value of blue carbon of ocean pasture.

Secondly, the government should use subsidies as the main incentive to mobilize all subjects to participate in blue carbon governance. On the one hand, the target of subsidies should be reasonably determined. Subsidy funds should be rationally allocated, so that the subsidy funds benefit marine ranching enterprises, trading platforms, blue carbon demand enterprises and other subjects. However, it should also focus on subsidizing the construction of trading platforms. On the other hand, the total amount of subsidies should be reasonably set. The amounts of subsidies should be adjusted according to the trading situation of the blue carbon market, so as not to increase the financial burden excessively, but also to give full play to the incentive effect of subsidies.

Thirdly, build an interest linkage mechanism based on multi-agent cooperation, and expand the revenue space of blue carbon cooperative governance of marine ranching. Strengthen the cooperation of marine ranching enterprises, blue carbon trading platform, blue carbon demand enterprises, the government and other subjects, establish a multi-agent marine ranching blue carbon ecological value of the realization of the interest linkage mechanism, form a risk-sharing and benefit-sharing pattern of blue carbon governance in marine ranching.

5.3. Strengths and limitations

Compared to the published research results, the strengths of this paper lie in 2 aspects. On the one hand, differing from previous studies that generally focus on the economic value of marine ranching, this paper focuses on the ecological value of blue carbon in marine ranching, providing a new theoretical basis for ecological compensation in marine ranching. On the other hand, most of the previous blue carbon governance focuses on inter-governmental and inter-regional cooperation. However, we integrate blue carbon trading platform and government into the blue carbon ecological value realization model, making it more consistent with the government-led and market-oriented operation of the blue carbon ecological value realization mechanism.

However, there are limitations in this paper. First, the central and local governments play different roles in realizing the blue carbon ecological value of marine ranching. To simplify the model, this paper does not subdivide the government into the central and local governments. Second, the government can support the ecological value of blue carbon in marine ranching in several ways. However, this paper only considers the government's financial subsidies as a policy tool, and the effects of other policy tools can be explored in the future.

6. Conclusion

Blue carbon ecological value realization of ocean pastures is an important policy tool to help reduce greenhouse gas emissions. This paper constructs a blue carbon ecological value realization model including marine ranching enterprises, blue carbon demand enterprises, blue carbon trading platforms and government. It explores each subject's blue carbon cooperative governance strategy using cooperative game and non-cooperative game models. The conclusions of the study are as follows.

First, in the case of non-cooperative governance of blue carbon in marine ranching, (1) the initial demand for blue carbon positively affect blue carbon output, and blue carbon production cost and platform transaction cost negatively affect blue carbon output. (2) The initial demand for blue carbon, the production cost of blue carbon, and the platform transaction cost positively affects the price of blue carbon. (3) The subsidies given to marine ranching enterprises, the total government blue carbon subsidies, and the initial demand of blue carbon positively impact the profit of each market subject. The production cost of blue carbon and the platform transaction cost negatively impact each market subject's profit. (4) The initial demand of blue carbon has a positive impact on government utility, and the production cost of blue carbon and platform transaction cost negatively affect government utility.

Second, in the case of cooperative governance of blue carbon in marine ranching, (1) blue carbon utility of demand enterprises and blue carbon utility of government have positive effects on blue carbon output, and blue carbon production cost has negative effects on blue carbon output. (2) The initial demand for blue carbon positively affects blue carbon price, and the production cost of blue carbon, the demand for enterprise's blue carbon utility, and the government's blue carbon utility negatively affect the blue carbon price. (3)

The subsidies given to marine ranching enterprises, total government blue carbon subsidies, demand enterprises' blue carbon utility, and government blue carbon utility positively affect the profit of each subject. Blue carbon production cost and platform transaction cost negatively affect the profit of marine ranching enterprises and blue carbon trading platforms, respectively. (4) Demand enterprises' blue carbon utility has a positive impact on government utility, and total government blue carbon subsidy and blue carbon production cost negatively affect government utility.

Third, cooperative governance of multiple subjects is more conducive to realizing ocean pasture's blue carbon ecological value. Compared with non-cooperative governance, in the case of multi-agent cooperative governance, the platform commission is lower, the blue carbon trading price is lower, the marine ranching enterprises blue carbon output is higher, the profit of marine ranching enterprise's is higher, the profit of blue carbon trading platform is higher, the profit of blue carbon demand enterprises is higher, the utility of government is higher, and the overall profit is higher.

Author contribution statement

Xuechang Zhang: Performed the experiments; Wrote the paper.
Jingwei Cheng: Conceived and designed the experiments; Analyzed and interpreted the data.
Shan Zheng: Contributed reagents, materials, analysis tools or data.

Data availability statement

Data included in article/supplementary material/referenced in article.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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