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Reduce pollution, establish protected areas, manage fisheries properly? How to protect coral reefs based on carbon trading

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As coral reefs around the world have suffered serious damage, it is necessary to protect them. Common modes of coral reef protection include reducing pollution, setting up reserves and managing fisheries rationally. In order to derive the applicable scope of various protection modes for coral reefs, this article constructs three differential game models and compares and analyzes the equilibrium results obtained by the models. Finally, the study shows that whether for developed or developing countries, when the benefits of coral reef treatment are small, the mode of reducing pollution can achieve the maximum benefit. As the benefits of coral reef treatment gradually increase, the mode of setting up nature reserves can achieve the maximum benefit. It is worth noting that the greater the carbon emission rights obtained by the number of coral reefs, the greater the benefits of coral reef treatment, the more likely developed countries will adopt the mode of setting up reserves.

KEYWORDS

developed countries, developing countries, differential game, protection mode, maximum benefit

1 Introduction

Coral reefs around the world serve many important functions. Firstly, coral reefs are one of the most diverse and rich ecosystems in marine ecosystems, providing habitats for many marine organisms. They are places where many species live and reproduce, including fish, shellfish, sea turtles, seaweeds, and more. Secondly, coral reefs play an important role in protecting coastal and coastal areas from natural disasters such as wave erosion and hurricanes. They can mitigate the impact of waves and prevent shoreline erosion. This is very important for the protection of coastal communities and disaster risk management. In addition, coral reefs also play a key role in global climate change. They can absorb large amounts of carbon dioxide and slow down the process of ocean acidification, protecting the balance of marine ecosystems. Corals are also the main builders in coral reef systems, forming reef structures by secreting calcium skeletons, which are crucial for the formation of seabed topography and biodiversity (Zhao et al., 2019). Finally, coral reefs also provide important resources for tourism and economic development. Many people travel to coral reefs around the world for diving, snorkeling, and watching, which brings considerable income to the local economy and promotes the increase of job opportunities.

At the same time, coral reefs are of great significance in terms of global carbon cycle and carbon emissions, mainly reflected in the following aspects. First, carbon storage. Although the coral reef is relatively small in area, due to its rich biodiversity, the coral reef ecosystem can absorb and store a large amount of carbon. The biomes of the coral reef, especially seagrasses and algae, can absorb carbon dioxide from the atmosphere through photosynthesis, fixing carbon elements into organic matter. Second, carbon emission mitigation. After death, the organic matter in the coral reef ecosystem will form a carbon storage pool deposited on the seabed. This sedimentation process enables a large amount of carbon element to be stored for a long time, avoiding return to the atmosphere. In this way, the coral reef plays a role in mitigating carbon emissions. Third, mitigation of the impacts of climate change. As a natural coastal protection system, coral reefs can mitigate the impact of storms and waves on coastal areas, thereby reducing the impact of sea level rise and extreme climate events on coastal areas caused by climate change (Armstrong et al., 2019). In summary, coral reefs play an important role in the global carbon cycle and carbon emissions. In order to achieve global climate goals and address climate change, the protection of coral reefs has important value in the management and mitigation of carbon emissions.

Coral reefs around the world have suffered serious damage. The main damage factors include the following. First, climate change. Global warming leads to rising sea temperatures. Corals are extremely sensitive to high temperatures, and prolonged high temperatures can cause coral bleaching and may lead to mass coral death. Second, seawater acidification. A large amount of carbon dioxide emissions into the atmosphere dissolve in seawater, forming carbonic acid, leading to seawater acidification (Smith et al., 2020). Acidified seawater has a negative impact on coral growth and skeleton formation. Third, overfishing. Overfishing disrupts the balance of the food chain in coral reef ecosystems, reducing the number and diversity of coral reefs (Seraphim et al., 2020). Fourth, marine pollution. Wastewater discharged from agriculture and cities leads to eutrophication of water bodies. The presence of excessive nutrients in seawater promotes the growth of algae, causing coral reefs to suffocate and die. Fifth, destructive fishing and destructive tourism. Irresponsible fishing activities and unrestrained tourist activities, such as trampling coral and using destructive fishing methods such as bombs and poisoned fish, have caused direct damage to coral reefs. These destructive factors work together to lead to the degradation and death of coral reefs around the world. To protect coral reefs, countries and organizations around the world are working to promote sustainable fisheries management, reduce carbon emissions, strengthen marine reserves and promote responsible tourism. These efforts aim to protect the integrity and biodiversity of coral reef ecosystems and ensure their sustainable development.

In the face of the destruction of coral reefs around the world, reducing pollution, setting up reserves and managing fisheries properly are one of the important modes to protect coral reefs. The following are the specific roles and measures of these modes. First, reducing pollution. Measures are taken to reduce the impact of marine pollution on coral reefs. These include limiting wastewater discharge, strengthening agricultural and urban wastewater treatment, reducing plastic and other garbage pollution, etc (Liu et al., 2021). Through these measures, the concentration of nutrients in water can be reduced and the excessive growth of algae can be reduced. Second, setting up reserves. Setting up coral reef reserves is an important measure to protect coral reef ecosystems. Reserves can limit the interference of human activities and reduce the impact of fishing, tourism and other destructive behaviors (Meekan et al., 2019). Through scientific management and the expansion of reserves, the protection level of coral can be improved and the ecological restoration can be promoted. Third, managing fisheries properly. Sustainable fisheries management measures are implemented to reduce the pressure on coral reef ecosystems. This includes setting appropriate fishing quotas, limiting the use of destructive fisheries fishing methods, and taking measures to protect and manage important fisheries resources. In fisheries management, the protection of coral reef habitats should be emphasized and the relationship between benefits and protection measures should be balanced (Osuka et al., 2021). These modes require cooperation and support from governments, scientific institutions, NGOs and the public. Coral reef conservation worldwide requires a policy and regulatory framework, and a collaborative effort to implement and monitor it. Only through integrated conservation measures can we maximize the protection of the world's coral reefs and ensure the health and sustainability of their ecosystems.

Coral reefs have a huge impact on the marine ecosystem. This has also been highly valued by the academic community. With the deepening of research on coral reef protection, a large number of research findings have emerged. These studies on coral reef protection mainly focus on the causes of coral reef destruction and how to protect coral reefs.

In terms of the causes of coral reef destruction, Lowe et al. (2020) believed that environmental disturbance events were the causes of coral reef destruction. Avigdor (2019) believed that "climate change" led to coral reef destruction. Weber et al. (2020) analyzed the microbiological characteristics of damaged and protected coral reefs. These factors include human interference, environmental change, and microorganisms.

A large number of research achievements have emerged in the protection of coral reefs. These research achievements are mainly carried out from the two aspects of technology and management. Some scholars have studied the use of advanced technology to protect coral reefs, for example, Larsen et al. (2023) studied the use of high-resolution fluid dynamics to track pollutants near coral reefs;

Selmoni et al. (2020) analyzed the use of marine genomics to enhance the protection strategy of coral reefs; Kleypas et al. (2021) designed a blueprint for the survival of coral reefs; Paulino et al. (2020) used molecular technology to protect coral reefs. These technologies involve theories and methods related to physics, biology, geography, etc. Some scholars have studied the use of appropriate management methods or management modes to protect coral reefs, Topor et al. (2019) believed that promoting fish diversity can enhance the function of coral reefs; Hall et al. (2022) believed that banning harpoon fishing can improve the protection effect of coral reefs; Nolan et al. (2021) created a reserve quality score to determine the priority of coral reef space protection; Armstrong et al. (2019) analyzed the behavioral level of how much people are willing to pay for the protection of coral reefs; Hopf et al. (2019) believed that nature reserves play an important role in fish populations and fish production in coral reef systems; Yanovski and Abelson (2019) believed that structural complexity enhancement is a restoration tool for coral reefs. These management methods cover related theories such as biodiversity, protected areas, and ethology.

Carbon trading plays an important role in coral reef protection, promoting the protection of coral reefs and the sustainable development of marine ecological environment through economic incentives, financial support and technical cooperation. This is conducive to protecting the ecological environment, reducing carbon emissions and promoting sustainable development. Some scholars have conducted research on carbon trading. For example, the synergistic effect of carbon trading on carbon dioxide and air pollutants (Li et al., 2021); whether carbon trading can achieve carbon neutrality (Chen and Lin, 2021); the role of carbon trading system in green and balanced development (Wang and He, 2022); the optimal scheduling model of virtual power plant based on carbon trading (Zhang et al., 2023).

However, the above studies have not combined carbon trading with coral reef protection. Providing certain carbon emission rights to both developed and developing countries involved in coral reef protection could promote effective protection of coral reefs around the world. To this end, the following needs to be done. First, establish an international assessment and monitoring agency. To ensure the fairness of carbon emission rights allocation and trading, an international assessment and monitoring agency for coral reef protection could be set up to assess countries' efforts in coral reef protection and monitor the use of carbon emission rights (Marshall et al., 2019). Second, develop clear assessment criteria. To produce meaningful and measurable incentive effects, the international assessment and monitoring agency needs to develop clear assessment criteria to quantify the contributions of countries involved in coral reef protection (Carriger et al., 2019). These criteria could include indicators such as coral reef coverage, species diversity and biomass. Specific protection measures taken by countries, such as fishing restrictions and water quality improvement, should also be considered. Third, encourage international cooperation and technological exchange. Developed countries usually have stronger technologies and experience in environmental protection and sustainable development. The international community should encourage these countries to carry out cooperation and technological exchanges with developing countries in relevant fields to help them improve their capacity for coral reef protection (Rani et al., 2020). Fourth, strengthen legal and regulatory construction. To ensure the compliance and fairness of carbon emission trading, countries should formulate corresponding domestic laws and regulations and reach agreements through bilateral and multilateral frameworks to ensure the legitimacy and transparency of carbon emission trading at the international level. In conclusion, providing certain carbon emission allowances to both developed and developing countries involved in coral reef protection is a potential win-win measure that needs global efforts to promote. It will not only help improve the environmental problems faced by coral reefs, but also promote the balance and fairness of carbon emission allowances between countries.

In order to make up for the deficiencies of the above research, this article combines carbon trading with coral reef protection. In this case, countries participating in the protection of coral reefs can obtain certain carbon emission rights. Based on carbon trading, the game models of reducing pollution, establishing protected areas, and managing fisheries properly are constructed. Then the equilibrium results under different modes are compared. This provides a reference for developed and developing countries to effectively protect coral reefs based on carbon trading.

2 Methodology

2.1 Problem description, hypothesis, and variable definition

2.1.1 Problem description

The destruction of coral reefs has a certain impact on all countries in the world. In the process of global coral reef governance, there is a game between developed and developing countries. This is because developed and developing countries have different interests and attitudes towards coral reef governance due to differences in resources, technology and economic development. Developed countries usually have more advanced technology and funds, and can play a greater role in coral reef protection. They often have more research institutions and expertise, and can provide technical support, monitoring and assessment tools, as well as financial assistance. However, the development mode of these countries may lead to higher carbon emissions and resource consumption, increasing the risk of global climate change and damage to coral reefs. Developing countries often face more serious economic and social development problems, and are faced with limited resources and lack of appropriate technology and funds to address the challenges of coral reef protection. For some developing countries, coral reefs may also be important economic resources, such as tourism and fishing. Therefore, in the governance process, developing countries may pay more attention to economic interests and sustainable development, and may hesitate to take some protection measures. The key to solving this game is to promote international cooperation and shared responsibility (Arizono and Takemoto, 2022). The international community should provide developing countries with technical, financial and capacity-building support to ensure that they can participate and benefit from it. At the same time, developed countries should assume more responsibility to reduce carbon emissions and environmental impacts, and balance the needs of protection and development through reasonable cooperation mechanisms. Only through cooperation and consultation can effective governance and protection of coral reefs be achieved at a global scale.

At the same time, the decision-making of developed and developing countries in the global coral reef governance process is constantly changing. This is because countries' policies, economic conditions and environmental awareness can change over time and under different circumstances, which in turn affect their stance on coral reef protection and management. Developed countries may strengthen their commitment to coral reef protection and management after realizing the importance of coral reefs to the global ecosystem and human well-being. They may increase financial inputs, technical support and research cooperation to address issues such as climate change, pollution and overfishing. Developing countries may strengthen their efforts to protect and sustainably use coral reefs after realizing the importance of coral reefs to their own economy and sustainable development. They may formulate and implement more targeted policies to promote sustainable tourism and fisheries management to ensure the ecological and economic functions of coral reefs. International environmental agreements, international cooperation mechanisms and intergovernmental organizations may also influence the decision-making of developed and developing countries. These mechanisms may promote the implementation of coral reef protection and sustainable management by providing financial, technical transfer and capacity building support. Therefore, global coral reef governance involves dynamic consultation and trade-offs among different countries and stakeholders. Policies and decisions may change over time, but the goal of maintaining the health and sustainability of coral reef ecosystems should be pursued by a global consensus.

In general, there are three main modes for the governance of coral reefs around the world:

(1) Reduce seawater pollution. Reducing seawater pollution is one of the important measures to protect coral reefs around the world. The following are some methods and measures that can help protect coral reefs from seawater pollution. First, wastewater treatment. Strengthen the construction and operation of wastewater treatment facilities to ensure that wastewater is properly treated and filtered to reduce the amount of wastewater containing harmful substances and nutrients into the ocean (Wang et al., 2022). Second, agricultural management. Improve agricultural practices and take measures to reduce the emissions of pesticides, fertilizers and other pollutants from farmland into coastal waters to avoid eutrophication and pollution of harmful substances. Third, control industrial emissions. Strengthen the control of pollutant emissions from industry and manufacturing and promote the use of cleaner and more environmentally friendly technologies to reduce the pollution of industrial wastewater and waste gas on the marine environment. Fourth, garbage management. Strengthen measures for garbage recycling and treatment to reduce the amount of plastics, wastes and other garbage into the ocean to avoid physical damage to coral reefs and water pollution (Viejo et al., 2023). Fifth, drainage management. Improve urban drainage systems to reduce the mixing of rainwater and sewage discharge to avoid sewage entering the ocean and polluting the marine ecosystem. Sixth, strengthen environmental education. Promote public awareness, strengthen environmental protection and marine ecosystem education and publicity, promote people's understanding of pollution problems, and inspire individual and collective action. These measures require the cooperation and joint efforts of governments, enterprises, social organizations and the public. The international community also needs to strengthen cooperation and information sharing, and jointly promote global actions on marine environmental protection and pollution control. By reducing seawater pollution, we can significantly reduce the impact on coral reef ecosystems, protect and promote the ecological recovery and sustainable development of coral reefs.

(2) Establishing protected areas. Establishing protected areas is one of the important measures to protect coral reefs around the world. By setting up reserves, interference from human activities can be limited, the ecosystem of coral reefs can be protected, and their recovery and sustainable development can be promoted. The following are some specific roles and measures for setting up reserves. First, limiting fishing and destructive behaviors. Reserves can limit or completely prohibit fishing and other activities that may cause damage to coral reefs within their boundaries. This helps to protect rare and vulnerable species to fishing pressure, and reduce the destructive impact of fishing on coral reef ecosystems (Hopf et al., 2019). Second, regulating tourism activities. Reserves can limit or regulate tourism activities, such as controlling the number of tourists and limiting the frequency of diving sites. This helps to reduce the negative impacts of excessive tourism, such as coral destruction, pollution and garbage problems. Third, promoting scientific research and monitoring. Setting up reserves can provide a relatively less disturbed environment, providing valuable opportunities for scientists and researchers to study coral reef ecosystems. Through specialized monitoring and research, the status, ecological processes and threats of coral reefs can be better understood, providing a scientific basis for the formulation and adjustment of conservation measures. Fourth, education and awareness raising. Protected areas provide the public with educational and experiential opportunities to increase awareness of the importance and vulnerability of coral reefs. Educational activities and communication can raise people's awareness of the importance of protecting coral reefs and inspire individual and collective conservation actions. The establishment of protected areas requires the cooperation and support of governments, scientific institutions, non-governmental organizations and the public. The establishment of protected areas must rely on scientific research, policy formulation and management measures, as well as public participation and support. By establishing protected areas, we can ensure the protection and restoration of coral reefs' ecological functions, and contribute to the sustainable development of coral reefs around the world.

(3) Managing fisheries properly. Reasonable management of fisheries is one of the important measures to protect coral reefs around the world. The following are some methods and measures

that can help protect coral reefs from overfishing and destructive fishing activities. First, fisheries management and monitoring. Establish fisheries management institutions and measures, formulate and implement regulations on fisheries fishing quotas, seasonal fishing bans, and prohibitions on the use of destructive fishing tools to ensure the sustainable use of fisheries resources (Seraphim et al., 2020). At the same time, strengthen the monitoring and enforcement of fisheries activities to combat illegal fishing and fisheries violations. Second, develop sustainable fisheries practices. Promote fishermen to adopt sustainable fisheries practices, such as selecting appropriate fishing gear, avoiding overfishing and non-compliant fishing, and reducing the impact of fisheries on marine ecosystems. In addition, promote low-damage fishing technologies to reduce the direct damage of fisheries to coral reefs. Third, set up fisheries reserves. Set up reserves in key fisheries resource areas to restrict or prohibit fishing activities, providing shelter and opportunities for recovery for important fisheries species and coral reefs. This helps maintain the health of fisheries resources and provide fishermen with sustainable fisheries. Fourth, promote cooperation and multi-party participation. Enhance cooperation and dialogue among fishers, governments, scientific institutions and other stakeholders to jointly develop and implement fisheries management measures to ensure a balance between fisheries development and ecological protection. The protection of coral reefs around the world requires sustainable and eco-friendly fisheries management. By properly managing fisheries, we can ensure the health and recovery of coral reefs and related ecosystems, while maintaining the sustainable use of fisheries resources and the livelihoods of fishers.

The relationship between three modes of coral reefs protection is shown in Figure 1.

2.1.2 Hypothesis

Hypothesis 1: Sea pollution in developing countries is less.

There may be several reasons for the smaller amount of marine pollution in developing countries. First, relatively low industrial development. Developing countries may have a relatively low level of industrialization and emit less pollutants into the sea from industrial activities. This is mainly due to the lower level of economic development and industrialization, and therefore the relatively smaller negative impact of industrial pollution on the marine environment. Second, lower levels of agriculture and urbanization. Agricultural and urbanization activities may generate a smaller pollution load on the sea. Pollution from pesticides and fertilizers produced by agriculture, as well as inadequate urban drainage systems, may cause marine pollution. However, in some developing countries, these pollution loads may be smaller due to the relatively low levels of agriculture and urbanization. Third, relatively low population density. Relatively low population density may also lead to smaller amounts of marine pollution. In developing countries, population density is usually low, thereby reducing the input of pollutants related to human activities. The lower the population density, the less waste water and waste are produced, thereby reducing the pollution of the sea. However, marine pollution is affected by a variety of factors, including industrial development, urbanization levels, agricultural practices, enforcement of environmental laws and regulations, and so on (Alpizar et al., 2020). Therefore, detailed empirical studies and data analysis are still needed for specific developing countries and regions to accurately assess their marine pollution status. At the same time, compared with developed countries, developing countries still need to continue to strengthen environmental protection and sustainable development practices to protect the marine ecological environment.

Hypothesis 2: Developed country 1 and developing country 2 are geographically close to each other.

In reality, developed and developing countries are not always geographically close together. It is just that some developed and developing countries are geographically close. Regardless of the economic level of each country, their position on the world map is determined by geographical factors, and this position is relatively fixed and will not change because of changes in the economic situation of the country. The geographical proximity of developed and developing countries makes sense for cooperation in protecting coral reefs, especially when these countries have common or adjacent seas. Here are some of the potential advantages of geographic proximity to coral reef conservation cooperation. First, enhance regional cooperation. Geographically close

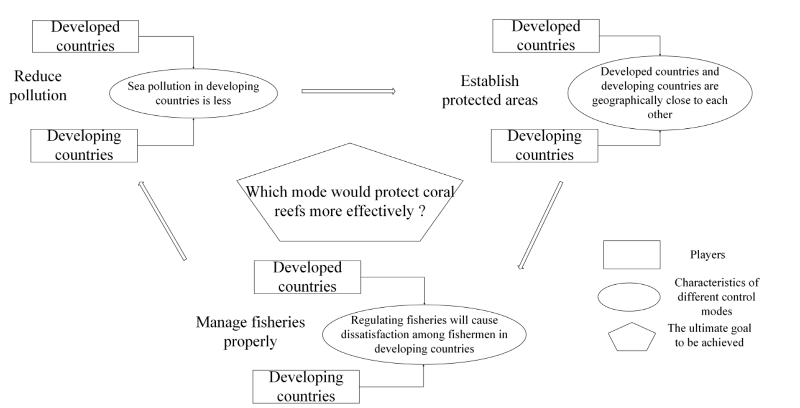

FIGURE 1
Relationship between three modes of coral reefs protection.

countries often share Marine ecosystems and similar environmental challenges, prompting them to engage in regional cooperation to solve problems together, such as protecting coral reefs. Such cooperation could include common research projects, resource sharing, and consistent conservation policies. Second, unified management plan. Coral reef ecosystems often cross national boundaries, and cooperation among neighbouring countries to develop and implement transboundary marine protected areas or harmonized management plans would benefit the protection of these fragile ecosystems because of the coherence of the ecosystems. Third, experience and resource sharing. Developed countries often have more scientific and financial resources and can share advanced conservation technology and management experience with developing countries to help improve the overall efficiency and effectiveness of coral reef protection (Costanza, 2000). For these reasons, geographical proximity provides an incentive for developed and developing countries to work together to protect coral reefs. However, this is not a necessary condition for cooperation - even far away, countries can cooperate on coral reef conservation through multilateral agreements, international organizations, and global initiatives.

Hypothesis 3: Regulating fisheries will cause dissatisfaction among fishermen in developing countries.

Managing fisheries may cause dissatisfaction among fishermen in developing countries for the following reasons. First, economic impact. Some fisheries management measures, such as limiting fishing seasons, regions or numbers, may lead to a decrease in fishermen's catch, thus having a negative impact on their income. This economic uncertainty may cause dissatisfaction among fishermen, especially for fishermen in developing countries who rely on fisheries for their livelihood, which may cause pressure on their livelihood. Second, competition and reduction of resources. The limited nature of fisheries resources may lead to competition and reduction of resources, and cause competition and conflict among fishermen. Fishermen may doubt the management measures and believe that the reduction of resources is due to their improper management, which may lead to their dissatisfaction with the management agencies. Third, unfair distribution. Some fisheries management measures may cause unfair problems in resource distribution. For example, if the allocation of resource quotas is unfair or opaque, some fishermen cannot get a fair share, which may cause dissatisfaction and dissatisfaction. Fourth, lack of participation and communication. Fishermen may feel inadequate participation in the management process and communication in decision-making, lacking sufficient consideration of their rights and interests. This sense of lack of fishermen's participation may lead to their dissatisfaction with management measures and resistance to their implementation. Managing fisheries requires balancing the protection of marine ecosystems with the livelihood needs of fishers. To address these issues, the following measures should be taken. First, fishers' participation and cooperation. Ensure that fishers have opportunities to participate in the decision-making process of fisheries management, and encourage fishers to cooperate with management agencies to negotiate solutions to issues of common concern. Second, equitable distribution and protection of fishers' rights and interests. Ensure that fisheries resources are fairly distributed to meet the needs of different fishers, and ensure that the rights and interests of fishers are protected in the management process. Third, provide alternative income sources and training opportunities. Provide alternative income sources and training opportunities for fishers affected by management measures to help them adapt to changes in fisheries management. Fourth, strengthen information transmission and communication. Strengthen information transmission and communication with fishers to ensure that they understand the purpose, impact and implementation details of management measures, and provide fishers' training and technical support. Through more balanced and inclusive fisheries management, fishers' dissatisfaction can be reduced and sustainable fisheries can be achieved.

2.1.3 Variable definition

When managing coral reefs through modeling, there are a variety of cost, benefit, and reputational types of factors that need to be considered. The following are some of the key factors that should be considered when selecting variables for modeling. First, the cost-type factors, which mainly include the cost of protecting coral reefs and the additional cost of reducing pollution. Second, the benefit-type factors. For example, benefits gained from protecting coral reefs; benefits from changes in the marine environment; reductions in income from managing fisheries; and carbon credits per unit of coral reef management. Third, reputational factors. These include reputation for environmental improvement; reputation for managing reefs; and public dissatisfaction with regulating fisheries.

When constructing the differential game model in this article, many parameters and variables are designed. These parameters and variables are defined as shown in Table 1.

2.2 Differential game of three protection modes

Differential game is a branch of game theory. It is also known as dynamic game or evolutionary game. It changes with time. Different from static game, differential game focuses on the change of players' strategies and behaviors in the game, and analyzes them in continuous time periods. In differential game, players will adjust their strategies according to a certain equation or system. This equation or system is usually established based on the dynamic laws of interaction between players. By studying the optimal strategies and behaviors of players, the evolutionary laws and stable results of the game can be obtained at continuous equilibrium points in time. Differential game has a wide range of applications, including economics, ecology, social sciences and so on. Through the analysis of differential game, it can help us understand and predict the dynamic behavior and evolution process in complex systems (Bai and Ma, 2023).

In the study of coral reef protection in developed and developing countries, it is critical to consider cost, benefit, and state variables when constructing differential game models because these elements have a direct impact on understanding and predicting the dynamics of conservation behavior. The following

TABLE 1 The main definition of variables and parameters in this article.

variables and parameters	specific meaning
$Y=\{R,S,M\}$	three modes of coral reef protection (reduce pollution, establish protected areas, manage fisheries properly)
Independent variable	
$F_{Y1}(t)$	the amount of coral reef treatment in developed countries under the coral reef protection mode Y
$F_{Y2}(t)$	the amount of coral reef treatment in developing countries under the coral reef protection mode Y
$x_{Y1}(t)$	the developed countries' reputation for protecting coral reef under the control mode Y
$x_{Y2}(t)$	the developing countries' reputation for protecting coral reef under the control mode Y
Parameter	
ρ	the discount rate that occurs over time, $0\le\rho\le1$
δ	decay of reputation, $\delta>0$
a_1, a_2	the benefits of developed countries or developing countries from the protection of coral reef at a unit level, a_1, $a_2>0$
c_1,c_2	the cost of a unit of coral reef protection by the developed countries or developing countries. c_1, $c_2>0$
l	the positive impact of reputation, $l>0$
a_C	carbon credits for a unit of coral reef managed, $a_C>0$
f_E	the fringe reputation gained by a better environment, $f_E>0$
f_1,f_2	reputation for a developed or developing country that manages a unit of coral reef, f_1,$f_2>0$
a_E	unit benefits from marine environmental change, $a_E>0$
c_E	the additional cost of reducing pollution, $c_E>0$
f_M	public discontent as a result of developing countries regulating fisheries, $f_M>0$
a_M	reduction in revenue from the management of a unit of fisheries, $a_M>0$
function	
$J_{Y1}(t)$	the social welfare function of developed countries under the coral reef protection mode Y
$J_{Y2}(t)$	the social welfare function of developing countries under the coral reef protection mode Y
$V_{Y1}(t)$	the social benefits of developed countries under the coral reef protection mode Y
$V_{Y2}(t)$	the social benefits of developing countries under the coral reef protection mode Y

are a few reasons why these elements are critical. First, the trade-off between costs and benefits. Coral reef protection activities typically involve costs, whether they are direct economic costs or social and environmental costs (e.g., lower incomes due to restrictions on economic activity). Conversely, protecting coral reefs also brings benefits such as ecological services and economic benefits. In differential game models, specifying costs and benefits helps to analyze how different actors make the best strategic choices between maximizing benefits and minimizing costs. Second, predicting future states. Efforts to protect coral reefs affect their future health or coverage. The dynamics of state variables (e.g., the coral reef health index) is a central part of the model because it directly affects the generation of long-term benefits and the reduction of future costs. Predictions of future state help shape targeted conservation strategies and measure the long-term impacts of different behaviors. Third, game dynamics. Protecting coral reefs is a dynamic process involving multiple parties, and the behavior of different countries affects each other's decisions and the ultimate effectiveness of protection. Differential game models can help simulate such game dynamics by considering costs and benefits, and examine how cooperation or other mechanisms can improve the overall effectiveness of coral reef protection. Fourth, assessing policy interventions. By modeling different policy interventions and their long-term effects, policymakers can better understand the resource inputs required and the benefits likely to be derived from protecting coral reefs, as well as how these policies may affect the current and future state of coral reefs. In short, the consideration of costs, benefits, and state variables is the basis for creating a realistic and useful differential game model, and they are key elements in predicting and improving coral reef conservation measures and their long-term sustainability (Wu and Zhang, 2022).

If developed and developing countries protect coral reefs by reducing pollution mode, the social welfare functions of developed and developing countries can be expressed as Equation 1 and Equation 2:

$$J_{R1}=\int_0^{\infty}\left[(a_1+a_C+a_E)F_{R1}(t)-\frac{c_1+c_E}{2}F_{R1}^2(t)+lx_{R1}(t)\right]e^{-\rho t}dt \tag{1}$$

$$J_{R2}=\int_0^{\infty}\left[(a_C+a_E)F_{R2}(t)-\frac{c_2}{2}F_{R2}^2(t)+lx_{R2}(t)\right]e^{-\rho t}dt \tag{2}$$

In the above formula, $(a_1+a_C+a_E)F_{R1}(t)$ represents the benefits that developed countries receive from protecting coral reefs. $a_CF_{R1}(t)$ represents the carbon emission rights that developed countries receive from protecting coral reefs by reducing pollution patterns. $a_EF_{R1}(t)$ represents the benefits that developed countries receive from a better marine environment. $\frac{c_1+c_E}{2}F_{R1}^2(t)$ represents the costs that developed countries pay to protect coral reefs. $\frac{c_E}{2}F_{R1}^2(t)$ represents the additional costs that developed countries pay to reduce pollution. $lx_{R1}(t)$ represents the positive impact of reputation on the social benefits of developed countries. $(a_C+a_E)F_{R2}(t)$ represents the benefits that developing countries receive from protecting coral reefs. $a_CF_{R2}(t)$ represents the carbon emission rights that developing countries receive from protecting coral reefs by reducing pollution patterns. $a_EF_{R2}(t)$ represents the benefits that developing countries receive from a better marine environment. $\frac{c_2}{2}F_{R2}^2(t)$ represents the costs that developing countries pay to protect coral reefs. $lx_{R2}(t)$ represents the positive impact of reputation on the social benefits of developing countries.

It is worth noting that under the pollution reduction model, the expression of the social welfare function is different in developed and developing countries. It is mainly caused by the following reasons. Developed countries have more developed industries and higher pollution levels than developing countries. Reducing pollution would allow developed countries to increase the benefits of cleaning up coral reefs, but it would also increase the costs.

The change in the reputation of developed countries and developing countries under the reducing pollution mode can be expressed as Equation 3 and Equation 4:

$$\dot{x}_{R1}(t) = (f_1 + f_E)F_{R1}(t) - \delta x_{R1}(t) \tag{3}$$

$$\dot{x}_{R2}(t) = (f_2 + f_E)F_{R2}(t) - \delta x_{R2}(t) \tag{4}$$

In the above formula, $f_1 F_{R1}(t)$ means the reputation of developed countries for protecting coral reefs. $f_E F_{R1}(t)$ means the reputation of developed countries for being better off. $\delta x_{R1}(t)$ means the reputation of developed countries for being worse off. $f_2 F_{R2}(t)$ means the reputation of developing countries for protecting coral reefs. $f_E F_{R2}(t)$ means the reputation of developing countries for being better off. $\delta x_{R2}(t)$ means the reputation of developing countries for being worse off.

If developed and developing countries protect coral reefs by establishing protected areas modes, the social welfare functions of developed and developing countries can be expressed as Equation 5 and Equation 6:

$$J_{S1} = \int_0^{\infty} \left[(a_1 + a_C)F_{S1}(t) - \frac{c_1}{2}F_{S1}^2(t) + l x_{S1}(t)\right] e^{-\rho t} dt \tag{5}$$

$$J_{S2} = \int_0^{\infty} \left[(a_2 + a_C)F_{S2}(t) - \frac{c_2}{2}F_{S2}^2(t) + l x_{S2}(t)\right] e^{-\rho t} dt \tag{6}$$

In the above formula, $(a_1 + a_C)F_{S1}(t)$ represents the benefits that developed countries gain from protecting coral reefs. $a_C F_{S1}(t)$ represents the carbon emission rights that developed countries gain by setting up a protected area mode to protect coral reefs. $\frac{c_1}{2}F_{S1}^2(t)$ represents the costs that developed countries pay for protecting coral reefs. $l x_{S1}(t)$ represents the positive impact of reputation on the social benefits of developed countries. $a_C F_{S2}(t)$ represents the benefits that developing countries gain from protecting coral reefs. $\frac{c_2}{2}F_{S2}^2(t)$ represents the carbon emission rights that developing countries gain by setting up a protected area mode to protect coral reefs. $\frac{c_2}{2}F_{S2}^2(t)$ represents the costs that developing countries pay for protecting coral reefs. $l x_{S2}(t)$ represents the positive impact of reputation on the social benefits of developing countries.

The change in the reputation of developed countries and developing countries under the establishing protected areas mode can be expressed as Equation 7 and Equation 8:

$$\dot{x}_{S1}(t) = f_1 F_{S1}(t) - \delta x_{S1}(t) \tag{7}$$

$$\dot{x}_{S2}(t) = f_2 F_{S2}(t) - \delta x_{S2}(t) \tag{8}$$

In the above formula, $f_1 F_{S1}(t)$ means the reputation of developed countries for protecting coral reefs. $\delta x_{S1}(t)$ means the decline of the reputation of developed countries. $f_2 F_{S2}(t)$ means the reputation of developing countries for protecting coral reefs. $\delta x_{S2}(t)$ means the decline of the reputation of developing countries.

If developed and developing countries protect coral reefs by managing fisheries properly mode, the social welfare functions of developed and developing countries can be expressed as Equation 9 and Equation 10:

$$J_{M1} = \int_0^{\infty} \left[(a_1 + a_C - a_M)F_{M1}(t) - \frac{c_1}{2}F_{M1}^2(t) + l x_{M1}(t)\right] e^{-\rho t} dt \tag{9}$$

$$J_{M2} = \int_0^{\infty} \left[(a_2 + a_C - a_M)F_{M2}(t) - \frac{c_2}{2}F_{M2}^2(t) + l x_{M2}(t)\right] e^{-\rho t} dt \tag{10}$$

In the above formula, $(a_1 + a_C - a_M)F_{M1}(t)$ represents the benefits that developed countries gain from protecting coral reefs. $a_C F_{M1}(t)$ represents the carbon emission rights that developed countries gain from protecting coral reefs through reasonable management of fishery. $a_M F_{M1}(t)$ represents the losses that fishermen in developed countries suffer from reasonable management of fishery. $\frac{c_1}{2}F_{M1}^2(t)$ represents the costs that developed countries pay for protecting coral reefs. $l x_{M1}(t)$ represents the positive impact of reputation on social benefits of developed countries. $(a_2 + a_C - a_M)F_{M2}(t)$ represents the benefits that developing countries gain from protecting coral reefs. $a_C F_{M2}(t)$ represents the carbon emission rights that developing countries gain from protecting coral reefs through reasonable management of fishery. $a_M F_{M2}(t)$ represents the losses that fishermen in developing countries suffer from reasonable management of fishery. $\frac{c_2}{2}F_{M2}^2(t)$ represents the costs that developing countries pay for protecting coral reefs. $\frac{c_2}{2}F_{M2}^2(t)$ represents the positive impact of reputation on social benefits of developing countries.

The change in the reputation of developed countries and developing countries under the managing fisheries properly mode can be expressed as as Equation 11 and Equation 12:

$$\dot{x}_{M1}(t) = f_1 F_{M1}(t) - \delta x_{M1}(t) \tag{11}$$

$$\dot{x}_{M2}(t) = (f_2 - f_M)F_{M2}(t) - \delta x_{M2}(t) \tag{12}$$

In the above formula, $f_1 F_{M1}(t)$ means the reputation of developed countries for protecting coral reefs. $\delta x_{M1}(t)$ means the decline of the reputation of developed countries. $f_2 F_{M2}(t)$ means the reputation of developing countries for protecting coral reefs. $f_M F_{M2}(t)$ means the dissatisfaction of fishermen caused by the management of fisheries. $\delta x_{M2}(t)$ means the decline of the reputation of developing countries.

3 Results

In the differential game, the protection degree of developed and developing countries to coral reefs is not only affected by control variables and parameters, but also changes with time. In order to better calculate the control quantity and social benefits, the HJB formula is adopted. The HJB formula is a partial differential equation, which is the core of optimal control.

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3.1 HJB formula

Under the mode of reducing pollution, the HJB equation of the social welfare function of the developed and developing countries as Equation 13 and Equation 14:

$$\rho V_{R1} = \max_{F_{R1}(t)} \left\{ \begin{bmatrix} (a_1 + a_C + a_E)F_{R1}(t) - \dfrac{c_1 + c_E}{2} F_{R1}^2(t) + \\ lx_{R1}(t)] + \dfrac{\partial V_{R1}}{\partial x_{R1}} [(f_1 + f_E)F_{R1}(t) - \delta x_{R1}(t) \end{bmatrix} \right\} \tag{13}$$

$$\rho V_{R2} = \max_{F_{R2}(t)} \left\{ \begin{bmatrix} (a_C + a_E)F_{R2}(t) - \dfrac{c_2}{2} F_{R2}^2(t) \\ + lx_{R2}(t)] + \dfrac{\partial V_{R2}}{\partial x_{R2}} [(f_2 + f_E)F_{R2}(t) - \delta x_{R2}(t) \end{bmatrix} \right\} \tag{14}$$

Under the mode of establishing protected areas, the HJB equation of the social welfare function of the developed and developing countries as Equation 15 and Equation 16:

$$\rho V_{S1} = \max_{F_{S1}(t)} \left\{ \begin{bmatrix} (a_1 + a_C)F_{S1}(t) - \dfrac{c_1}{2} F_{S1}^2(t) \\ + lx_{S1}(t)] + \dfrac{\partial V_{S1}}{\partial x_{S1}} [f_1 F_{S1}(t) - \delta x_{S1}(t) \end{bmatrix} \right\} \tag{15}$$

$$\rho V_{S2} = \max_{F_{S2}(t)} \left\{ \begin{bmatrix} (a_2 + a_C)F_{S2}(t) - \dfrac{c_2}{2} F_{S2}^2(t) \\ + lx_{S2}(t)] + \dfrac{\partial V_{S2}}{\partial x_{S2}} [f_2 F_{S2}(t) - \delta x_{S2}(t) \end{bmatrix} \right\} \tag{16}$$

Under the mode of managing fisheries properly, the HJB equation of the social welfare function of the developed and developing countries as equation 17 and Equation 18:

$$\rho V_{M1} = \max_{F_{M1}(t)} \left\{ \begin{bmatrix} (a_1 + a_C - a_M)F_{M1}(t) - \dfrac{c_1}{2} F_{M1}^2(t) \\ + lx_{M1}(t)] + \dfrac{\partial V_{M1}}{\partial x_{M1}} [f_1 F_{M1}(t) - \delta x_{M1}(t) \end{bmatrix} \right\} \tag{17}$$

$$\rho V_{M2} = \max_{F_{M2}(t)} \left\{ \begin{bmatrix} (a_2 + a_C - a_M)F_{M2}(t) - \dfrac{c_2}{2} F_{M2}^2(t) + lx_{M2}(t)] \\ + \dfrac{\partial V_{M2}}{\partial x_{M2}} [(f_2 - f_M)F_{M2}(t) - \delta x_{M2}(t) \end{bmatrix} \right\} \tag{18}$$

3.2 Result of equilibrium

Proposition 1: Under the mode of reducing pollution, the amount of coral reef treatment and social benefits of developed and developing countries are respectively (the specific solving procedure is shown in Appendix 1) Equations 19–22:

$$F_{R1}^*(t) = \frac{a_1 + a_C + a_E + \frac{l}{\rho+\delta}(f_1 + f_E)}{c_1 + c_E} \tag{19}$$

$$F_{R2}^*(t) = \frac{a_C + a_E + \frac{l}{\rho+\delta}(f_2 + f_E)}{c_2} \tag{20}$$

$$\begin{aligned} V_{R1}^* = {} & \frac{1}{\rho}(a_1 + a_C + a_E)\frac{a_1+a_C+a_E+\frac{l}{\rho+\delta}(f_1+f_E)}{c_1+c_E} - \frac{c_1+c_E}{2}\frac{1}{\rho}\left[\frac{a_1+a_C+a_E+\frac{l}{\rho+\delta}(f_1+f_E)}{c_1+c_E}\right]^2 \\ & + \frac{l}{\rho+\delta}\frac{1}{\rho}(f_1+f_E)\frac{a_1+a_C+a_E+\frac{l}{\rho+\delta}(f_1+f_E)}{c_1+c_E} + \frac{l}{\rho+\delta}x_{R1} \end{aligned} \tag{21}$$

$$\begin{aligned} V_{R2}^* = {} & \frac{l}{\rho+\delta}x_{R2} + \frac{1}{\rho}(a_C + a_E)\frac{a_C+a_E+\frac{l}{\rho+\delta}(f_2+f_E)}{c_2} - \frac{c_2}{2}\frac{1}{\rho}\left[\frac{a_C+a_E+\frac{l}{\rho+\delta}(f_2+f_E)}{c_2}\right]^2 \\ & + \frac{1}{\rho}\frac{l}{\rho+\delta}(f_2+f_E)\frac{a_C+a_E+\frac{l}{\rho+\delta}(f_2+f_E)}{c_2} \end{aligned} \tag{22}$$

Conclusion 1: The greater the unit benefits from marine environmental change, the greater the degree of coral reef governance in both developed and developing countries.

Proposition 2: Under the mode of establishing protected areas, the amount of coral reef treatment and social benefits of developed and developing countries are respectively (the specific solving procedure is shown in Appendix 2) Equations 23–26:

$$F_{S1}^*(t) = \frac{a_1 + a_C + \frac{l}{\rho+\delta}f_1}{c_1} \tag{23}$$

$$F_{S2}^*(t) = \frac{a_2 + a_C + \frac{l}{\rho+\delta}f_2}{c_2} \tag{24}$$

$$\begin{aligned} V_{S1}^* = {} & \frac{l}{\rho+\delta}x_{S1} + \frac{1}{\rho}(a_1 + a_C)\frac{a_1+a_C+\frac{l}{\rho+\delta}f_1}{c_1} - \frac{c_1}{2}\frac{1}{\rho}\left(\frac{a_1+a_C+\frac{l}{\rho+\delta}f_1}{c_1}\right)^2 \\ & + \frac{l}{\rho+\delta}\frac{1}{\rho}f_1\frac{a_1+a_C+\frac{l}{\rho+\delta}f_1}{c_1} \end{aligned} \tag{25}$$

$$V_{S2}^{\star} = \frac{l}{\rho+\delta} x_{S2} + \frac{1}{\rho}(a_2 + a_C)\frac{a_2+a_C+\frac{l}{\rho+\delta}f_2}{c_2} - \frac{c_2}{2}\frac{1}{\rho}\left(\frac{a_2+a_C+\frac{l}{\rho+\delta}f_2}{c_2}\right)^2 + \frac{l}{\rho+\delta}\frac{1}{\rho}f_2\frac{a_2+a_C+\frac{l}{\rho+\delta}f_2}{c_2} \tag{26}$$

Conclusion 2: The more carbon emission rights a coral reef managed unit gets, the greater the degree of reef management by developed and developing countries.

Proposition 3: Under the mode of managing fisheries properly, the amount of coral reef treatment and social benefits of developed and developing countries are respectively (the specific solving procedure is shown in Appendix 3) Equations 27–30:

$$F_{M1}^{\star}(t) = \frac{a_1 + a_C - a_M + \frac{l}{\rho+\delta}f_1}{c_1} \tag{27}$$

$$F_{M2}^{\star}(t) = \frac{a_2 + a_C - a_M + \frac{l}{\rho+\delta}(f_2 - f_M)}{c_2} \tag{28}$$

$$V_{M1}^{\star} = \frac{l}{\rho+\delta}x_{M1} + \frac{1}{\rho}(a_1 + a_C - a_M)\frac{a_1+a_C-a_M+\frac{l}{\rho+\delta}f_1}{c_1} - \frac{c_1}{2}\frac{1}{\rho}\left(\frac{a_1+a_C-a_M+\frac{l}{\rho+\delta}f_1}{c_1}\right)^2 + \frac{1}{\rho}\frac{l}{\rho+\delta}f_1\frac{a_1+a_C-a_M+\frac{l}{\rho+\delta}f_1}{c_1} \tag{29}$$

$$V_{M2}^{\star} = \frac{1}{\rho}(a_2 + a_C - a_M)\frac{a_2+a_C-a_M+\frac{l}{\rho+\delta}(f_2-f_M)}{c_2} - \frac{c_2}{2}\frac{1}{\rho}\left[\frac{a_2+a_C-a_M+\frac{l}{\rho+\delta}(f_2-f_M)}{c_2}\right]^2 + \frac{l}{\rho+\delta}\frac{1}{\rho}(f_2 - f_M)\frac{a_2+a_C-a_M+\frac{l}{\rho+\delta}(f_2-f_M)}{c_2} + \frac{l}{\rho+\delta}x_{M2} \tag{30}$$

Conclusion 3: The greater the reduction in revenue per unit of fisheries managed, the less developed and developing countries manage coral reefs.

3.3 Numerical analysis

In order to describe the changes of social utility of developed and developing countries in the process of protecting coral reefs in more detail, this article adopts the numerical analysis method. The following assumptions are made for relevant parameters.

The discount rate ρ that occurs over time is 0.9. Decay δ of reputation is 0.1. The cost c_1, c_2 of a unit of coral reef protection by the developed countries or developing countries is 2. The positive impact l of reputation is 1. The fringe reputation f_E gained by a better environment is 1.5. Reputation f_1,f_2 for a developed or developing country that manages a unit of coral reef is 2. Unit benefits a_E from marine environmental change is 3. The additional cost c_E of reducing pollution is 2. Public discontent f_M as a result of developing countries regulating fisheries is 2.5. Reduction a_M in revenue from the management of a unit of fisheries is 2.

When the carbon credits a_C for a unit of coral reef managed is 2, this article can calculate the social benefits of developed countries as Equations 31–33:

$$V_{R1}^{\star} = 1 + 0.139 \times (a_1 + 8.5)^2 \tag{31}$$

$$V_{S1}^{\star} = 1 + 0.278 \times (a_1 + 4)^2 \tag{32}$$

$$V_{M1}^{\star} = 1 + 0.278 \times (a_1 + 2)^2 \tag{33}$$

The following graph (named Figures 2, 3) can also be produced:

When the carbon credits a_C for a unit of coral reef managed is 5, this article can calculate the social benefits of developed countries as Equations 34–36:

$$V_{R1}^{\star} = 1 + 0.139 \times (a_1 + 11.5)^2 \tag{34}$$

$$V_{S1}^{\star} = 1 + 0.278 \times (a_1 + 7)^2 \tag{35}$$

$$V_{M1}^{\star} = 1 + 0.278 \times (a_1 + 5)^2 \tag{36}$$

The following graph (named Figure 4) can also be produced:

Conclusion 4: When the benefits of coral reef restoration are small, the pollution reduction mode can provide the most benefits for developed countries. As the benefits of coral reef restoration increase, the nature reserve mode can provide the most benefits for developed countries. The greater the carbon emission right obtained from the restoration of a unit number of coral reefs, the more likely developed countries will adopt the nature reserve mode as the benefits of coral reef restoration increase.

When the carbon credits aC for a unit of coral reef managed is 2, this article can calculate the social benefits of developing countries as Equations 37–39:

$$V_{R2}^{\star} = 21.08 \tag{37}$$

$$V_{S2}^{\star} = 1 + 0.278 \times (a_2 + 4)^2 \tag{38}$$

$$V_{M2}^{\star} = 1 + 0.278 \times (a_2 - 0.5)^2 \tag{39}$$

The following graph (named Figure 5) can also be produced:

When the carbon credits a_C for a unit of coral reef managed is 5, this article can calculate the social benefits of developing countries as Equations 40–42:

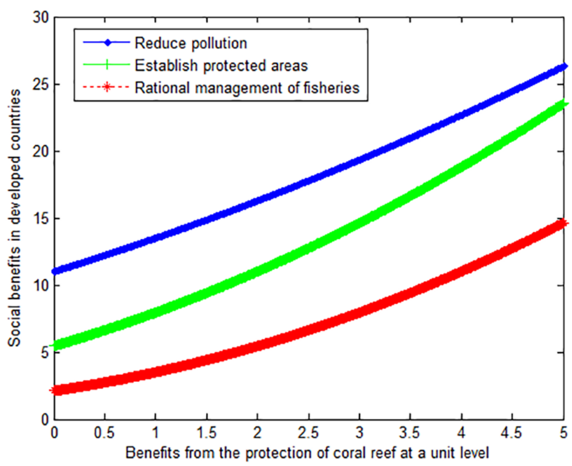

FIGURE 2
Impact of benefits of developed countries on social welfare.

$$V_{R2}^{\star} = 37.77 \tag{40}$$

$$V_{S2}^{\star} = 1 + 0.278 \times (a_2 + 7)^2 \tag{41}$$

$$V_{M2}^{\star} = 1 + 0.278 \times (a_2 + 2.5)^2 \tag{42}$$

The following graph (named Figure 6) can also be produced:

Conclusion 5: When the benefits of reef restoration are small, the pollution reduction mode offers the greatest benefit to developing countries. As the benefits of reef restoration increase, the nature reserve mode offers the greatest benefit to developing countries.

4 Discussion

The impact of marine environmental change on coral reefs includes factors such as temperature increase, ocean acidification, sea level rise, and pollutants. These changes will directly affect the survival and reproductive capacity of coral reefs, and then have a negative impact on the stability and biodiversity of coral reef ecosystems (Smith et al., 2020). The reason for conclusion 1 is mainly that the degree of coral reef governance in developed and developing countries is driven by benefits. Developed countries usually have more advanced science and technology and stronger economic capacity, which can better deal with the threats brought by marine environmental change to coral reefs. In addition, developed countries usually have higher income levels and consumption capacity, which can obtain greater economic benefits from the ecological services provided by coral reefs (such as tourism and fishery resources). Therefore, developed countries are more inclined to strengthen the management and protection of coral reefs. In contrast, developing countries may face the challenges of limited resources and economic development pressures, and they may pay more attention to economic growth and social development. In the case of limited resources, the input and cost required for coral reef governance may be inhibited by other urgent development needs. However, with the improvement of environmental awareness and the promotion of international cooperation, more and more developing countries are realizing the importance of coral reefs and taking measures to strengthen the protection and management of coral reefs. In summary, the impact of changes in the marine environment on coral reefs makes the need for their governance and protection more urgent. There are differences in the degree of governance of coral reefs between developed and developing countries, but with the increase of global environmental awareness and the promotion of international cooperation, the consensus on the protection and sustainable management of coral reefs is growing. Meanwhile conclusion 1 has several implications for global coral reef governance. First, it raises awareness of protection. When changes in the marine environment pose a higher threat to coral reefs, the benefits derived from protecting coral reefs are correspondingly higher, which may increase public awareness of the importance of coral reef protection, thus obtaining more social support for policymakers and conservation activities. Second, international cooperation is encouraged. Increased unit benefits often require greater cooperation to combat changes in the marine environment. In this case, inter-country cooperation becomes an important factor in enhancing the effectiveness of coral reef governance, which may lead to an increase in international agreements and collaborative projects. Thirdly, there is an adjustment in resource allocation. When the unit benefits of coral reefs increase, developed and developing countries are more likely to reallocate more resources to governance projects, such as scientific research, monitoring and direct environmental interventions, which may lead to a reallocation of resources away from other projects for the protection and restoration of coral reef environments.

Conclusion 1 identifies the impacts of changes in the marine environment on the effectiveness of coral reef units and suggests that such changes may provide incentives for both developed and developing countries to enhance the extent of coral reef governance.

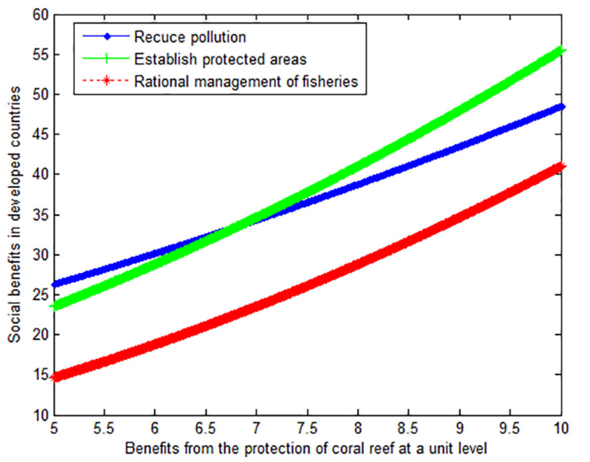

FIGURE 3
Impact of benefits of developed countries on social welfare.

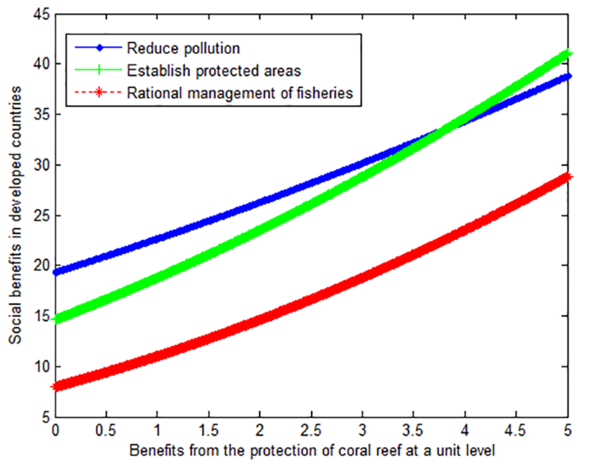

FIGURE 4
Impact of benefits of developed countries on social welfare.

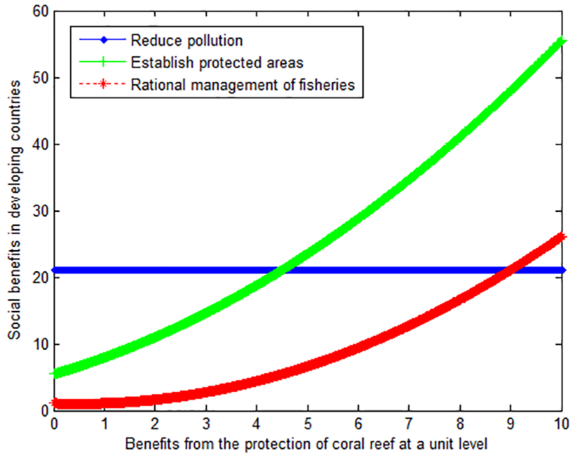

FIGURE 5
Impact of benefits of developing countries on social welfare.

Interpreting this finding in both economic and ecological terms, we can understand its implications for policy decision-making and implementation. On the economic side, policy makers can use this finding to conduct a cost-benefit analysis. The economic case for investing in coral reef protection and restoration is stronger if environmental change increases coral reef unit benefits, for example, through higher revenues from coral reef-related tourism, enhanced biodiversity, or more efficient carbon sequestration; understanding that unit benefits increase can help a country determine where to invest its resources and funds. Coral reef projects with higher unit benefits are likely to receive more funding because they offer more attractive economic returns; develop incentives to attract private investment, such as through carbon credits or ecological offsets, and ensure that environmental management is accompanied by a reasonable return on economic activity. On the ecological side, from an ecological point of view, increased unit benefits from environmental change may mean that certain coral reef ecosystems are under increased threat. As a result,

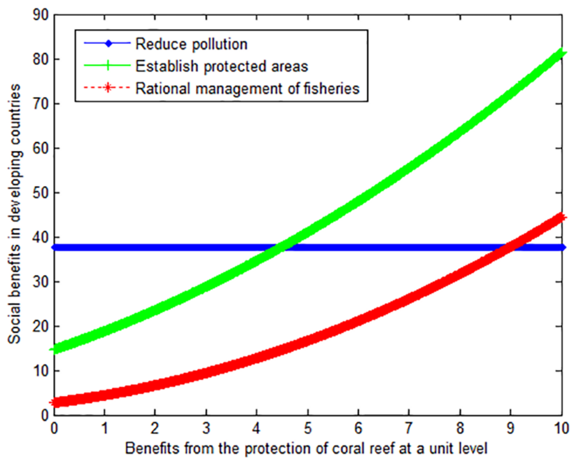

FIGURE 6
Impact of benefits of developing countries on social welfare.

these areas may require more urgent and focused protection and restoration efforts; policy decisions should use this to recognize that management programmes need to be flexible and adaptable to the impacts of environmental change. This may involve regularly monitoring environmental changes and adjusting management plans to maximize the ecological benefits of coral reefs. By incorporating this economic and ecological information into policy decisions, policymakers can more fully consider the costs and benefits of investing in coral reef management while ensuring long-term environmental sustainability. Such policy design can promote the effective protection and management of coral reef ecosystems, laying the foundation for maintaining their ecological service value and supporting economic development.

Granting carbon credits to countries with high levels of reef governance can be seen as an incentive to encourage their active participation in reef protection and governance. In this case, the more carbon credits a country receives for a given unit of reef governance, the better its reef governance performance. Conclusion 2 is mainly due to the following reasons. The degree of reef governance in both developed and developing countries is largely influenced by national environmental policies and international cooperation. Granting carbon credits to countries with high levels of reef governance can encourage these countries to be more active in protecting and managing the reef ecosystem. This incentive can lead to more significant progress in resource allocation, measures taken and reef protection in both developed and developing countries (Armstrong et al., 2019). However, it should be noted that such carbon credit incentives should be seen as an adjunct rather than a main reef governance strategy. The protection and governance of reefs should be centered on the health and sustainability of the ecosystem, rather than solely based on the acquisition of carbon credits. Countries should ensure that the measures they take are comprehensive and effective to ensure the long-term survival and prosperity of coral reef ecosystems in the context of global change. Conclusion 2 demonstrates how revenues received by coral reef management units through carbon trading can serve as an incentive, which in turn may increase financial and technological investment in coral reef management in both developed and developing countries. The following are the possible implications of Conclusion 2 for global coral reef governance, firstly, the provision of financial flows. Carbon emissions trading can provide coral reef management units with new sources of funding for coral reef protection and restoration efforts, which is particularly beneficial to resource-poor developing countries. Second, it enhances management incentives. The ability of coral reefs to earn carbon credits for their carbon sequestration capacity increases the economic incentives to protect and restore coral reefs, which in turn incentivizes countries to invest more in coral reef management. Third, integrating climate change strategies. This finding highlights the relationship between coral reef protection and global climate change mitigation, and coral reef protection, as part of a climate action plan, may be given higher priority in national climate policies. Fourth, it promotes the expansion of carbon markets. The involvement of coral reef management may further expand the carbon market, which is dominated by forest carbon sinks, to include the blue carbon (carbon stored in marine ecosystems)

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market, thereby providing additional funding for environmental protection projects.

Conclusion 2 emphasizes the importance of carbon credits in coral reef management and points to a positive correlation between the degree of management and the amount of carbon credits acquired. This can provide important information for policy decisions on economics and ecology. On the economic side, coral reefs can act as a carbon sink, providing services that reduce the amount of carbon in the atmosphere. If coral reef management units are able to acquire more carbon credits, this will provide economic incentives for both developed and developing countries to invest in coral reef protection and restoration; trading of carbon credits could be a source of funding for coral reef protection; national and regional policies could facilitate coral reef conservation projects to increase their revenues through carbon credits, translating environmental benefits into economic benefits; measuring the direct costs versus the potential benefits to be gained through the carbon credits market can help policymakers assess the economic feasibility of various conservation measures. Ecologically, the function of coral reefs as carbon sinks emphasizes their role in global mitigation strategies. This finding supports the development of policies that help to increase the capacity of carbon sinks and improve the health of coral reefs; the biodiversity of coral reefs also benefits carbon storage. Management strategies should therefore consider both the conservation of biodiversity and the enhancement of the carbon sink services provided by ecosystems; enhanced coral reef management can help to increase ecosystem resilience to climate change-induced disasters such as sea level rise and ocean acidification, further protecting carbon sinks. By integrating these economic and ecological messages into policy design, policymakers can better target coral reef protection projects and finance them through carbon trading. This approach can increase the attractiveness of coral reef protection and attract more public and private sector investment, while ensuring that the sustainable management of coral reefs is harmonized with greenhouse gas emission reduction targets.

According to Conclusion 3, the greater the benefits of managing a reduction in fisheries per unit, the lower the degree of reef governance in both developed and developing countries. This is because fisheries are one of the important economic sectors in many countries and regions, especially in developing countries. The use of fisheries resources is closely related to coral reefs, as coral reefs are habitats and breeding sites for many important marine species (Zhao et al., 2019). Developed countries, which generally have more advanced fisheries management systems and stronger economic capacity, are in a better position to manage fisheries resources. These countries can invest more resources and technology to ensure sustainable fisheries practices and protect coral reefs as the basis of fisheries resources. Developing countries, however, may face some challenges in fisheries management. Factors such as limited resources, inadequate regulation, poverty and development needs may limit the ability of developing countries to manage fisheries resources effectively. When decisions must be made between economic development and fisheries resource protection, some developing countries may face greater pressure, resulting in lower levels of reef governance. It is important to note, however, that fisheries management and reef governance are not necessarily mutually exclusive. Sustainable fisheries management practices can promote both economic development and reef protection, ensuring the health and biodiversity of reefs by reducing overfishing and ecological destruction. Efforts such as international cooperation, scientific research, and environmental education and awareness-raising can also contribute to better protection and governance of reefs. Therefore, developing countries can improve the governance of reefs by adopting appropriate management practices, strengthening regulation, and promoting sustainable fisheries practices. At the same time, conclusion 3 may have the following implications for global coral reef governance. First, if there is a dependence on fisheries revenues, then funding for coral reef management may be reduced, leading to inadequate implementation of protection and restoration measures. Second, small or insufficient fisheries revenues may reduce the interest and commitment of governments and local communities to coral reef governance, as they may need to divert limited resources and attention to more directly profitable areas. Third, as fisheries revenues decline, fisheries-dependent communities may have to fish more intensively to sustain their livelihoods, which may lead to overfishing and further damage to coral reef ecosystems. Fourthly, the continued degradation of coral reefs may affect fish habitats and breeding grounds, reducing fisheries yields, which in turn leads to less fisheries revenue and a further reduction in coral reef management, creating a negative cycle.

Conclusion 3 points to a potential negative correlation between fisheries revenues and coral reef management, in that as revenues per unit of fisheries decrease, this may lead to a reduction in the intensity of management of coral reefs in both developed and developing countries. This finding has several implications for real-world policy making. On the economic side, if coral reef management is dependent on fisheries revenues, decreasing revenues may lead to fiscal constraints that affect the resources available for coral reef protection and management. Policy makers may need to seek alternative fiscal instruments or financing mechanisms to support coral reef management efforts; policy makers may need to consider mitigating declining revenues through improved fisheries management or encouraging diversification of economic activities to increase fishermen's sources of income and reduce dependence on a single fishery; and policy development will need to consider the trade-offs between longterm sustainability and short-term revenues to ensure that fisheries practices do not jeopardize the the health of coral reefs while securing the livelihoods of fishers. On the ecological side, educating and raising community awareness of conservation can make local people aware of the long-term relationship between coral reef health and fisheries income and promote sustainable fishing practices; when coral reefs are neglected, the ecosystem services associated with them (e.g., fisheries, tourism, coastal protection, etc.) may also be compromised. Policymakers can strengthen support for coral reef management by assessing the full value of coral reef ecosystem services; overfishing affects coral reef health and further reduces fisheries productivity. Thus, protecting coral reef ecology can be a way to sustain and enhance fishery resources. This economic and ecological information provides an important basis for policy decision-making and implementation. Policymakers need to develop and implement sound management strategies that not only take into account economic pressures and livelihoods, but also protect and enhance the long-term health and productivity of coral reef ecosystems and ensure that fisheries and other reef-related economic activities are sustainable.

When managing coral reefs, developed countries may adopt different strategies to achieve maximum benefits depending on the benefits they can obtain. Conclusion 4 is mainly due to the following reasons. When the benefits of managing coral reefs are small, the pollution reduction mode can achieve maximum benefits for developed countries. This is because when the benefits are small and the costs of managing are high, pollution reduction can achieve economic benefits by reducing their own environmental costs and risks. Developed countries usually have more advanced environmental technologies and policies, as well as more stringent environmental standards, and can therefore protect coral reef ecosystems by reducing pollution while avoiding the additional costs and legal liabilities that may be brought about. As the benefits of managing coral reefs gradually increase, the nature reserve mode can achieve maximum benefits for developed countries (Nolan et al., 2021). When the benefits increase and the costs of managing are relatively low, developed countries may be more inclined to establish nature reserves around coral reefs to ensure the long-term health and biodiversity protection of coral reef ecosystems. Nature reserves provide a protected environment that helps to reduce the direct threats to coral reefs from human activities, and can attract ecotourism and provide other ecological services, thereby generating economic benefits from these activities (Hopf et al., 2019). However, it should be noted that the governance of coral reefs is a complex issue that involves many factors, including ecological, economic and social aspects. Developed countries should take into account the needs of different stakeholders when formulating governance strategies and find a balance point for sustainable development. In addition, developing countries can also achieve the protection of coral reef ecosystems and obtain economic benefits through reasonable governance strategies, such as adopting environmental management measures, encouraging sustainable economic activities and carrying out international cooperation. Therefore, the best governance strategies should be formulated according to specific situations and the needs of specific stakeholders to achieve maximum benefits and sustainable development. The findings in conclusion 4 address the relationship between the economic benefits of coral reef restoration, pollution reduction strategies, and management models such as nature reserves. The implications of these findings for global coral reef governance may include the following. First, adjustments in management strategies. Developed countries may adjust their management strategies according to the economic benefits derived from coral reef restoration. Where restoration benefits are small, they may focus on measures to reduce pollution. As the benefits of restoration increase, there may be a shift towards the establishment of nature reserves. Second, the incentive structure changes. The benefits of carbon credits can be used as an incentive for countries to invest in coral reef protection and restoration. As the economic returns provided by coral reefs through carbon capture increase, countries may be more inclined to adopt the protected area model to maximize their environmental benefits and economic returns. Third, there is a trade-off between economic and environmental benefits. The choice of management model needs to be a trade-off between the existing economic situation and the expected environmental benefits, not only in terms of immediate benefits but also in terms of long-term impacts. Fourth, reflecting the value of ecological services. As countries realize the value of the ecological services (e.g., carbon capture) of coral reef ecosystems, they may be more inclined to invest resources in protecting and restoring these ecosystems.

Conclusion 4 reveals the relationship between coral reef restoration benefits and appropriate management strategies, suggesting that developed countries may choose different reef management options under different reef health states and economic incentives. The following is a guide on how to translate these findings into practical policy decisions and implementation, both economically and ecologically. On the economic side, policymakers need to consider the costs and benefits of different management approaches (e.g., pollution reduction and the establishment of nature reserves); pollution reduction measures may be more cost-effective when the benefits of reef restoration are low because they avoid high future restoration costs; incentives for coral reef protection are provided through market-based mechanisms, such as the provision of carbon credits; and, as the benefits of coral reef restoration increase and as the availability of carbon rights, developed countries are more likely to invest in long-term conservation measures, such as the establishment of nature reserves; policymakers need to assess the resourcing needs of various management options; for example, when coral reef restoration benefits are low, more funding may be needed for pollution prevention and basic environmental management; and as restoration benefits increase, more resources may be needed for the establishment and maintenance of nature reserves for long-term sustainability. sustainability. On the ecological front, policymakers must recognize coral reefs as an important ecosystem that provides a wealth of ecosystem services (e.g., biodiversity conservation, fisheries production, tourism attraction and carbon storage). Where the benefits of reef restoration are high, the value of these services can be maximized through the establishment of nature reserves; as the ecosystem changes and more information on the benefits of reef restoration becomes available, management strategies need to be adapted accordingly. Policy makers need to consider adaptive management to respond to these changes; policy decisions should be based on scientific research and ongoing monitoring of reef health to ensure that management strategies achieve the desired ecological outcomes. In summary, the above findings encourage policy makers to adopt appropriate management measures based on the potential benefits of coral reef restoration and the associated economic incentives. This requires a multifaceted approach that takes into account both conservation needs and economic viability. By quantifying the value of the ecological services of coral reefs, creating effective incentives and realizing adaptive management, healthy coral reef restoration can be promoted and bring economic benefits to developed countries while protecting the global ecosystem.

Finally, explain Conclusion 5. When the benefits of reef management are small, the pollution reduction mode can maximize the benefits for developing countries. For developing countries, economic development and poverty reduction are primary goals, so reducing pollution is an important strategy when managing coral reefs. By reducing pollution, developing countries can reduce the costs of environmental management and restoration and avoid the risk of causing health and ecological damage. This helps maintain the health of coral reef ecosystems, promote the sustainable use of fisheries resources, and provide a sustainable source of livelihoods for local residents. As the benefits of reef management increase, the nature reserve mode can maximize the benefits for developing countries. With the restoration of reef resources and the health of ecosystems, nature reserves can become an important economic and ecological resource for developing countries to achieve sustainable development. By establishing nature reserves, developing countries can attract ecotourism, promote employment and economic development of local communities, and gain economic benefits from ecological services (Nolan et al., 2021). In addition, nature reserves can also provide long-term protection and management mechanisms to ensure the sustainable development of coral reef ecosystems and the protection of biodiversity. It is important to emphasize that developing countries should develop the best governance strategies according to their own practical conditions and needs, taking into account ecological, economic and social factors. The governance of coral reefs needs to balance the needs of different stakeholders and ensure sustainable development and the health of the ecosystem. Therefore, the choice of governance strategies should take into account different scenarios and specific objectives to achieve maximum benefits and sustainable development. Meanwhile, the findings of conclusion 5 may have the following implications for global coral reef governance. First, strategy selection is linked to benefits. Developing countries may choose governance strategies based on the expected benefits of coral reef restoration. When the direct benefits of restoration are low, they may focus more on more cost-efficient measures such as pollution reduction. As the benefits of restoration increase, there may be a shift towards more long-term conservation measures such as nature reserves. Second, the balance between development and conservation. Developing countries face pressures to protect the environment as they seek economic development. The health of coral reefs is related to marine biodiversity, fisheries, tourism, etc., so countries may adopt governance approaches adapted to the benefits of coral reef restoration at different stages. Third, the impact of domestic and foreign funding. Coral reef management in developing countries is often capital-intensive, so international funding and external investment may, to some extent, determine the choice and implementation of management strategies. Fourth, socio-economic considerations. Developing countries face unique socio-economic challenges, and management strategies may take into account how to maximize the socio-economic benefits of coral reefs, such as the livelihoods and incomes of local communities.

Conclusion 5 deals with the relationship between the benefits of coral reef restoration and the choice of conservation strategies in developing countries. Effective policy action can be taken on the basis of this information. On the economic side, for coral reefs with low restoration benefits, measures to reduce pollution may require lower initial investment while providing immediate economic benefits to developing countries by rapidly improving local environmental quality; in the long term, as reef health improves, it may also be possible to shift to longer-term sustained investments such as the construction of natural protected areas; and developing countries may need to consider economic activities other than tourism and fisheries to reduce dependence on damaged coral reefs and provide economic ancillary support for coral reef protection strategies. economic activities other than tourism and fisheries to reduce dependence on damaged reefs and provide economic support to complement coral reef protection strategies; developing country policymakers need to focus on the sustainable development of coral reefs and their associated industries by designing policies that promote a combination of ecological protection and economic growth to ensure that long-term benefits are maximized. On the ecological side, by reducing pollution, further degradation of coral reefs can be halted and the provision of ecosystem services, such as fisheries and shoreline protection, can begin to be restored in the short term, while the establishment of nature reserves is more conducive to the restoration and maintenance of biodiversity in the long term, ultimately leading to greater ecological benefits; developing-country policymakers need to follow through with the implementation of adaptive management measures, and in the continuous monitoring of Policy makers in developing countries need to implement adaptive management measures and dynamically adjust protection measures based on continuous monitoring of environmental changes and coral reef recovery; Encouraging local communities to participate in the protection of coral reefs not only improves the efficiency of the implementation of protection measures, but also helps to enhance the environmental awareness of the local population and the ability of sustainable development; Policies should adopt comprehensive management measures, combining scientific research, technology introduction, regulations and community education to create a comprehensive coral reef protection and restoration program. Considering the above findings together, policy makers in developing countries should take into account the current restoration benefits of coral reefs, as well as the potential long-term environmental and socio-economic benefits that can be realized through different conservation models when setting coral reef management strategies. Policymaking should focus on building a system of conservation strategies that can realize a win-win situation for both ecological restoration and economic development.

The realism and applicability of constructing differential game models to study the protection of coral reefs in developed and developing countries is reflected in the following aspects. First. Differential game modeling provides a framework in which theoretical analyses and practical situations, such as the allocation of resources, costs and benefits required to protect coral reefs, can be integrated. Such a framework helps to realize the link between policy design and practical implementation. Second. In the model, the state variable can represent the reputation gained from protecting coral reefs, which reflects the actual effects of conservation measures. By observing changes in state variables over time, the model can help predict the long-term sustainability of conservation programs. Third. Investments in coral reef protection vary from country to country in terms of advanced technology, capital, and human resources. Differential game modeling can quantify the different costs and potential benefits, providing policy makers with the necessary economic assessment. Fourth. Developed countries may have more resources for conservation, while developing countries face resource constraints. The model can indicate how to effectively allocate these unequal resources and calculate the optimal strategies for various policy measures. Fifth. The differential game model can simulate the dynamic interactions of several parties in the game when protecting coral reefs, and then reveal the patterns of cooperation and competition arising from the interests and resource constraints of each party, thus providing strategic insights for promoting international cooperation. In summary, differential game modeling enhances the understanding of the strategic interactions between developed and developing countries in coral reef conservation, assesses the long-term impacts of different conservation strategies on coral reefs and related economic systems, and provides a practical and forward-looking tool for developing effective conservation policies. However, the applicability of the model also depends on the accuracy and comprehensiveness of the input data, the consistency of the model's simplifying assumptions with real-world scenarios, and the validity of the interpretation of the model's results and the implementation of the scenarios.

5 Conclusion

Under the condition of carbon trading, developed and developing countries participating in the protection of coral reefs can obtain certain carbon emission rights. In order to study the applicable range of various protection modes of coral reefs, this article constructs a differential game model of three modes: reducing pollution, setting up a nature reserve, and reasonably managing fisheries. And the equilibrium results are compared and analyzed. Finally, the research conclusions show that, whether for developed or developing countries, when the benefits of coral reef treatment are small, the mode of reducing pollution can achieve the maximum benefit. With the gradual increase of the benefits of coral reef treatment, the mode of setting up a nature reserve can achieve the maximum benefit. It is worth noting that the greater the carbon emission rights obtained by the number of coral reefs under treatment, and with the gradual increase of the benefits of coral reef treatment, developed countries are more likely to adopt the mode of setting up a nature reserve.

The research in this article can also be extended. For example, the article assumes that developing country seas are less polluted; developed countries and developing countries are geographically closer; and regulating fisheries will cause dissatisfaction among fishermen in developing countries. At the same time, the article does not consider the interaction between developed and developing countries when building the model. In future research, these assumptions and limitations can be removed for further study. Meanwhile, some gaps in the research can also be addressed in future research. First, it is necessary to determine the specific criteria adopted by developed and developing countries in coral reef protection modes under different conditions. Second, the research results of coral reef protection under carbon trading can be translated into practical policy recommendations for reference in areas with severe coral reef destruction. Third, in the process of coral reef protection in different seas, developed and developing countries should determine the order of action for relevant research, rather than taking action simultaneously. Fourth, consider the interaction between developed and developing countries to establish the relevant differential game model.

Data availability statement

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

Author contributions

YB: Conceptualization, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. RH: Data curation, Methodology, Software, Writing – original draft. LW: Data curation, Investigation, Methodology, Software, Writing – original draft. DL: Software, Supervision, Writing – review & editing.

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Conflict of interest

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

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2024.1331045/full#supplementary-material

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