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Restore water resources, diversify vegetation or control invasive species? How to effectively manage wetland based on carbon trading

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Wetland ecosystems have suffered serious damage. To increase the incentive to protect wetlands, the government can allocate certain carbon emission allowances to environmental organizations that protect wetlands. Common wetland governance modes include restoring water quantity, diversifying vegetation and controlling invasive species. In order to derive the applicable range of various wetland governance modes, this article constructs three differential game models and compares and analyzes the equilibrium results obtained by the models. Finally, the research shows that if the additional reputation gained by restoring water quantity per unit is small, the government can achieve the maximum benefit by choosing the restoring water quantity mode. If the additional reputation gained by restoring water quantity per unit is large, the government can achieve the maximum benefit by choosing the diversifying vegetation mode. Due to the existence of carbon trading, environmental organizations will take wetland ecosystem protection measures. If the additional reputation gained by restoring water quantity per unit is small and the revenue gained by governing wetlands per unit is large, the environmental organizations can achieve the maximum benefit by choosing the controlling invasive species mode. Otherwise, the environmental organizations can achieve the maximum benefit by choosing the diversifying vegetation mode.

KEYWORDS
ecological management, differential game, carbon credit, control mode, environmental organizations

1 Introduction

Wetlands around the world have suffered enormous damage (Park, 2024). Wetlands are very important ecosystems that provide many important ecological functions, including water resource regulation, biodiversity maintenance, and carbon storage (Zhang et al., 2022). However, wetlands are facing serious threats due to the impact such as urbanization, agriculture, industry, and climate change. Many wetlands are facing the direct impact of human activities such as land reclamation, landfill, water pollution, and illegal fishing (Bai et al., 2025). The decrease in wetland area has resulted in the loss of habitat for many species and the destruction of ecological balance. In addition, global warming has also had a certain impact on wetlands, such as sea level rise and the increase in extreme weather events, which further threaten the survival of wetlands (Chen et al., 2025).

Governments and environmental organizations face some challenges of lack of motivation in wetland conservation. This may be because wetland conservation requires long-term investment and maintenance, and its benefits are often not directly reflected in the economy. The following are some factors that may affect lack of motivation. First, governments may be more concerned with economic development and job creation, and ignore the long-term value of wetland conservation. Wetland conservation requires capital investment and continuous management, which may not bring direct economic returns to the government in the short term (Duncan et al., 2023). Second, the public and government officials may lack understanding of the value and importance of wetlands, and may lack a true understanding of wetland ecosystems (Campbell et al., 2024). This leads to low priority of wetland conservation on the government's agenda. Third, wetlands often involve multiple stakeholders, including farmers, developers, ecotourism. Conflicts between different interests may hinder conservation efforts. For example, wetlands have a large amount of vegetation, and different stakeholders have different claims on the vegetation of wetlands (Tendar and Sridith, 2021). Fourth, some regions may lack clear wetland conservation laws and policies, or existing laws are not strict enough. This may lead to ineffective enforcement and inadequate conservation measures. In order to solve these problems, the government should formulate more stringent laws and policies to protect wetlands, and ensure their implementation and effective enforcement (Bell-James et al., 2023). At the same time, each of us can also actively participate in wetland protection, support the work of environmental protection organizations, and push the government to take more active measures to protect wetlands.

The granting of carbon credits by the government to environmental organizations is an incentive mechanism that can help increase the motivation for wetland conservation. Carbon credits usually refer to the transfer of carbon storage saved or restored by wetlands into tradable assets to reduce greenhouse gas emissions and mitigate climate change (Pande, 2024). By granting carbon credits, the government can give environmental organizations certain economic returns to encourage them to continue to carry out wetland conservation and management (Bell-James, 2023). This provides an economic incentive that increases the motivation for wetland conservation. In addition, the introduction of carbon credits can also promote the link between wetland conservation and climate change issues. Wetlands are excellent carbon sinks that can absorb and store large amounts of carbon dioxide (Borgulat et al., 2022). By granting carbon credits, the government can link wetland conservation with the reduction of greenhouse gas emissions, so that the public and environmental organizations can realize the importance of wetland conservation for climate change.

Common wetland conservation measures include restoring water quantity, increasing vegetation diversity, and controlling invasive species. These measures aim to improve the ecological function and biodiversity of wetlands, and promote the health and sustainable development of wetlands (Magnússon et al., 2021). Restoring water quantity of wetlands can be achieved by improving water supply, repairing water network, reducing drainage, and maintaining water level. This helps to maintain the wetland's moist environment, provide suitable habitat conditions, and support the survival and reproduction of wetland plants and animals. Increasing vegetation diversity can provide more habitats and food resources, and promote biodiversity. This can be achieved through the restoration and protection of wetland vegetation, the introduction of native species, and the diversification of vegetation structure. Controlling invasive species can be achieved through monitoring and early detection of invasive species, and taking appropriate physical, biological, or chemical control methods (Heer et al., 2019). This helps to maintain the stability of the original species and ecosystem of wetlands. The specific conditions faced by each wetland are different. Each wetland governance model has its own scope of application. Only by selecting the appropriate governance mode can we effectively protect the ecosystem function and biodiversity of wetlands, and maintain the sustainable development of wetlands around the world.

At the theoretical level, this study draws on previous research to a certain extent. For instance, Ostrom broke away from the traditional "government-market" dichotomy and proposed a self-governance perspective, offering new insights into the management of wetlands as a common-pool resource (Ostrom et al., 1978). Wetland management involves multiple stakeholders and is prone to collective action dilemmas. Drawing on her self-governance theory, this paper suggests that stakeholders can collaboratively establish rules, clarify rights and responsibilities, and address issues of resource overuse and responsibility shirking. Additionally, the theory's rich contributions to public administration and institutional economics can aid in constructing institutional arrangements that integrate wetland management with carbon trading.

The environmental economics research by Dasgupta is also of significant importance to this study. By incorporating natural resources into economic growth models, he emphasized the impact of resource constraints on economic development. This serves as a reminder that wetland management must consider the finite nature of resources and their carrying capacity, ensuring that carbon trading aligns with the sustainable development of wetlands. His method of analyzing resource management strategies through mathematical models can be applied to study the effects of different wetland management strategies on carbon sequestration functions, ecosystem service values, and economic benefits. This provides a basis for selecting optimal strategies and achieving a comprehensive consideration of economic and environmental benefits (Dasgupta, 2024).

In the face of degraded wetlands, effective management is needed. Some scholars have studied how to manage wetlands. For example, Lu et al. (2022) analyzed the use of siphons to generate tidal flows, thereby removing nutrients from wetlands. Li et al. (2021a) studied how to use rainwater to restore wetlands. Si et al. (2021) analyzed the positive effect of natural pyrite on the removal of nitrate in constructed wetlands. Zhong et al. (2021) studied the effect of biochemically coupled biochar on the enhanced removal of nitrogen from wetlands. These scholars mainly studied how to manage wetlands from a technical level.

If only technical means are used to manage wetlands, it is sometimes insufficient. Some scholars have analyzed how to manage wetlands from the perspective of management methods. For example, Jogo and Hassan (2010) used system dynamics to simulate the effects of different policy regimes on wetland function and economic well-being. Ando and Getzner (2006) used econometrics to analyze the role of ownership, ecology and economics in public wetland conservation decisions. Mirzaei and Zibaei (2021) use an optimization approach to manage water resource conflicts among different water users and usage patterns in a basin. Integrating multiple management perspectives, such as system dynamics, econometrics, and optimization methods, enables a more comprehensive approach to addressing the complex issues in wetland management, proving more effective and preferable compared to relying on a single technical approach.

The multidisciplinary approach to wetland management offers valuable insights for other environmental governance domains. By integrating diverse management tools and policy instruments, it is possible to more effectively achieve the dual objectives of environmental protection and sustainable development. In wetland management, carbon trading, as a market-based environmental policy tool, can incentivize governments and environmental organizations to allocate resources more efficiently among strategies such as restoring water resources, diversifying vegetation, or controlling invasive species, thereby promoting the sustainable development of wetland ecosystems (Chu and Yuan, 2025). Carbon trading has a very important impact on the environment. Some scholars have studied how carbon trading affects the environment. For example, Li and Wang (2022) analyzed the spatial spillover effect of carbon trading on carbon emission reduction in pilot areas in China. Chen and Lin (2021) analyzed whether carbon neutrality can be achieved through carbon trading. Li et al. (2021b) analyzed the synergistic effect of carbon trading on carbon dioxide and air pollutants. Wang and He (2022) analyzed the role of carbon trading system in green and balanced development based on efficiency and equity.

The management of wetlands is very important for carbon storage, but the above scholars have not applied carbon trading to the process of wetland management. This carbon credit trading mechanism helps to improve the awareness of the value of wetlands, increase the importance of their protection, and promote the implementation of sustainable wetland management and protection measures (Zhang C. et al., 2024). The government can also support environmental organizations in wetland management through other means, such as providing funds, technical support and policy guidance, so as to strengthen the protection and sustainable use of wetland ecosystems (Sapiains et al., 2025).

In wetland ecosystems, there exists a complex ecological trade-off among water resource management, vegetation diversification, and invasive species control. Water resource management directly influences the hydrological conditions of wetlands, thereby determining the growth environment for vegetation. Vegetation diversification, in turn, indirectly affects the quality and availability of water resources by enhancing ecosystem stability and carbon sequestration capacity. Invasive species control aims to protect native vegetation and water resources, but its effectiveness often depends on the coordinated management of water resources and vegetation. For instance, overemphasizing water resource restoration may lead to the spread of invasive species, while neglecting vegetation diversification could weaken the carbon sequestration function of the ecosystem. Thus, finding a balance among these three aspects represents a core challenge in wetland management.

In other studies, various models have been employed to explore these ecological trade-offs. For example, dynamic optimization models provide a theoretical basis for water resource and vegetation management by maximizing carbon sequestration benefits, but they may overlook the impact of invasive species. Ecosystem service assessment models support decision-making by quantifying the ecological benefits of different management strategies, yet they often lack dynamic and game-theoretic perspectives. While these models may succeed in specific contexts, they also have limitations. This study introduces a differential game model to incorporate the strategic interactions between governments and environmental organizations into the analytical framework. By solving the optimal management path using the Hamilton-Jacobi-Bellman (HJB) equation, it more comprehensively captures the dynamic characteristics of multi-stakeholder interests and ecological trade-offs in wetland management, thereby offering a more systematic solution for carbon trading-based wetland management.

In order to make up for the shortcomings of the above research, this article combines carbon trading with wetland governance. This study employs a differential game model to focus on wetland management based on carbon trading, with governments and environmental organizations as the game players. Specifically, it examines the strategic choices and interactions between the two parties under three management modes: water resource restoration, vegetation diversification, and invasive species control. By constructing Hamilton-Jacobi-Bellman (HJB) equations for each mode to solve for the optimal strategies, the study provides decision-making support for effective wetland management, aiming to achieve the following objectives. First, the differential game model precisely captures the dynamic decision-making processes of various stakeholders under the carbon trading mechanism across the three wetland management strategies—water resource restoration, vegetation diversification, and invasive species control—clarifying the optimal action strategies for each stakeholder at different time points. Second, based on the model, the study quantitatively analyzes the long-term dynamic impacts of different management strategies and their combinations on economic indicators such as cost investment and carbon trading revenue, evaluating the strengths and weaknesses of each strategy. Third, leveraging the equilibrium solutions of the differential game model and considering the characteristics of wetlands in different regions as well as the realities of carbon trading markets, the study identifies management strategy options that achieve dual optimization of ecological and economic benefits. This provides scientifically grounded and actionable decision-making support for the formulation of wetland management policies, aiming to achieve efficient and sustainable management of wetland resources.

Among the three wetland management objectives—water resource restoration, vegetation diversification, and invasive species control—there exist both synergistic effects and potential conflicts. Water resource restoration provides a foundation for vegetation diversification by improving wetland hydrological conditions while simultaneously curbing the spread of invasive species. Vegetation diversification, in turn, indirectly supports water resource management and invasive species control by enhancing ecosystem stability and carbon sequestration capacity. However, overemphasizing water resource restoration may alter ecological niches and promote the growth of certain invasive species, while focusing solely on vegetation diversification may neglect direct control of invasive species, leading to ecological imbalances. Therefore, under the carbon trading mechanism, it is essential to dynamically balance the synergies and conflicts among these objectives through a differential game model to achieve an optimal strategy combination for wetland management.

Research on effective wetland management within the context of carbon trading holds significant practical importance. Wetland ecosystems are increasingly threatened by issues such as reduced water resources, vegetation homogenization, and invasive species. Carbon trading can transform the carbon sequestration function of wetlands into economic benefits, providing new impetus for wetland management (Bell-James, 2023). This study focuses on making optimal choices among the three wetland management strategies—restoring water resources, diversifying vegetation, and controlling invasive species—to maximize wetland management benefits. Conducting an in-depth analysis using the differential game model and the Hamilton-Jacobi-Bellman (HJB) equation is particularly necessary.

The construction of the differential game model is a critical component of this study. First, it is essential to reasonably define the participants: the government, as the regulatory and guiding party, aims to maximize wetland ecological and social benefits, while environmental organizations seek to maximize ecological protection and public interests. Next, the strategy sets for each participant must be determined, encompassing varying degrees of water resource restoration, vegetation diversification, and invasive species control measures. Simultaneously, state variables need to be constructed to describe the dynamic changes in management activities, such as the reputations of the government and environmental organizations. On this basis, payoff functions reflecting the objectives of the participants are established. Finally, the Hamilton-Jacobi-Bellman (HJB) equation is applied to solve the differential game model, yielding the optimal strategy combinations for each participant and providing a scientific decision-making basis for effective wetland management.

2 Methodology

2.1 Problem description, hypothesis, and variable definition

2.1.1 Problem description

When the government provides carbon credits to environmental protection organizations as an incentive measure, there may be some factors of game and cooperation (Pande, 2024). The following are the possible game situations. First, environmental protection organizations may strive for more carbon credits to obtain more financial support and resources to support their protection work. They may strive to demonstrate their protection results and carbon storage capacity to obtain more carbon credits. Second, the government may formulate a set of guidelines and standards to determine the allocation of carbon credits (Zhang C et al., 2024). They may focus on the amount of carbon storage and contribution to climate change, and consider the actual action and management of environmental protection organizations on wetland protection. Third, to ensure the credibility and accuracy of carbon credits, it is crucial to monitor and verify the amount of carbon storage in wetlands. The government and environmental protection organizations need to work together to ensure the scientific and accurate monitoring methods, and ensure the transparency and verifiability of data. Fourth, the economic interests and the objective of environmental protection need to be balanced between the government and environmental protection organizations. The government may consider giving appropriate economic returns, but also needs to ensure that it does not over consume carbon credit resources to ensure a sustainable incentive mechanism (Chu and Yuan, 2025). In this game and cooperation relationship, transparent communication and cooperation are crucial to ensure the effective allocation of carbon credits. Governments and environmental organizations can jointly formulate cooperation plans and protection goals, and ensure the transparency and traceability of data and actions to build mutual trust and understanding. Through consultation and cooperation, governments and environmental organizations can work together to protect wetlands and achieve a win-win situation for the environment and the economy. For convenience, it is assumed that the government is game player 1 and the environmental organizations are game player 2.

Decision-making between governments and environmental organizations in providing carbon credits to protect wetlands is usually long-term and constantly changing. This is mainly caused by the following factors. First, governments may consider many factors when formulating carbon credit policies, including domestic and foreign climate change policies, national development plans, and links with international carbon markets (Zhang C et al., 2024). These policies may be adjusted over time and with changes in environmental conditions. Second, to ensure the accuracy and effectiveness of carbon credits, governments need to monitor and assess the carbon storage capacity of wetlands. This requires regular data collection and analysis to adjust and update the allocation of carbon credits. Third, wetlands and climate systems are interrelated and affected by environmental changes. Governments and environmental organizations need to pay close attention to the health of wetland ecosystems, climate change trends, and other environmental factors (Booth and Giuntoli, 2025). These changes may affect the estimate of carbon storage capacity and the allocation of carbon credits. Fourth, governments and environmental organizations need to maintain communication and cooperation to jointly formulate long-term wetland protection plans. This includes discussing the allocation mechanism of carbon credits, monitoring methods, and conditions for cooperation (Ecklu and Thomas, 2025). Both parties need to regularly evaluate progress and effectiveness and make adjustments as needed. In conclusion, the decision-making process between governments and environmental organizations is a dynamic process that needs to take into account multiple factors and adjust according to the changing needs of wetland protection and environment. Ongoing cooperation, monitoring and evaluation are key to ensuring effective wetland protection and carbon credit allocation. Differential games can analyze this ever-changing problem.

Under the framework of the differential game model, the government and environmental organizations, as the two parties in the game, have objective functions based on the economic and ecological benefits of wetland management, respectively. The government's goal is to maximize social welfare, including carbon sequestration revenue, regional economic development, and improvements in residents' quality of life, while the environmental organization's goal is to maximize ecological benefits, such as biodiversity conservation, enhanced carbon sequestration capacity, and ecosystem stability (Booth and Giuntoli, 2025). The choices made by both parties among the three management strategies—restoring water resources, diversifying vegetation, and controlling invasive species—will directly impact the carbon sequestration capacity and ecological health of wetlands. The core of the model lies in dynamically optimizing the cost-benefit trade-offs for both parties under different strategies and exploring how the carbon trading mechanism incentivizes them to select optimal strategies to achieve sustainable wetland management.

Specifically, the model introduces time variables and state variables (such as the reputations of the government and environmental organizations) to construct the payoff and cost functions for both parties. The cost of restoring water resources includes infrastructure construction, with benefits reflected in improved residents' livelihoods and enhanced carbon sequestration capacity. The cost of diversifying vegetation includes species introduction and monitoring, with benefits reflected in increased biodiversity and improved carbon sequestration capacity (Tendar and Sridith, 2021). The cost of controlling invasive species includes eradication and monitoring, with benefits reflected in ecosystem stability and maintained carbon sequestration capacity (Ajayi et al., 2025). By solving the Nash equilibrium of the game, the model can reveal the influence of carbon trading prices, policy subsidies, and management costs on the strategic choices of both parties, providing a theoretical basis for the formulation of wetland management policies.

In the process of wetland management, there are three common modes.

1. Water recovery. In the process of wetland management, the mode of water recovery is one of the keys. The following are some common methods for wetland water recovery. First, the natural water cycle of wetlands is the key to maintaining wetland health and ecosystem function. The mode of restoring natural water cycle aims to ensure that wetlands receive enough water and circulate properly in underground and surface water systems (Balerna et al., 2024). This can be achieved by restoring water supply to wetlands, repairing water system networks, maintaining stable water levels. Second, a multi-level water management model can be established. The mode is based on water management measures at different levels to meet the water needs of wetlands and maintain ecological balance (Zhao et al., 2025). This includes formulating reasonable water management strategies, such as flood control measures, hydrological regulation and farmland drainage management to further ensure the water recovery of wetlands. Third, in the process of wetland management, the efficient water resource utilization mode can ensure the rational use and allocation of water resources to meet the water needs of wetlands. This includes adopting water resource conservation technologies, implementing water recycling, carrying out rainwater collection, reducing dependence on external water resources and improving the efficiency of water resource utilization (Li et al., 2021a). Fourth, the mode of wetland water recovery also requires community participation and cooperation. This involves cooperation with local communities, governments, and stakeholders to develop and implement effective water management and protection measures. Active community participation can provide more support and participation, promoting the success of wetland water recovery. In general, the water recovery mode in wetland management process needs to comprehensively consider natural water cycle, multi-level water management, efficient water resource utilization, and community participation and cooperation. The selection and implementation of these modes should be based on the characteristics, feasibility, and sustainability of wetlands, in order to achieve the goals of wetland ecosystem recovery and sustainable development.
2. Diversifying vegetation. In the process of wetland management, diversifying vegetation is an important management mode, which helps improve the ecological function and biodiversity of wetlands. The following are several common methods of wetland management to diversify vegetation. First, this mode aims to restore the natural vegetation of wetlands, especially native plant species. This includes selecting appropriate native plant species through methods such as seed introduction, seed dispersal, plant transplantation in the same area, and planting and restoring them at the right time and under the right conditions. Native vegetation plays an important role in the stability and restoration of wetland ecosystems. Second, this mode focuses on the structural diversity of wetland vegetation, that is, introducing plants of different heights, life cycles and functions into wetlands. This helps provide more diverse habitats and food resources, provide

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more suitable habitat conditions, attract more species, and promote biodiversity. Third, invasive species pose a threat to the diversity of wetland vegetation and ecosystem functions. This mode aims to control and manage invasive plant species to reduce their impact on native plants through competition. This can be achieved through regular monitoring, physical removal. Fourth, the vegetation diversification mode in the process of wetland management should also pay attention to the protection of endangered plants (Zhang Y. et al., 2021). This can involve the establishment of protected areas for endangered plants, the implementation of priority protection measures, the establishment of seed banks and plant reserves, to support the survival and breeding of endangered plants. When implementing these wetland management modes, it is necessary to comprehensively consider the characteristics of wetlands, climatic conditions, geographical environment and ecosystem needs. The appropriate vegetation diversification mode should be combined with other wetland protection measures to form a comprehensive management strategy to achieve the healthy and ecological sustainable development of wetlands.

3. Control of invasive species. In the process of wetland management, the control of invasive species is an important management goal. The following are several common wetland management modes for controlling invasive species. First, the government and environmental organizations can establish an effective surveillance system to detect the presence and spread of invasive species early (Heer et al., 2019). Wetland plants can be investigated and identified on-site by demarcating investigation areas and using methods such as the sample method and the sample line method. Citizen science tools such as iNaturalist can effectively crowdsourced data collection and real-time monitoring. The public can upload photos and location information of observed species on this platform, where artificial intelligence algorithms and expert networks can quickly identify potential invasive species. These data are then integrated into a Geographic Information System (GIS) to generate hotspot maps of invasive species distribution, thereby contributing to the effective control of their spread (Ozolina et al., 2025). Second, the physical control methods such as the manual pulling and weeding to reduce the population density of invasive plants and the spread of seeds. Third, this chemical control methods need to be used with caution, following the principles of safety and environmental protection, and complying with relevant regulations and recommendations. Fourth, Biological control is the use of natural enemies, pathogens or other biological species to control the growth and spread of invasive species. This may include the introduction of natural enemies that exist in nature or specially cultivated biological control agents to control the number and behavior of invasive species. Fifth, the government and environmental organizations can engage in education and public participation. This mainly includes educating the public, local communities and stakeholders about the awareness and impact of invasive species. Through education, publicity and training, the public's awareness of invasive species is improved, and they are encouraged to take positive actions, such as avoiding the introduction of non-native species, rational use of plants, timely reporting of invasive species. When implementing the governance mode for controlling invasive species, it is necessary to comprehensively consider the characteristics of invasive species, local conditions, governance effect and sustainability. A comprehensive wetland invasive species management plan requires a multi-pronged approach. First, it is essential to conduct thorough monitoring to promptly understand the distribution, population, and spread trends of invasive species (Arasumani et al., 2025). Next, targeted eradication measures should be implemented, such as physical removal, chemical control, or the introduction of natural enemies for biological control. Finally, emphasis should be placed on the restoration and protection of wetland ecosystems to enhance their resilience and prevent the resurgence of invasive species, thereby ensuring ecological balance in wetlands. Simultaneously, during the early stages of species invasion in wetlands, the ecosystem lacks strategies to cope with new competitors, and native species exhibit weak resistance, allowing invasive species to spread and making control difficult. Over time, as the biodiversity and stability of wetland ecosystems gradually recover, native species become better adapted and more resistant to invasive species. Concurrently, humans have developed effective management tools such as species monitoring and biological control. These factors collectively make controlling invasive species easier. For example, this phenomenon has been observed in the management of zebra mussels in the Great Lakes region of the United States and the control of water hyacinth invasions in multiple countries (Hornbach et al., 2023; Jha and Li, 2025).

The relationship between the three management modes of wetland ecosystem is shown in Figure 1.

In Figure 1, government and environmental organizations may seek to manage wetland ecosystems, one of the reasons is carbon credits. Governments can take corresponding policies and measures to incentivize environmental organizations to participate in wetland ecosystem management. In Figure 1, the arrows represent the motivation of governments and environmental organizations to carry out wetland management. The contents in the ellipse represent the characteristics of each wetland management mode. The contents in the rectangular box represent the players in wetland management. The contents in the pentagon represent the purpose of wetland ecosystem management.

2.1.2 Hypotheses

1. The restoration of wetland water quantity can bring convenience to residents' water consumption.

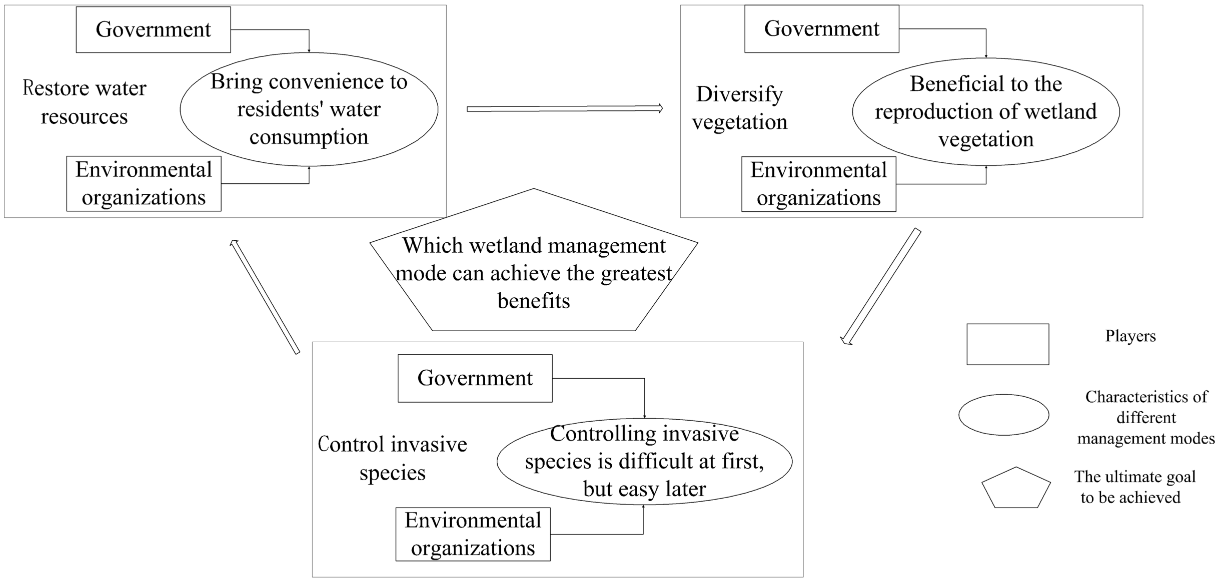

FIGURE 1
Relationship between these three management modes of wetland ecosystem.

When wetlands are restored, they can collect rainfall and watershed water. Once wetlands re-establish their water storage capacity, the stored water can provide water conveniences for residents in various ways. First, the restoration of wetlands can promote water infiltration, recharge water to the groundwater aquifer for use by the groundwater supply system (Balerna et al., 2024). This can increase the reserves of groundwater and provide a reliable source of water supply. Second, wetlands can act as natural water filter systems, removing pollutants, nutrients and impurities through the filtering effect of wetland vegetation and sediments in wetlands, and thus improving water quality. In this way, water purified by wetlands can be used by residents without additional water treatment process. Third, accumulation of water and regulation of peak flood flow. Wetlands can act as natural reservoirs, able to accumulate rainfall and alleviate peak flood flow. This can reduce flood risks and make water resources in nearby areas more sustainable. Fourth, after the restoration of wetlands, the water stored in wetlands can be used for agricultural irrigation, providing a stable water resource for crops and increasing agricultural output. In summary, the restoration of wetlands can provide sustainable water resources, facilitate residents' water needs, and bring a series of environmental and economic benefits.

2. The vegetation diversification mode is conducive to the reproduction of wetland vegetation.

The vegetation diversity pattern is beneficial to the reproduction of wetland vegetation for the following reasons. First, it balances the allocation of resources. Under the vegetation diversity pattern, different species have different growth requirements and adaptability. Through a diverse combination of vegetation, it can be ensured that various plants in wetlands can make full use of and obtain the required resources, such as light, water, soil nutrients. This is conducive to the healthy growth and reproduction of vegetation (Magnússon et al., 2021). Second, it promotes mutual symbiosis. Under the vegetation diversity pattern, complex interactions between different plants are established. For example, the roots of some plants can provide nitrogen sources for other plants, while the shade of other plants can protect some plants from excessive sunlight. This mutually beneficial symbiotic relationship helps to improve the viability and reproduction opportunities of plants. Third, it provides diverse reproduction opportunities. Vegetation diversity means that there are many different plant species in wetlands. These plants may have different reproductive strategies, such as pollen transmission, seed dispersal, cloning. Therefore, under the vegetation diversity pattern, plants in wetlands can improve their reproductive success rate through different reproductive channels. Fourth, it enhances ecological stability. The vegetation diversity pattern can increase the resilience and stability of wetland ecosystems. When some plants are threatened by environmental stress or pests, others may still be able to maintain their health, thus maintaining the overall stability of wetland vegetation. In summary, the vegetation diversity pattern provides abundant resources, interaction opportunities and ecological stability for vegetation reproduction in wetlands, which is conducive to maintaining the ecological balance of wetlands and enriching plant diversity.

2.1.3 Variable definition

Drawing on the literature regarding wetland management by Wu et al. (2025) and Bai and Wang (2024), this paper establishes a differential game model. This involves the formulation of modes, variables, parameters, and functions. Wetland management encompasses three modes: restoring water resources, diversifying vegetation, and controlling invasive species. Independent variables include the wetland management levels of the government and environmental organizations under these modes, as well as their reputations in managing forest fires. Parameters consist of the discount rate over time, reputation decay, ecological benefits of wetland management, costs of controlling wetlands, positive impacts of reputation, government allocation of carbon credits, reputation from managing wetlands, additional reputation from restoring water resources, benefits to residents' water usage, vegetation reproduction rates, additional reputation from vegetation diversity, and the difficulty of controlling invasive species. This paper also defines the social welfare function for the government and the social benefit function for environmental organizations under the management modes. The detailed content is shown in Table 1.

This paper will explain the aforementioned variables and parameters. The government's wetland management level represents its investment or efficiency in wetland management, which may include policy formulation, financial support, and regulatory enforcement. High-level management indicates that the government can effectively promote wetland restoration, vegetation diversification, or invasive species control, thereby enhancing ecological benefits and carbon trading revenue. The environmental organizations' wetland management level represents its degree of participation or efficiency in wetland management, which may include investments in environmental technologies, engagement in carbon trading, or the implementation of ecological restoration projects. High-level management indicates that environmental organizations can actively respond to policies and make substantive contributions to wetland conservation. The government's reputation in managing forest fires reflects public trust or social evaluation of its performance in forest fire management. A high reputation signifies that the government can effectively prevent and control fires, thereby increasing public support for wetland management policies. The environmental organizations' reputation in managing forest fires reflects its social evaluation or industry recognition in forest fire governance. A high reputation indicates that environmental organizations can actively participate in fire prevention and control, enhancing their competitiveness in the carbon trading market.

The discount rate over time is used to measure the present value of future benefits or costs, reflecting the degree to which the government and environmental organizations prioritize the long-term benefits of wetland management. A high discount rate indicates a greater focus on short-term gains, which may undermine the motivation for long-term ecological conservation. Reputation decay represents the natural rate at which the reputation of the government or environmental organizations declines over time. A high decay rate implies the need for continuous investment to maintain reputation; otherwise, it may lead to a decline in public trust. The ecological benefits of wetland management per unit scale for the government or environmental organizations represent the ecological gains brought by each unit of wetland management measures, such as restoring water resources or diversifying vegetation. These benefits may include increased carbon storage, enhanced biodiversity, or improved ecosystem services. The cost of controlling one unit of wetland for the government or environmental organizations represents the economic cost per unit of wetland management measures, including financial, human, or technical investments. High costs may limit the promotion and implementation of management measures. The reputation gained per unit of wetland management for the government or environmental organizations reflects the enhancement of their reputation from each unit of management

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

Variables and parameters	Specific meaning
$Y=\{R,D,C\}$	three modes of wetland management (restore water resources, diversify vegetation, control invasive species)
Independent variable	
$G_{Y1}(t)$	the level of wetland management in the government under the control mode Y
$G_{Y2}(t)$	the level of wetland management in the environmental organizations under the control mode Y
$x_{Y1}(t)$	the government's reputation for managing forest fires under the control mode Y
$x_{Y2}(t)$	the environmental organizations' reputation for managing forest fires under the control mode Y
Parameter	
ρ	the discount rate that occurs over time, $0\le\rho\le1$
δ	decay of reputation, $\delta>0$
b_1,b_2	ecological benefits from the management of wetlands at a unit scale by government or environmental organizations, $b_1,b_2>0$
c_1,c_2	the cost of government or environmental organizations to control a unit of wetland, $c_1,c_2>0$
l	the positive impact of reputation per unit quantity, $l>0$
C_a	carbon credits allocated by the government to environmental organizations, $C_a>0$
a_1,a_2	reputation of a government or environmental organizations for managing wetlands at the unit level, $a_1,a_2>0$
a_R	additional reputation for restoring a unit amount of water, $a_R>0$
b_R	the benefits of facilitating residents' access to water resources, $b_R>0$
p	the reproductive rate of vegetation, $p>0$
a_D	additional reputation for a unit of vegetation diversity, $a_D>0$
h	the difficulty of controlling invasive species, $h>0$
Function	
$J_{Y1}(t)$	the social welfare function of government under the control mode Y
$J_{Y2}(t)$	the social welfare function of environmental organizations under the control mode Y
$V_{Y1}(t)$	the social benefits of government under the control mode Y
$V_{Y2}(t)$	the social benefits of environmental organizations under the control mode Y

measures. High reputation gains may incentivize more proactive wetland management behaviors. The additional reputation from restoring a unit of water volume represents the extra boost to the reputation of the government or environmental organizations for each unit of water restored. High reputation gains may prioritize water resource restoration projects. The benefits of facilitating residents' access to water resources represent the improvement in residents' quality of life resulting from water resource restoration, which may include drinking water supply, agricultural irrigation, or ecotourism revenue. A high benefit value indicates that water resource restoration has significant socio-economic value. The difficulty of controlling invasive species reflects the technical complexity or resource investment required for such control. High difficulty may constrain the actions of environmental organizations or governments in this area, necessitating stronger policy support or technological innovation.

These parameters and variables collectively form the core of the differential game model, which is utilized to analyze the strategic interactions between the government and environmental organizations, as well as the conditions under which different wetland management modes emerge.

2.2 Differential game of three control modes

Differential game theory is a branch that combines game theory and differential equation theory, mainly studying the strategic interactions of multiple decision-makers in continuous time dynamic systems. The theoretical background can be traced back to the 1950s, when Isaacs et al. proposed the "chase and escape problem" which laid the early foundation for differential games. The core of differential game lies in describing the dynamic behavior of participants through differential equations, and analyzing the strategy choices and equilibrium results of each party based on this. Unlike traditional static games, differential games emphasize time continuity and the evolution of state variables, enabling them to better characterize dynamic competition and cooperation problems in reality.

In the theoretical framework of differential games, participants influence the state of the system by controlling variables, with the goal of optimizing their own payoff function. This process typically involves the Hamilton Jacobi Bellman equation (HJB equation), which is used to solve the optimal strategy. At present, the differential game it is mainly applied in the fields of supply chain (Zhu et al., 2021), advertising decision (Viscolani and Zaccour, 2009), logistics management (Bai et al., 2022). It can be used to analyze decision-making problems such as resource allocation, market competition, and environmental management. Through differential game models, we can study and predict the behavior of decision makers, and provide decision-making recommendations and guidance for policy formulation.

Differential game is a model in game theory, used to study decision-making problems in decision-making processes that last very short time. In a differential game, players try to optimize their strategies to maximize their utility function, which is usually related to the interests of the players. Differential game models are based on differential equations to describe the evolution of the players' strategies, which are regarded as state variables of dynamic systems. The solution of the game is usually to find a stable equilibrium strategy, that is, there is no gradient change that can make the players get more utility. It should be noted that differential games usually assume that participants are rational and have complete information. In addition, differential game models require some technical and mathematical tools, such as differential equations and control theory, to model system dynamics. Therefore, in practical applications, analysis of complex systems may require more research and computational resources.

The framework of this differential game model aims to study the strategic interactions between the government and environmental organizations in wetland management, exploring the conditions for cooperative actions based on carbon trading, such as restoring water resources, diversifying vegetation, or controlling invasive species. As the policymaker and resource provider, the government promotes wetland conservation through carbon trading mechanisms, financial support, or regulatory measures (Bell-James et al., 2023). Meanwhile, environmental organizations actively participate in ecological restoration projects leveraging their technical expertise and public influence. The strategic choices and payoff functions of both parties reflect their differing objectives and potential for collaboration. The model captures the dynamic processes of wetland ecosystem changes through dynamic analysis, providing a theoretical foundation for the formation of cooperative conditions.

The emergence of cooperative actions depends on the balance between government policy incentives and the operational capacity of environmental organizations. When carbon trading revenues are significant and the government provides sufficient policy support, such as subsidies or technical assistance, environmental organizations are more inclined to collaborate with the government. Conversely, insufficient policy incentives or limited resources of environmental organizations may hinder cooperation. Additionally, dynamic factors over time, such as vegetation propagation rates and changes in the reputation of the game participants, also influence the evolution of cooperative conditions. Through this framework, optimal strategies for government and environmental organizations to synergistically achieve wetland conservation can be identified, providing scientific guidance for effective carbon trading-based management.

This study is based on a differential game model, with the government and environmental organizations as the game participants, and incorporates three wetland management modes —"water resource restoration," "vegetation diversification," and "invasive species control"—as strategic variables. By integrating the carbon trading mechanism, a dynamic optimization framework is constructed. Using the Hamilton-Jacobi-Bellman (HJB) equation, the optimal strategies and payoff functions for the government and environmental organizations under different modes are solved separately. The impact of carbon trading on the decision-making of each party is analyzed, and the synergistic effects and resource allocation optimization among the three modes are explored. Ultimately, this provides a theoretical foundation and policy recommendations for carbon trading-based wetland management. Specifically, the operational logic diagram of this study is shown in Figure 2.

If the government and environmental organizations adopt the mode of restoring water resources to manage wetlands, this study takes the government and environmental organizations as the game participants. Based on the carbon trading mechanism, it comprehensively considers factors such as investment costs, reputation gains, and carbon trading revenues during the water resource restoration process. With time as a variable, a differential equation describing the dynamic changes in the strategies of both parties is constructed, and a differential game model under the mode of restoring water resources is established. This model is used to analyze the strategic interactions and equilibrium states of both parties in the process of pursuing their own benefit maximization. Then, the social welfare function of the government and environmental organizations are represented by Equations 1, 2 respectively:

$$J_{R1} = \int_0^{\infty} \left[(b_1 + b_R) G_{R1}(t) - \frac{c_1}{2} G_{R1}^2(t) - C_a + l x_{R1}(t) \right] e^{-\rho t} dt \quad (1)$$

$$J_{R2} = \int_0^{\infty} \left[b_2 G_{R2}(t) - \frac{c_2}{2} G_{R2}^2(t) + C_a + l x_{R2}(t) \right] e^{-\rho t} dt \quad (2)$$

In the above formula, $b_1 G_{R1}(t)$ represents the benefits of restoring water resources for wetland ecology by government. The government's restoration of water resources primarily benefits wetland ecology by improving hydrological conditions, thereby enhancing the ecological functions of wetlands. Restoring water resources helps maintain the stability of wetland ecosystems, boosts their carbon sequestration capacity, and provides a favorable habitat for biodiversity (Xu et al., 2024). Additionally, restoring water resources can reduce the risk of wetland degradation, promote the self-repair capabilities of wetland ecosystems, and lay the foundation for long-term ecological conservation and sustainable development. $b_R G_{R1}(t)$ represents the benefits of facilitating water usage for local residents. The benefits brought to local residents by the government's restoration of water resources are primarily reflected in the improvement of water supply and quality, thereby meeting the production and daily life needs of the population. The restoration of water resources can enhance agricultural irrigation efficiency, ensure the safety of drinking water, and support local economic development. Additionally, the restoration of wetland

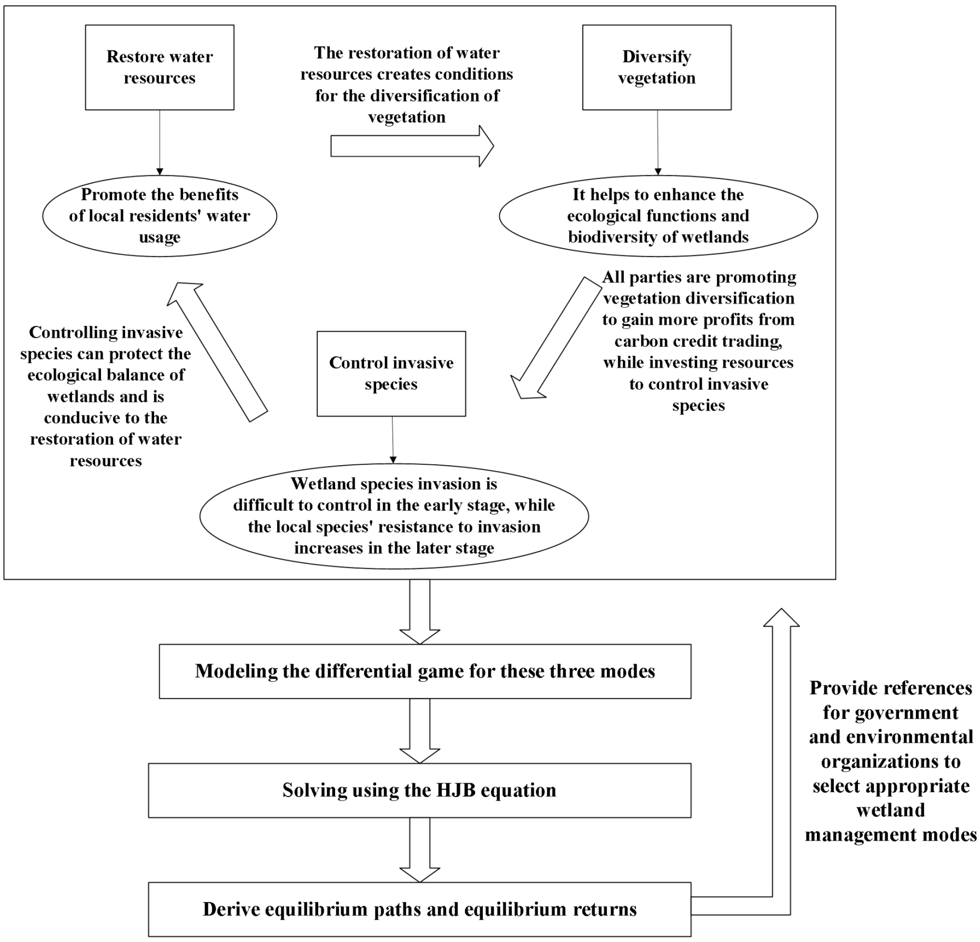

FIGURE 2
Operating logic diagram of the differential game model.

water resources can reduce the risk of flood disasters, improve regional climate conditions, and provide more livable ecological conditions for residents, thereby enhancing overall quality of life (Canto-Perello et al., 2021). $b_2G_{R2}(t)$ represents the benefits of restoring water resources for wetland ecology by environmental organizations. The benefits of environmental organizations' efforts to restore water resources for wetland ecosystems are primarily reflected in promoting ecological conservation and environmental education. By implementing water resource restoration projects, these organizations can enhance public awareness of the importance of wetland ecosystems and encourage community participation in ecological conservation activities. Additionally, restoring water resources provides environmental organizations with more research opportunities, helping them accumulate experience in wetland management and ecological restoration. This, in turn, provides a scientific basis for developing more effective protection strategies, further advancing the sustainable development of wetland ecosystems.

$\frac{c_1}{2}G_{R1}^2(t)$ represents the cost of government governing wetlands under the restoration water quantity mode. The cost of government wetland governance mainly includes direct investment in water resource restoration projects, construction and maintenance costs of related infrastructure, and long-term monitoring and management expenses for wetland ecosystems (Lang et al., 2025). The government needs to invest a large amount of funds in water resource allocation, wetland restoration technology application, and the formulation and implementation of related policies. In addition, the government also needs to bear the short-term economic and social costs that may arise from restoring water resources, such as temporary restrictions on agricultural or industrial water use, as well as administrative costs required to coordinate the interests of all parties. These costs reflect the economic cost that the government has paid to achieve wetland ecological protection and sustainable development under the restoration of water resources. $\frac{c_2}{2}G_{R2}^2(t)$ represents the cost of environmental organizations governing wetlands under the restoration water quantity mode. The cost of environmental organizations managing wetlands mainly includes technical investment in project implementation, human resource costs for ecological restoration, and organizational expenses for public education and community participation activities. Environmental organizations need to invest funds in the research and application of water resource restoration technologies, while also bearing the research costs of wetland ecological monitoring, data collection, and analysis. In addition, environmental organizations need to raise public awareness of the importance of water resource restoration through publicity and educational activities, which requires certain financial support. These costs reflect the economic burden borne by environmental organizations in promoting wetland ecological protection and public participation under the restoration of water resources model.

C_a represents the carbon credits granted by the government to environmental organizations. Under the model of restoring water resources, the carbon credit quota granted by the government to environmental organizations is an economic incentive for their contributions to wetland ecological restoration. By restoring water resources, environmental organizations can enhance the carbon sequestration capacity of wetlands, reduce greenhouse gas emissions, and contribute to regional or global carbon reduction goals. The government grants corresponding carbon credit quotas based on the actual carbon reduction effects of environmental organizations in wetland restoration projects. These carbon credits can be sold in the carbon trading market or used to offset other emission sources (Wang and He, 2022). This mechanism not only provides sustainable funding sources for environmental organizations, but also encourages them to actively participate in wetland ecological restoration and promote the coordinated development of carbon trading and wetland management.

$lx_{R1}(t)$ represents the positive impact of reputation on the government's revenue under the restoration water quantity mode. The positive impact of government reputation on its revenue growth is mainly reflected in enhancing public trust and international recognition. By successfully implementing water resource restoration projects, the government can demonstrate its leadership in ecological protection and sustainable development, thereby attracting more domestic and foreign investment and funding (Xu et al., 2024). In addition, a good reputation helps the government promote the development of the carbon trading market, attract more companies to participate in carbon credit purchases, and increase carbon trading revenue. At the same time, the government can also gain more international cooperation opportunities and policy support by enhancing its reputation, further expanding funding sources, and providing sustained economic security for wetland management and ecological restoration. $lx_{R2}(t)$ represents the positive impact of reputation on the revenue of environmental organizations under the restoration water quantity mode. The positive impact of the reputation of environmental organizations on their income is mainly reflected in attracting more donations, funding, and partners. Environmental organizations can demonstrate their professional capabilities and ecological protection achievements by effectively implementing water resource restoration projects, thereby winning the trust and support of the public and businesses. A good reputation helps environmental organizations obtain more public welfare funds, government subsidies, and international project funding. In addition, environmental organizations can increase their revenue through carbon credit trading, as their reputation enhances the market value of carbon credits and attracts more buyers. The improvement of reputation also brings more opportunities for environmental organizations to collaborate, such as joint projects with research institutions or enterprises, further expanding their sources of income.

The change in the reputation of government and environmental organizations under the mode of restoring water resources can be expressed as:

$$\dot{x}_{R1}(t) = a_1 G_{R1}(t) - \delta x_{R1}(t) \tag{3}$$

$$\dot{x}_{R2}(t) = (a_2 + a_R) G_{R2}(t) - \delta x_{R2}(t) \tag{4}$$

In the above formula (Equations 3, 4), $a_1G_{R1}(t)$ represents the reputation of the government for restoring wetland water resources. The reputation of the government is mainly reflected in its credibility and execution as the leader of ecological protection. By implementing water resource restoration projects, the government can demonstrate its determination and ability to address ecological crises and improve environmental quality, thereby winning the trust and support of the public. A good reputation helps the government promote the implementation of relevant policies, such as the improvement of carbon trading mechanisms and the implementation of ecological compensation policies, thereby providing more funding and resource support for wetland management and sustainable development. In addition, enhancing the reputation of the government can also attract the attention and cooperation of the international community, such as obtaining international environmental protection funds or participating in global ecological protection initiatives, further enhancing its influence in the field of ecological protection. $a_2G_{R2}(t)$ represents the reputation of environmental organizations for restoring wetland water resources. The reputation of environmental organizations is mainly reflected in their professional competence and public influence. Environmental organizations can demonstrate their professional capabilities in ecological restoration, technological innovation, and community mobilization by successfully implementing water resource restoration projects, thereby winning the trust and support of the public and businesses. A good reputation helps environmental organizations obtain more donations, funding, and partnerships, such as joint projects with research institutions or enterprises, further expanding their sources of income. In addition, environmental organizations can increase their revenue through carbon credit trading, as their reputation enhances the market value of carbon credits and attracts more buyers. The improvement of reputation also brings more social support and resources to environmental organizations, such as volunteer participation and media exposure, further enhancing their influence and voice in the field of environmental protection. $a_RF_{R2}(t)$ represents the additional reputation of environmental organizations for restoring water resources. The additional reputation of environmental organizations is mainly reflected in their ability to promote public participation and environmental education. By carrying out water resource restoration projects, environmental organizations can go deep into communities, mobilize public participation in wetland protection, and thus enhance public awareness and responsibility for environmental protection. This additional reputation not only enhances the social influence of environmental organizations, but also earns them more social support and resources, such as volunteer participation and media coverage. In addition, environmental organizations can further enhance public awareness and support for wetland conservation through environmental education activities, thereby creating favorable conditions for future project cooperation and fundraising (Menezes and Peci, 2023). This additional reputation not only helps environmental organizations obtain more financial support, but also enhances their influence and voice in the field of environmental protection, providing strong guarantees for wetland ecological restoration and sustainable development.

$\delta x_{R1}(t)$ represents the decline of the reputation of the government. The decline in government reputation is mainly due to its failure to effectively implement ecological protection policies or fulfill commitments. For example, if the government invests insufficiently or poorly in restoring water resources, diversifying vegetation, or controlling invasive species, it may lead to further deterioration of wetland ecosystems, thereby causing public dissatisfaction and questioning. $\delta x_{R2}(t)$ represents the decline of the reputation of environmental organizations. The decline in the reputation of environmental organizations may be due to poor project implementation or internal management issues. For example, if environmental organizations fail to achieve significant results in restoring water resources, diversifying vegetation, or controlling alien species, it may lead to public questioning of their professional competence and execution.

Under the mode of diversifying vegetation, with the government and environmental organizations as the game participants, this study considers the scenario of wetland vegetation diversification management based on carbon trading. It incorporates time-varying factors such as financial investment, human resource investment, carbon revenue, and reputation gains for both parties. A differential equation reflecting the dynamic adjustment of their strategies is constructed, and a differential game model under the mode of diversifying vegetation is established. This model is used to analyze the strategic interactions and equilibrium states of both parties in the process of pursuing their own benefit maximization. If the government and environmental protection organizations choose the vegetation diversification mode to manage wetlands, their social welfare function are represented by Equations 5, 6 respectively:

$$J_{D1} = \int_0^{\infty} \left[b_1 \ln(1+p) G_{D1}(t) - \frac{c_1}{2} G_{D1}^2(t) - C_a + l x_{D1}(t) \right] e^{-\rho t} dt \tag{5}$$

$$J_{D2} = \int_0^{\infty} \left[b_2 \ln(1+p) G_{D2}(t) - \frac{c_2}{2} G_{D2}^2(t) + C_a + l x_{D2}(t) \right] e^{-\rho t} dt \tag{6}$$

In the above formula, $\ln(1+p)$ represents the effect of vegetation propagation. p represents the rate of vegetation propagation. $b_1 \ln(1+p) G_{D1}(t)$ represents the benefits of diversifying vegetation for wetland ecology by government. The benefits of diversified vegetation for wetland ecology by the government are mainly reflected in enhancing the stability and carbon sequestration capacity of the ecosystem. Diversified vegetation can increase the biodiversity of wetlands, provide suitable habitats for different species, and enhance the ecosystem's ability to resist interference and self repair. In addition, diversified vegetation helps optimize the carbon cycle of wetlands, improve carbon absorption efficiency, and provide a solid foundation for carbon trading. By promoting vegetation diversification, the government can not only achieve long-term protection of wetland ecology, but also obtain economic benefits through carbon credit trading, providing support for sustainable development. $b_2 \ln(1+p) G_{D2}(t)$ represents the benefits of diversifying vegetation for wetland ecology by environmental protection organization. The benefits of diversified vegetation for wetland ecology by environmental organizations are mainly reflected in promoting ecological restoration and public participation. Environmental organizations can implement vegetation diversification projects to restore the natural structure of wetland vegetation, improve ecological functions, and provide protection for endangered species. In addition, the vegetation diversification project provides environmental organizations with opportunities to carry out environmental education and community participation, enhancing public awareness and support for wetland conservation. Environmental organizations can also obtain financial support through carbon credit trading to further promote wetland ecological restoration projects, thereby achieving a win-win situation between ecological protection and economic benefits.

The impact of vegetation growth rate on benefits follows a logarithmic pattern, primarily because the ecological benefits and carbon sequestration capacity of vegetation increase rapidly in the early stages. However, as vegetation coverage rises, its marginal benefits gradually decline. In the initial phase of vegetation growth, the coverage is relatively low in wetland ecosystems, where each additional increment in vegetation significantly enhances ecosystem stability, carbon absorption capacity, and biodiversity, thereby yielding higher benefits. Once vegetation coverage reaches a certain threshold, the ecosystem's carrying capacity tends to saturate, and the contribution of new vegetation to ecological benefits and carbon sequestration diminishes, leading to a slowdown in the growth rate of benefits (Zhang G. et al., 2024).

The logarithmic relationship reflects the law of diminishing marginal benefits. Specifically, an accelerated vegetation growth rate initially significantly enhances yields, but as vegetation coverage increases, the rate of yield growth gradually slows and eventually stabilizes. This pattern is common in ecological economics, as the exploitation and utilization of natural resources often follow a similar trend—initial investments yield high returns, but as resources become increasingly saturated, the rate of return gradually declines. Consequently, the impact of vegetation growth rate on yields exhibits a logarithmic form, demonstrating the diminishing marginal effects of ecological benefits and carbon sequestration capacity.

$\frac{c_1}{2}G_{D1}^2(t)$ represents the cost of government governing wetlands under the diversifying vegetation mode. The costs of government wetland governance primarily include direct investments in ecological restoration, long-term maintenance expenses, and administrative costs for policy implementation. Governments need to allocate funds for vegetation planting, soil improvement, and wetland infrastructure construction to ensure the successful implementation of vegetation diversification. Additionally, vegetation diversification requires long-term monitoring and maintenance, such as pest and disease control, invasive species management, and vegetation renewal, all of which increase operational costs (He et al., 2025). Furthermore, governments must formulate and implement relevant policies, coordinate resources among various stakeholders, and oversee project progress, all of which incur additional administrative costs. Although the costs are substantial, the ecological benefits and enhanced carbon sequestration capacity from vegetation diversification can generate long-term economic returns for the government through mechanisms like carbon trading. $\frac{c_2}{2}G_{D2}^2(t)$ represents the cost of environmental protection organization governing wetlands under the diversifying vegetation mode. The cost of wetland management by environmental organizations mainly includes direct project implementation expenses, technology research and development expenses, as well as expenses for public education and community participation. Environmental organizations need to invest funds in vegetation planting, research and application of ecological restoration technologies, as well as monitoring and evaluation of wetland ecosystems (Kou et al., 2024). In addition, environmental organizations typically conduct environmental education and community engagement activities to increase public awareness and support for wetland conservation, which also incur certain costs. Although environmental organizations face high financial pressure in project implementation, they can obtain certain economic support through channels such as carbon credit trading, social donations, and international funding, thereby covering some costs and promoting the sustainable development of wetland ecological restoration.

C_a represents the carbon credits granted by government to environmental protection organization.

$lx_{D1}(t)$ represents the positive impact of reputation on government revenue under the diversifying vegetation mode. The positive impact of government reputation on its revenue growth is mainly reflected in enhancing public trust and opportunities for international cooperation. By successfully implementing vegetation diversification projects, the government can demonstrate its leadership in ecological protection and sustainable development, thereby attracting more domestic and foreign investment and funding. A good reputation helps the government promote the development of the carbon trading market, attract more companies to purchase carbon credits, and increase carbon trading revenue. In addition, the government can gain more international cooperation opportunities and policy support by enhancing its reputation, further expanding funding sources, and providing sustained economic security for wetland management and ecological restoration. The improvement of reputation can also enhance the credibility of the government in society, promote public support for environmental policies, and create more economic and social benefits for the government. $lx_{D2}(t)$ represents the positive impact of reputation on environmental protection organization revenue under the diversifying vegetation mode. The positive impact of the reputation of environmental organizations on their income is mainly reflected in attracting more donations, funding, and partners. Environmental organizations can demonstrate their professional capabilities and ecological conservation achievements by effectively implementing vegetation diversification projects, thereby winning the trust and support of the public and businesses. A good reputation helps environmental organizations obtain more public welfare funds, government subsidies, and international project funding (Menezes and Peci, 2023). In addition, environmental organizations can increase their revenue through carbon credit trading, as their reputation enhances the market value of carbon credits and attracts more buyers. The improvement of reputation also brings more opportunities for environmental organizations to collaborate, such as joint projects with research institutions or enterprises, further expanding their sources of income. By enhancing their reputation, environmental organizations can not only receive more financial support, but also strengthen their influence and voice in the field of environmental protection, providing strong guarantees for wetland ecological restoration and sustainable development.

The change in the reputation of government and environmental organizations under the mode of diversifying vegetation can be expressed as:

$$\dot{x}_{D1}(t) = (a_1 + a_D)G_{D1}(t) - \delta x_{D1}(t) \tag{7}$$

$$\dot{x}_{D2}(t) = (a_2 + a_D)G_{D2}(t) - \delta x_{D2}(t) \tag{8}$$

In the above formula (Equations 7, 8), $a_1F_{D1}(t)$ represents the reputation of the government for managing wetlands. The reputation of government managed wetlands is mainly reflected in its effectiveness in promoting ecological restoration and biodiversity conservation. By implementing diversified vegetation projects, the government can demonstrate its leadership and execution in improving wetland ecosystems, enhancing carbon sequestration capacity, and addressing climate change. Successful diversified vegetation projects not only help restore the ecological functions of wetlands, but also enhance public trust and support for government environmental policies. The accumulation of this reputation can attract more domestic and foreign investment and funding for the government, such as increasing revenue through carbon trading mechanisms or obtaining support from international environmental funds. In addition, a good reputation can enhance the government's credibility in the field of ecological protection, laying the foundation for the implementation of future policies and the sustainable development of wetland management. $a_DF_{D1}(t)$ represents the additional reputation of the government for diversifying vegetation. The government's additional reputation is mainly reflected in its ability to promote technological innovation and community participation. The government can demonstrate its innovative ability and professionalism in the field of ecological protection by introducing advanced vegetation restoration technologies and ecological restoration methods. This additional reputation not only enhances the government's influence in research institutions and enterprises, but also attracts more partners and resources, such as collaborating with research institutions on research projects or developing carbon credit products in partnership with enterprises. In addition, by mobilizing communities to participate in diversified vegetation projects, the government can increase public awareness and participation in environmental protection, thereby winning broader social support. This additional reputation not only helps the government obtain more funds and resources, but also enhances its influence and voice in the field of ecological protection, providing strong guarantees for wetland ecological restoration and sustainable development. $\delta x_{D1}(t)$ represents the decline of the government's reputation.

$a_2F_{D2}(t)$ represents the reputation of environmental organizations for managing wetlands. The reputation of environmental organizations in managing wetlands is mainly reflected in their professional capabilities and ecological restoration achievements. By successfully implementing diversified vegetation projects, environmental organizations can demonstrate their professional level in restoring wetland ecosystems, enhancing biodiversity, and improving carbon sequestration capacity. The accumulation of this reputation helps environmental organizations win the trust and support of the public, businesses, and governments, thereby gaining more opportunities for donations, funding, and cooperation. For example, environmental organizations can increase their revenue through carbon credit trading, as their reputation enhances the market value of carbon credits and attracts more buyers. In addition, a good reputation can enhance the influence of environmental organizations in the field of ecological protection, creating favorable conditions for their participation in international environmental initiatives or obtaining international project funding, thereby providing more resources for the sustainable development of wetland management. $a_DF_{D2}(t)$ represents the additional reputation of environmental organizations for diversifying vegetation. The additional reputation of environmental organizations is mainly reflected in their ability to promote community participation and environmental education. By mobilizing public participation in diverse vegetation projects, environmental organizations can showcase their advantages in community mobilization and public education, thereby enhancing public awareness and responsibility for environmental protection. This additional reputation not only enhances the social influence of environmental organizations, but also earns them more social support and resources, such as volunteer participation and media coverage. In addition, environmental organizations can further enhance public awareness and support for wetland conservation by conducting environmental education activities, thereby creating favorable conditions for future project cooperation and fundraising. This additional reputation not only helps environmental organizations obtain more financial support, but also enhances their influence and voice in the field of ecological protection, providing strong guarantees for wetland ecological restoration and sustainable development. $\delta x_{D2}(t)$ represents the decline of environmental organizations' reputation.

Controlling invasive species in wetlands is initially hard but later becomes easy. In the early stage of wetland species invasion, it's tough as the wetland ecosystem lacks adaptive counter-measures. The original species have weak resistance, allowing invasive species to spread. However, over time, it gets easier for several reasons. Firstly, biodiversity recovers. The wetland ecosystem restores its biodiversity and stability, enabling original species to adapt and re-establish their ecological status (Heer et al., 2019). Secondly, the ecosystem's self-regulation comes into play. Once the ecological balance recovers, original species develop strategies to resist invasive species, and predators in the wetland can control their growth via the food chain. Thirdly, effective management interventions have been developed. These include species monitoring, eradication, physical control, and biological control, which can reduce the impact of invasive species and restore the wetland's original ecosystem.

Under the mode of controlling invasive species, with the government and environmental organizations as the primary actors, this study focuses on the management mode of wetland invasive species control based on carbon trading. It comprehensively considers time-varying factors such as cost inputs (e.g., human resources, material resources, and technology), carbon trading revenues, and reputation gains from effective control during the process of managing invasive species. A differential equation describing the dynamic evolution of strategic choices by both parties is constructed, thereby establishing a differential game model under the mode of controlling invasive species. This model is used to analyze the strategic interactions and equilibrium states of both parties in the process of pursuing their respective benefit maximization. If governments and environmental organizations adopt the mode of controlling invasive species to manage wetlands, then their social welfare function are represented by Equations 9, 10 respectively:

$$J_{C1} = \int_0^\infty \left[b_1 G_{C1}(t) - \frac{c_1}{2\ln(1+h)} G_{C1}^2(t) - C_a + lx_{C1}(t) \right] e^{-\rho t} dt \tag{9}$$

$$J_{C2} = \int_0^\infty \left[b_2 G_{C2}(t) - \frac{c_2}{2\ln(1+h)} G_{C2}^2(t) + C_a + lx_{C2}(t) \right] e^{-\rho t} dt \tag{10}$$

In the above formula, $\ln(1+h)$ represents the difficulty of controlling invasive species. h represents the difficulty coefficient of controlling invasive species. $b_1 G_{C1}(t)$ represents the benefits of government controlling species invasion on wetland ecosystem. The benefits of the government for wetland ecosystems mainly lie in restoring ecological balance and enhancing carbon sequestration capacity. Invasive alien species often damage the biodiversity and ecological functions of wetlands, leading to a decrease in native species and instability of ecosystems. By effectively controlling invasive species, governments can restore the natural vegetation and biological communities of wetlands, enhance the stability and self-healing capacity of ecosystems (González-Jaramillo and Cano-Santana, 2025). In addition, controlling invasive species can help optimize the carbon cycle of wetlands, reduce carbon emissions caused by invasive species, and improve the carbon absorption efficiency of wetlands. This not only provides a foundation for the government to obtain economic benefits through carbon trading, but also enhances the ecological service value of wetlands, such as water purification and flood regulation, thereby providing support for the sustainable development of society. $b_2 G_{C2}(t)$ represents the benefits of environmental protection organization controlling species invasion on wetland ecosystem. The benefits of environmental organizations to wetland ecosystems are mainly reflected in promoting ecological restoration and public participation. Environmental organizations can restore the natural vegetation and biodiversity of wetlands, provide protection for endangered species, and improve the ecological functions of wetlands by implementing alien species control projects. In addition, environmental organizations usually carry out environmental education and community participation activities to raise public awareness of the hazards of alien species and mobilize community forces to participate in wetland conservation. These activities not only enhance public awareness of environmental protection, but also win more social support and resources for environmental organizations. By controlling invasive species, environmental organizations can enhance the ecological value of wetlands and obtain financial support through carbon credit trading, further promoting the implementation of wetland ecological restoration projects, thereby achieving a win-win situation between ecological protection and economic benefits (Hart-Fredeluces et al., 2025).

$\frac{c_1}{2\ln(1+h)} G_{C1}^2(t)$ represents the cost of government controlling species invasion on wetland ecosystem. The cost of government wetland management mainly includes species monitoring, clearance actions, and long-term management expenses. The government needs to invest resources in establishing a monitoring system for invasive species in order to timely detect and assess the threat of invasive species. Clearance actions typically involve a combination of physical, chemical, or biological methods, such as manual clearance, chemical spraying, or introduction of natural enemies, which require significant financial and human support. In addition, controlling alien species is a long-term process, and the government needs to continuously invest in monitoring and management to prevent the re invasion or spread of species (González-Jaramillo and Cano-Santana, 2025). Despite the high cost, controlling invasive species can help restore the ecological balance of wetlands, enhance carbon sequestration capacity, and bring long-term economic returns to the government through mechanisms such as carbon trading. $\frac{c_2}{2\ln(1+h)} G_{C2}^2(t)$ represents the cost of environmental protection organization controlling species invasion on wetland ecosystem. The cost of wetland management by environmental organizations mainly includes direct project implementation expenses, technology research and development expenses, as well as expenses for public education and community participation. Environmental organizations need to invest funds in the research and application of monitoring, removal, and ecological restoration technologies for alien species. In addition, environmental organizations usually carry out environmental education and community participation activities to raise public awareness of the hazards of alien species and mobilize community forces to participate in wetland conservation, which also incurs certain costs.

C_a represents the carbon credits granted by government to environmental protection organization.

$lx_{C1}(t)$ represents the positive impact of reputation on government revenue under the mode of controlling species invasion. The positive impact of government reputation on its revenue growth is mainly reflected in enhancing public trust and opportunities for international cooperation. By successfully implementing alien species control projects, the government can demonstrate its leadership in ecological conservation and biodiversity maintenance, thereby attracting more domestic and foreign investment and funding. A good reputation helps the government promote the development of the carbon trading market, attract more companies to purchase carbon credits, and increase carbon trading revenue. In addition, the government can also gain more international cooperation opportunities and policy support by enhancing its reputation, such as participating in global ecological conservation initiatives or obtaining international environmental funds, further expanding funding sources, and providing sustained economic security for wetland management and ecological restoration. The improvement of reputation can also enhance the credibility of the government in society and promote public support for environmental policies. $lx_{C2}(t)$ represents the positive impact of reputation on environmental protection organization revenue under the mode of controlling species invasion. The positive impact of the reputation of environmental organizations on their income is mainly reflected in attracting more donations, funding, and partners. Environmental organizations can demonstrate their professional capabilities and ecological conservation achievements by effectively implementing alien species control projects, thereby winning the trust and support of the public and businesses. A good reputation helps environmental organizations obtain more public welfare funds, government subsidies, and international project funding (Menezes and Peci, 2023). In addition, environmental organizations can increase their revenue through carbon credit trading, as their reputation enhances the market value of carbon credits and attracts more buyers. The improvement of reputation also brings more opportunities for environmental organizations to collaborate, such as joint projects with research institutions or enterprises, further expanding their sources of income. By enhancing their reputation, environmental organizations can not only receive more financial support, but also strengthen their influence and voice in the field of environmental protection, providing strong guarantees for wetland ecological restoration and sustainable development.

The change in the reputation of government and environmental organizations under the mode of controlling invasive species can be expressed as:

$$\dot{x}_{C1}(t) = a_1 G_{C1}(t) - \delta x_{C1}(t) \tag{11}$$

$$\dot{x}_{C2}(t) = a_2 G_{C2}(t) - \delta x_{C2}(t) \tag{12}$$

In the above formula (Equations 11, 12), $a_1 G_{C1}(t)$ represents the reputation of the government for managing wetlands. The reputation of government managed wetlands is mainly reflected in their ability to respond to ecological threats and maintain ecological balance. By effectively implementing alien species control projects, the government can demonstrate its leadership and execution in protecting wetland ecosystems, preventing biodiversity loss, and maintaining carbon sequestration functions. Successful alien species control projects not only help restore the ecological functions of wetlands, but also enhance public trust and support for government environmental policies. The accumulation of this reputation can attract more domestic and foreign investment and funding for the government, such as increasing revenue through carbon trading mechanisms or obtaining support from international environmental funds. In addition, a good reputation can enhance the government's credibility in the field of ecological protection, laying the foundation for the implementation of future policies and the sustainable development of wetland management. $\delta x_{C1}(t)$ represents the decline of the government's reputation. $a_2 G_{C2}(t)$ represents the reputation of environmental organizations for managing wetlands. The reputation of environmental organizations in managing wetlands is mainly reflected in their professional capabilities and ecological restoration achievements. By successfully implementing alien species control projects, environmental organizations can demonstrate their professional level in addressing ecological threats, restoring wetland ecosystems, and maintaining biodiversity. The accumulation of this reputation helps environmental organizations win the trust and support of the public, businesses, and governments, thereby gaining more opportunities for donations, funding, and cooperation. For example, environmental organizations can increase their revenue through carbon credit trading, as their reputation enhances the market value of carbon credits and attracts more buyers. In addition, a good reputation can enhance the influence of environmental organizations in the field of ecological protection, creating favorable conditions for their participation in international environmental initiatives or obtaining international project funding, thereby providing more resources for the sustainable development of wetland management. $\delta x_{C2}(t)$ represents the decline of environmental organizations' reputation.

3 Results of differential game models

In the differential game, the governance of wetland ecosystem by government and environmental organizations 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 used. The HJB formula is a partial differential equation, which is the core of optimal control.

3.1 HJB formula

Under the mode of restoring water resources, this study, with the government and environmental organizations as the game participants and based on the carbon trading mechanism for wetland water resource restoration management, considers the strategic choices of both parties in water resource restoration. By incorporating the dynamic changes over time in costs (e.g., financial investment, technological costs) and benefits (e.g., carbon trading revenues, reputation gains), and based on optimal control theory, a partial differential equation concerning the value functions of both parties is constructed. Specifically, the Hamilton-Jacobi-Bellman (HJB) equation under the mode of restoring water resources is established to solve for the optimal strategies of both parties. The HJB equation of the social welfare function of the government and environmental organizations are as Equations 13, 14:

$$\rho V_{R1} = \max_{G_{R1}(t)} \left\{ \left[(b_1 + b_R) G_{R1}(t) - \frac{c_1}{2} G_{R1}^2(t) - C_a + l x_{R1}(t) + \frac{\partial V_{R1}}{\partial x_{R1}} \left[a_1 G_{R1}(t) - \delta x_{R1}(t) \right] \right] \right\} \tag{13}$$

$$\rho V_{R2} = \max_{G_{R2}(t)} \left\{ \left[b_2 G_{R2}(t) - \frac{c_2}{2} G_{R2}^2(t) + C_a + l x_{R2}(t) \right] + \frac{\partial V_{R2}}{\partial x_{R2}} \left[(a_2 + a_R) G_{R2}(t) - \delta x_{R2}(t) \right] \right\} \tag{14}$$

In the context of wetland vegetation diversification management based on carbon trading, with the government and environmental organizations as the primary game participants, this study incorporates the state variables of the vegetation diversification process, the control strategy variables of both parties in terms of financial investment, technical support, and human resource allocation, as well as the dynamic relationships over time between the resulting costs (including resource consumption and financial expenditure) and benefits (such as carbon sequestration revenue and ecological reputation). Following the principles of optimal control theory, a partial differential equation describing the optimal value functions of both parties is constructed, thereby establishing the Hamilton-Jacobi-Bellman (HJB) equation under the mode of diversifying vegetation. This equation is used to determine the optimal strategies of both parties in their pursuit of benefit maximization. The HJB equation of the social welfare function of the government and environmental organizations are as Equations 15, 16:

$$\rho V_{D1} = \max_{G_{D1}(t)}\left\{\left[b_1 \ln(1+p)G_{D1}(t) - \frac{c_1}{2}G_{D1}^2(t) - C_a + lx_{D1}(t)\right] + \frac{\partial V_{D1}}{\partial x_{D1}}\left[(a_1+a_D)G_{D1}(t) - \delta x_{D1}(t)\right]\right\} \tag{15}$$

$$\rho V_{D2} = \max_{G_{D2}(t)}\left\{\left[b_2 \ln(1+p)G_{D2}(t) - \frac{c_2}{2}G_{D2}^2(t) + C_a + lx_{D1}(t)\right] + \frac{\partial V_{D2}}{\partial x_{D2}}\left[(a_2+a_D)G_{D2}(t) - \delta x_{D2}(t)\right]\right\} \tag{16}$$

In the management model of controlling invasive species in wetlands based on carbon trading, with the government and environmental organizations as the game participants, this study considers the population of invasive species and the ecological condition of wetlands as state variables, and the actions of both parties in monitoring, application of control measures, and financial investment as control variables. By integrating time-varying factors such as control costs, carbon trading revenues, and ecological improvement benefits, and based on the principles of optimal control theory, a partial differential equation is constructed to characterize the value functions under the optimal strategies of both parties. Specifically, the Hamilton-Jacobi-Bellman (HJB) equation under this management model is established. Under the mode of controlling invasive species, the HJB equation of the social welfare function of the government and environmental organizations are as Equations 17, 18:

$$\rho V_{C1} = \max_{G_{C1}(t)}\left\{\left[b_1 G_{C1}(t) - \frac{c_1}{2\ln(1+h)}G_{C1}^2(t) - C_a + lx_{C1}(t)\right] + \frac{\partial V_{C1}}{\partial x_{C1}}\left[a_1 G_{C1}(t) - \delta x_{C1}(t)\right]\right\} \tag{17}$$

$$\rho V_{C2} = \max_{G_{C2}(t)}\left\{\left[b_2 G_{C2}(t) - \frac{c_2}{2\ln(1+h)}G_{C2}^2(t) + C_a + lx_{C2}(t)\right] + \frac{\partial V_{C2}}{\partial x_{C2}}\left[a_2 G_{C2}(t) - \delta x_{C2}(t)\right]\right\} \tag{18}$$

3.2 Result of equilibrium in differential game models

Proposition 1: Under the mode of restoring water resources, the control degree of wetland ecosystem and social benefits of government and environmental organizations are respectively Equations 19–22 (the specific solving procedure is shown in Appendix 1):

$$G_{R1}^*(t) = \frac{b_1 + b_R + a_1\frac{l}{\rho+\delta}}{c_1} \tag{19}$$

$$G_{R2}^*(t) = \frac{b_2 + \frac{l}{\rho+\delta}a_2 + \frac{l}{\rho+\delta}a_R}{c_2} \tag{20}$$

$$\begin{aligned} V_{R1}^* &= \frac{l}{\rho+\delta}x_{R1} + \frac{1}{\rho}(b_1+b_R)\frac{b_1+b_R+a_1\frac{l}{\rho+\delta}}{c_1} \\ &\quad - \frac{c_1}{2}\frac{1}{\rho}\left(\frac{b_1+b_R+a_1\frac{l}{\rho+\delta}}{c_1}\right)^2 - \frac{1}{\rho}C_a \\ &\quad + \frac{l}{\rho+\delta}\frac{1}{\rho}a_1\frac{b_1+b_R+a_1\frac{l}{\rho+\delta}}{c_1} \end{aligned} \tag{21}$$

$$\begin{aligned} V_{R2}^* &= \frac{l}{\rho+\delta}x_{R2} + \frac{1}{\rho}b_2\frac{b_2+\frac{l}{\rho+\delta}a_2+\frac{l}{\rho+\delta}a_R}{c_2} \\ &\quad - \frac{c_2}{2}\frac{1}{\rho}\left(\frac{b_2+\frac{l}{\rho+\delta}a_2+\frac{l}{\rho+\delta}a_R}{c_2}\right)^2 + \frac{1}{\rho}C_a + \frac{l}{\rho+\delta}\frac{1}{\rho}(a_2 \\ &\quad + a_R)\frac{b_2+\frac{l}{\rho+\delta}a_2+\frac{l}{\rho+\delta}a_R}{c_2} \end{aligned} \tag{22}$$

Conclusion 1: The greater the benefit generated by facilitating residents' use of water resources, the greater the degree of government's governance of wetlands. The greater the additional reputation gained by restoring water resources per unit, the greater the degree of environmental protection organizations' governance of wetlands.

Conclusion 1 implies that in water resource restoration projects, the government places greater emphasis on enhancing socio-economic benefits, while environmental organizations prioritize the accumulation of reputation. Therefore, in wetland management, the government should prioritize supporting water resource restoration projects that significantly improve the quality of life for residents, while simultaneously encouraging active participation from environmental organizations through policy incentives such as carbon trading revenues or reputation rewards. This dual-pronged strategy can maximize the comprehensive benefits of wetland management.

Proposition 2: Under the mode of diversifying vegetation, the control degree of wetland ecosystem and social benefits of government and environmental organizations are respectively Equations 23–26 (the specific solving procedure is shown in Appendix 2):

$$G_{D1}^*(t) = \frac{b_1\ln(1+p) + \frac{l}{\rho+\delta}(a_1+a_D)}{c_1} \tag{23}$$

$$G_{D2}^*(t) = \frac{b_2\ln(1+p) + \frac{l}{\rho+\delta}(a_2+a_D)}{c_2} \tag{24}$$

$$\begin{aligned} V_{D1}^* &= \frac{l}{\rho+\delta}x_{D1} + \frac{1}{\rho}b_1\ln(1+p)\frac{b_1\ln(1+p)+\frac{l}{\rho+\delta}(a_1+a_D)}{c_1} \\ &\quad - \frac{c_1}{2}\frac{1}{\rho}\left[\frac{b_1\ln(1+p)+\frac{l}{\rho+\delta}(a_1+a_D)}{c_1}\right]^2 - \frac{1}{\rho}C_a \\ &\quad + \frac{\partial V_{D1}}{\partial x_{D1}}\frac{1}{\rho}(a_1+a_D)\frac{b_1\ln(1+p)+\frac{l}{\rho+\delta}(a_1+a_D)}{c_1} \end{aligned} \tag{25}$$

$$V_{D2}^{*}=\frac{1}{\rho}b_2\ln(1+p)\frac{b_2\ln(1+p)+\frac{l}{\rho+\delta}(a_2+a_D)}{c_2}-\frac{c_2}{2}\frac{1}{\rho}\left[\frac{b_2\ln(1+p)+\frac{l}{\rho+\delta}(a_2+a_D)}{c_2}\right]^2+\frac{1}{\rho}C_a+\frac{l}{\rho+\delta}\frac{1}{\rho}(a_2+a_D)\frac{b_2\ln(1+p)+\frac{l}{\rho+\delta}(a_2+a_D)}{c_2}+\frac{l}{\rho+\delta}x_{D2} \tag{26}$$

Conclusion 2: The greater the additional reputation per unit of vegetation diversity, the greater the degree of government and environmental organizations' management of wetlands.

Conclusion 2 demonstrates that vegetation diversification not only enhances the stability of wetland ecosystems but also generates significant reputational benefits for both the government and environmental organizations. Therefore, in wetland management, priority should be given to promoting vegetation diversification projects, with support provided through carbon trading mechanisms or policy subsidies. The government and environmental organizations can collaborate synergistically, leveraging their respective strengths to jointly enhance wetland vegetation diversity, thereby achieving a win-win scenario of ecological benefits and reputational gains.

Proposition 3: Under the mode of controlling invasive species, the control degree of wetland ecosystem and social benefits of government and environmental organizations are respectively Equations 27–30 (the specific solving procedure is shown in Appendix 3):

$$G_{C1}^{*}(t)=\frac{\left(b_1+\frac{l}{\rho+\delta}a_1\right)\ln(1+h)}{c_1} \tag{27}$$

$$G_{C2}^{*}(t)=\frac{\left(b_2+\frac{l}{\rho+\delta}a_2\right)\ln(1+h)}{c_2} \tag{28}$$

$$V_{C1}^{*}=\frac{l}{\rho+\delta}x_{C1}+\frac{1}{\rho}b_1\frac{\left(b_1+\frac{l}{\rho+\delta}a_1\right)\ln(1+h)}{c_1}-\frac{c_1}{2\ln(1+h)}\frac{1}{\rho}\left[\frac{\left(b_1+\frac{l}{\rho+\delta}a_1\right)\ln(1+h)}{c_1}\right]^2-\frac{1}{\rho}C_a+\frac{l}{\rho+\delta}\frac{1}{\rho}a_1\frac{\left(b_1+\frac{l}{\rho+\delta}a_1\right)\ln(1+h)}{c_1} \tag{29}$$

$$V_{C2}^{*}=\frac{l}{\rho+\delta}x_{C2}+\frac{1}{\rho}b_2\frac{\left(b_2+\frac{l}{\rho+\delta}a_2\right)\ln(1+h)}{c_2}-\frac{c_2}{2\ln(1+h)}\frac{1}{\rho}\left[\frac{\left(b_2+\frac{l}{\rho+\delta}a_2\right)\ln(1+h)}{c_2}\right]^2+\frac{1}{\rho}C_a+\frac{l}{\rho+\delta}\frac{1}{\rho}a_2\frac{\left(b_2+\frac{l}{\rho+\delta}a_2\right)\ln(1+h)}{c_2} \tag{30}$$

Conclusion 3: The greater the difficulty of controlling invasive species, the greater the degree of wetland management by governments and environmental organizations.

According to conclusion 3, in wetland management, particular attention should be paid to the prevention and control of invasive species, and long-term management plans should be formulated. The government can alleviate the pressure on environmental organizations through policy support, such as dedicated funding or technical assistance, while environmental organizations can leverage their professional expertise to collaborate with the government in addressing the challenges posed by invasive species, thereby ensuring the health and stability of wetland ecosystems.

3.3 Case analysis

In order to describe the change of social utility of government and environmental organizations in more detail in the process of controlling wetland ecosystem, numerical analysis is used in this article. Dongting Lake is one of China's critical freshwater wetlands, which in recent years has faced challenges such as water resource shortages, vegetation degradation, and the spread of invasive species due to human activities and climate change (Xiong and Yang, 2025). To restore wetland ecological functions and enhance carbon sequestration capacity, the local government has collaborated with environmental organizations to implement comprehensive management measures, including water resource restoration, vegetation diversification, and invasive species control. In line with China's "Opinions on Deepening the Reform of the Ecological Protection Compensation System," which emphasizes "improving the ecological protection compensation mechanism for wetlands and gradually achieving full coverage of ecological protection compensation for nationally important wetlands (including internationally important wetlands)," these policy documents have established institutional arrangements for a long-term mechanism of wetland ecological protection compensation, integrating it with carbon trading mechanisms.

In the context of the Dongting Lake wetland conservation and carbon sequestration project in China, the cost for the government or environmental organizations to manage a unit of wetland is relatively high, primarily due to the complex technologies and long-term investments involved in wetland management. For instance, water resource restoration requires the construction of hydraulic facilities, vegetation diversification necessitates the introduction of native species and continuous monitoring, and invasive species control demands regular removal and surveillance. These measures all require substantial financial, human, and technical support (Thieme et al., 2024). In contrast, the benefits of facilitating residents' access to water resources are primarily reflected in the short-term improvement of residents' quality of life and the promotion of regional economic development. These benefits are more direct and easily quantifiable, making them more prominent in cost-benefit analyses.

However, while the benefits of facilitating residents' access to water resources are significant, their impact on enhancing the reputation of the government or environmental organizations is relatively limited. The unit reputation of wetland management is more closely tied to long-term ecological benefits and carbon sequestration capacity. Although these benefits contribute substantially to ecological health and climate change mitigation, their effects are more indirect and difficult to manifest in the short term. Therefore, in the short term, the benefits of providing water access to residents may be perceived as greater than the unit reputation of wetland management. However, in the long term, the ecological benefits and reputation accumulation from wetland management are more critical for sustainable development. This trade-off relationship provides an important basis for the analysis of differential game models. For convenience, this paper hypothesizes that the cost c_1,c_2 of government or environmental organizations to control a unit of wetland is 3; the reputation a_1, a_2 of a government or environmental organizations for managing wetlands at the unit level is 2; the benefits b_R of facilitating residents' access to water resources is 2.5.

In the Dongting Lake wetland conservation and carbon sequestration project in China, the difficulty of controlling invasive species is significantly greater than the propagation rate of vegetation, primarily due to the strong adaptability and dispersal capabilities of invasive species. For example, invasive species such as water hyacinth can rapidly reproduce and occupy ecological niches under favorable conditions, forming monoculture dominant communities that suppress the growth of native vegetation (Hussein et al., 2024). Moreover, the eradication of invasive species requires sustained human, material, and technical resources, including physical removal, chemical control, and biological management. These measures are not only costly but also often yield temporary results, with a high likelihood of recurrence (Arasumani et al., 2025). In contrast, although the propagation rate of vegetation is constrained by environmental conditions, the restoration and reproduction of native vegetation are relatively controllable through proper water resource management and species introduction. Additionally, natural succession can gradually enhance the stability of the ecosystem.

On the other hand, the control of invasive species also involves complex ecological and anthropogenic factors. For instance, water resource restoration may create favorable conditions for invasive species, while vegetation diversification, although helpful in suppressing invasive species, requires a longer time to demonstrate its effects. Additionally, the control of invasive species often necessitates cross-regional collaboration and long-term monitoring, which places higher demands on the coordination capabilities and resource investments of managers (Hussein et al., 2024). In contrast, the propagation rate of vegetation is more dependent on local environmental conditions and management measures, and its restoration effects can be observed in the short term, making its management relatively less challenging. Therefore, the difficulty of controlling invasive species far exceeds that of managing vegetation propagation, representing a significant challenge in wetland management. For convenience, this paper hypothesizes that the reproductive rate p of vegetation is 2. The difficulty h of controlling invasive species is 3.

Meanwhile, the paper makes the following assumptions about other variables that do not affect the results. The discount rate ρ that occurs over time is 0.9. Decay δ of reputation is 0.1. The positive impact l of reputation per unit quantity is 1. Carbon credits C_a allocated by the government to environmental organizations is 12. When the additional reputation a_R for restoring a unit amount of water or the additional reputation a_D for a unit of vegetation diversity are 1, this article can calculate the social benefits of government as Equations 31–33:

$$V_{R1}^{*} = -12.33 + 0.185(b_1 + 4.5)^2 \tag{31}$$

$$V_{D1}^{*} = -12.33 + 0.185(1.1b_1 + 3)^2 \tag{32}$$

$$V_{C1}^{*} = -12.33 + 0.2(b_1 + 2)^2 \tag{33}$$

The following graph (named Figure 3) can also be produced:

When the additional reputation for restoring a unit amount of water or the additional reputation for a unit of vegetation diversity is relatively small, regardless of how the ecological benefits from the management of wetlands at a unit scale by the government vary, the economic returns from the restore water resources mode will dominate the strategy. Due to insufficient reputational incentives, economic returns become the key factor in government decision-making, thereby controlling the dominant strategy in wetland management. Specifically, the government may prioritize actions related to water resource restoration that yield greater economic benefits. For details, please refer to Figure 3.

When the additional reputation a_R for restoring a unit amount of water or the additional reputation a_D for a unit of vegetation diversity are 3, this article can calculate the social benefits of government as Equations 34–36:

$$V_{R1}^{*} = -12.33 + 0.185(b_1 + 4.5)^2 \tag{34}$$

$$V_{D1}^{*} = -12.33 + 0.185(1.1b_1 + 5)^2 \tag{35}$$

$$V_{C1}^{*} = -12.33 + 0.2(b_1 + 2)^2 \tag{36}$$

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

When the additional reputation for restoring a unit amount of water or the additional reputation for a unit of vegetation diversity is relatively large, regardless of how the ecological benefits from the management of wetlands at a unit scale by the government vary, the economic returns from the diversify vegetation mode will dominate the strategy. This is because the reputational incentives are already sufficiently strong, and economic returns become the new critical consideration. As a result, in the government's strategic choices for wetland management, priority will be given to actions that generate greater economic benefits from the vegetation diversification mode. Consequently, the economic returns of the vegetation diversification mode will control the government's dominant strategy. For details, please refer to Figure 4.

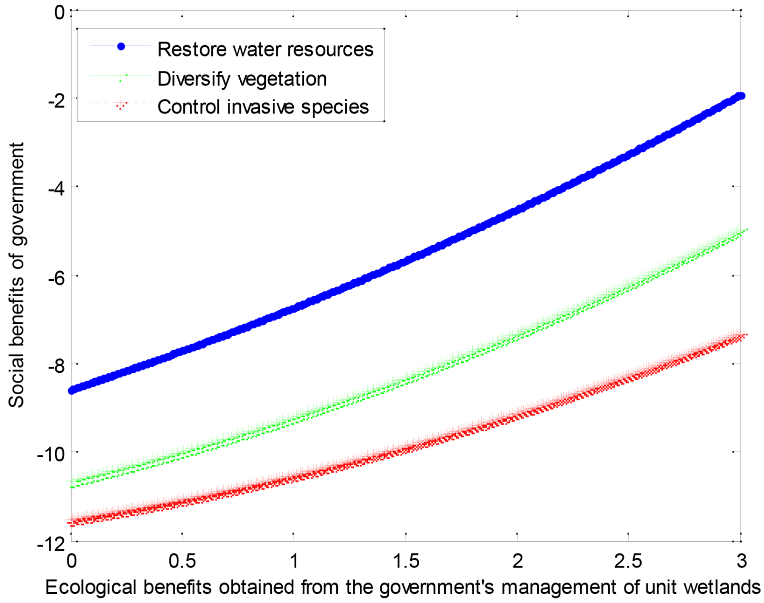

FIGURE 3
Impact of ecological benefits of government on social welfare.

Conclusion 4: The government can obtain the maximum benefit by choosing the restoration mode of water resources quantity if the additional reputation gained by restoring water resources quantity per unit is small. The government can obtain the maximum benefit by choosing the management mode of diversifying vegetation if the additional reputation gained by restoring water resources quantity per unit is large.

When the additional reputation a_R for restoring a unit amount of water or the additional reputation a_D for a unit of vegetation diversity are 1, this article can calculate the social benefits of environmental organizations as Equations 37–39:

$$V_{R2}^{*} = 14.33 + 0.185(b_2 + 3)^2 \tag{37}$$

$$V_{D1}^{*} = 14.33 + 0.185(1.1b_2 + 3)^2 \tag{38}$$

$$V_{C1}^{*} = 14.33 + 0.256(b_2 + 2)^2 \tag{39}$$

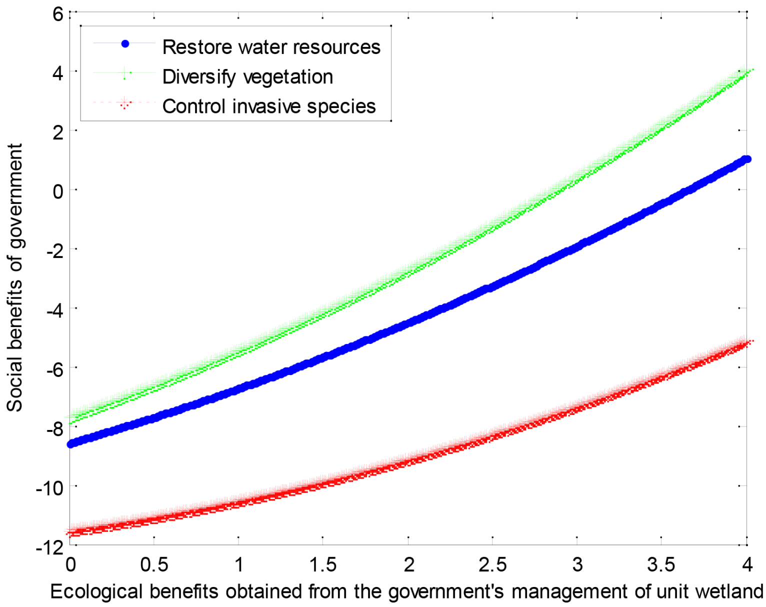

FIGURE 4
Impact of ecological benefits of government on social welfare.

The following graphs (named Figures 5, 6) can also be produced:

When the additional reputation for restoring a unit amount of water or the additional reputation for a unit of vegetation diversity is relatively small, and the ecological benefits from the management of wetlands at a unit scale by environmental organizations are also limited, the economic returns from the diversify vegetation mode will dominate the strategy for environmental organizations. Under this dual disadvantage, environmental organizations, when formulating wetland management strategies, will prioritize factors that yield tangible economic returns. Since both reputational incentives and ecological benefit incentives are insufficient at this stage, the economic returns of the vegetation diversification mode become the critical consideration. This will control the dominant strategy of environmental organizations in wetland management, leading them to favor action plans that generate greater economic benefits from the vegetation diversification mode. For details, please refer to Figure 5.

When the additional reputation for restoring a unit amount of water or the additional reputation for a unit of vegetation diversity is relatively small, and the ecological benefits from the management of wetlands at a unit scale by environmental organizations exceed a certain threshold, the economic returns from the controlling invasive species mode will dominate the strategy for environmental organizations. For details, please refer to Figure 6.

In the context of a differential game exploring effective wetland management based on carbon trading, the two participants in the game are the government and environmental organizations. When the additional reputation values for restoring a unit amount of water or achieving a unit of vegetation diversity are small, it implies that environmental organizations struggle to gain significant reputational incentives from actions related to water resource restoration and vegetation diversification. However, once the ecological benefits achieved by environmental organizations in the management of wetlands at a unit scale surpass a certain threshold, it indicates that environmental organizations have already attained considerable ecological achievements in wetland management, such as improving water quality and enhancing biodiversity. At this point, due to insufficient reputational incentives and the ecological benefits having reached a certain level, environmental organizations will shift their focus to economic returns. Among various wetland management modes, the economic returns of the controlling invasive species mode will become the key factor influencing the decision-making of environmental organizations, thereby controlling their dominant strategy. This will prompt environmental organizations to prioritize action plans that generate greater economic benefits from the controlling invasive species mode, aiming to maximize economic returns on the foundation of existing ecological achievements.

Conclusion 5: If the additional reputation gained by restoring water resources per unit is small and the benefit gained by managing wetlands per unit is small, then environmental organizations can get the maximum benefit by choosing the management mode of diversifying vegetation. If the additional reputation gained by restoring water resources per unit is small and the benefit gained by managing wetlands per unit is large, then environmental organizations can get the maximum benefit by choosing the management mode of controlling invasive species. It is worth noting that the social benefits of environmental organizations are greater than zero, mainly due to the carbon credits granted by the government to environmental organizations.

When the additional reputation a_R for restoring a unit amount of water or the additional reputation a_D for a unit of vegetation

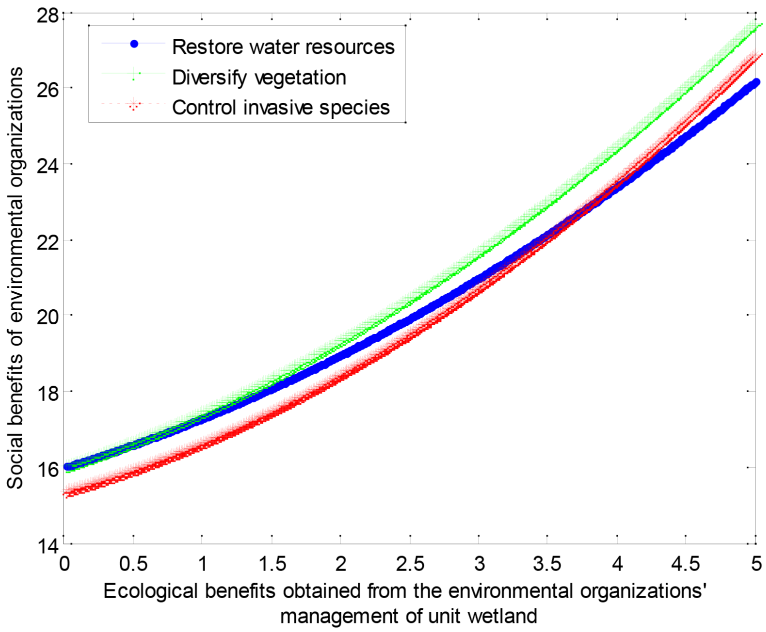

FIGURE 5
Impact of ecological benefits of environmental organizations on social welfare.

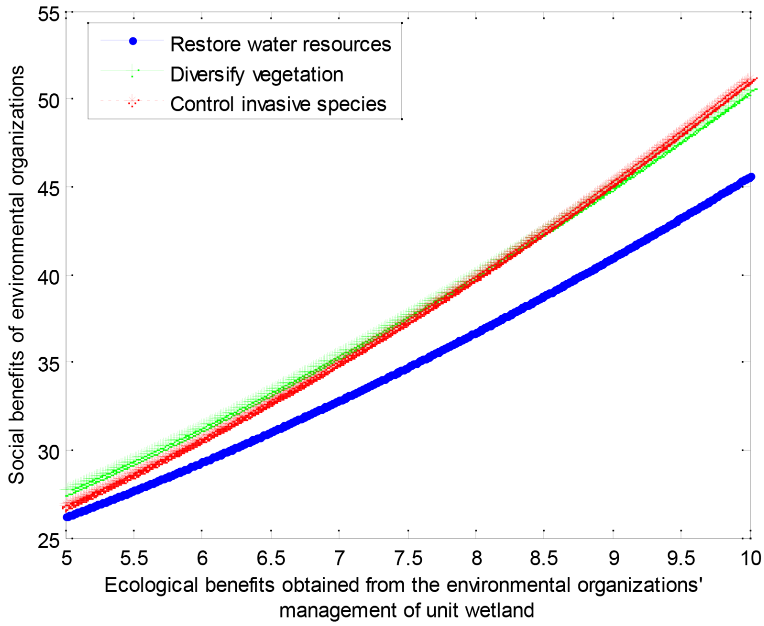

FIGURE 6
Impact of ecological benefits of environmental organizations on social welfare.

diversity are 3, this article can calculate the social benefits of environmental organizations as Equations 40–42:

$$V_{R2}^{*} = 14.33 + 0.185(b_2 + 5)^2 \quad (40)$$

$$V_{D1}^{*} = 14.33 + 0.185(1.1b_2 + 5)^2 \quad (41)$$

$$V_{C1}^{*} = 14.33 + 0.256(b_2 + 2)^2 \quad (42)$$

The following graph (named Figure 7) can also be produced:

When the additional reputation for restoring a unit amount of water or the additional reputation for a unit of vegetation diversity is relatively large, regardless of how the ecological benefits from the management of wetlands at a unit scale by environmental organizations vary, the economic returns from the diversify vegetation mode will dominate the strategy for environmental organizations. For details, please refer to Figure 7.

In the study of effective wetland management based on carbon trading using a differential game model, the two participants in the game are the government and environmental organizations. When the additional reputation for restoring a unit amount of water or the additional reputation for a unit of vegetation diversity is relatively large, it implies that environmental organizations can achieve significant reputational gains through actions related to water resource restoration and vegetation diversification. In this scenario, regardless of how the ecological benefits achieved by environmental organizations in the management of wetlands at a unit scale vary—whether their achievements in improving wetland ecosystems and enhancing biodiversity are high or low—the reputational incentives are already sufficiently strong. At this point, environmental organizations will place greater emphasis on economic factors in their decision-making process. The economic returns of the vegetation diversification mode thus become the critical consideration, controlling the dominant strategy of environmental organizations in wetland management. This leads environmental organizations to favor action plans that generate greater economic benefits from the vegetation diversification mode, aiming to pursue economic gains on the foundation of existing reputational incentives.

Conclusion 6: Environmental organizations can gain the most benefit from the management mode of diversifying vegetation if the additional reputation gained by restoring water resources per unit is large.

4 Discussion

According to conclusion 1, the greater the benefit of facilitating residents' use of water resources, the greater the degree of government governance of wetlands. This is similar to but different from the study of Canto-Perello et al. (2021). Canto-Perello et al. (2021) proposed that it is necessary to establish a water quality-centered sustainable development mode of water resources, and then determine the priority of governance. In this article, the degree of governance of wetlands is primarily determined by the social, economic, and ecological benefits they provide. Wetlands play an important role in the protection and regulation of water resources. Wetlands can play the role of natural filters, purifying water quality and preventing water pollution. Wetlands can also store water, maintain the balance of hydrological cycle and reduce the risk of flood disasters (Mirzaei and Zibaei, 2021). Therefore, the greater the degree of government governance of wetlands, the better

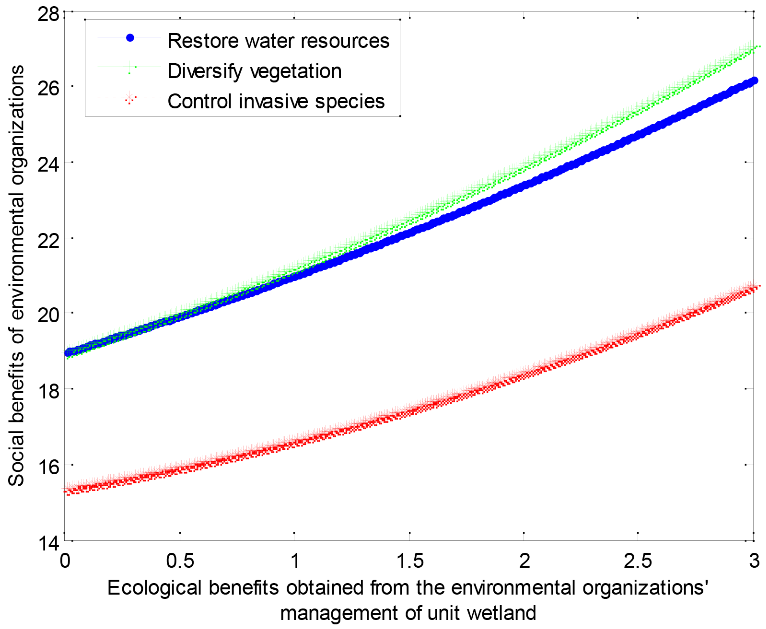

FIGURE 7
Impact of ecological benefits of environmental organizations on social welfare.

it can protect water resources, improve the effective utilization rate of water resources, and reduce the waste and pollution of water. Government governance of wetlands can be achieved in many ways, such as building water conservancy facilities, improving water quality, regulating the allocation of water resources. These measures can effectively protect water sources, provide sustainable water resources and water environment, and ensure the safe supply of water. Therefore, there is a close correlation between facilitating residents' use of water resources and government governance of wetlands. The greater the demand for water resources from residents, the more important the government's efforts in wetland protection and management to ensure sustainable use and equitable distribution of water resources.

Based on conclusion 1, the following measures can be implemented to effectively manage wetlands based on carbon trading. The government should actively enhance the efficiency of residents' utilization of water resources, increase investment in infrastructure such as water supply and irrigation around wetlands, and conduct educational campaigns on the rational use of water resources. Incentives such as subsidies or tax benefits should be provided to residents and environmental organizations that practice scientific water use. As the efficiency of residents' water use improves, the government should simultaneously increase funding for wetland management, allocating resources to ecological restoration, monitoring, and species control. Additionally, the government should formulate wetland conservation plans and policies, while strengthening regulatory enforcement (Bell-James et al., 2023). For environmental organizations, the government and society should jointly establish a reputational incentive system. Through official recognition, media publicity, and other means, environmental organizations should gain higher additional reputation for restoring a unit of water resources. This will motivate environmental organizations to enhance their efforts in wetland management, playing a greater role in water resource restoration, vegetation diversification, and invasive species control.

According to conclusion 2, the greater the additional reputation brought by the vegetation diversity per unit, the greater the degree of wetland governance by the government and environmental protection organizations. This is similar to the study of Li et al. (2022). Li et al. (2022) proposed that the spatial distribution of the importance of biodiversity conservation was inconsistent, and with the change of the threshold of the preferred protected area, the protection focus of the Sanjiangyuan National Park and the existing protected areas should be updated accordingly. There are the following reasons for this situation. First, vegetation diversity is one of the key indicators of the health and stability of the wetland ecosystem. When the vegetation diversity of a wetland area is high, it means that the wetland has more ecological service functions and biodiversity value (Campbell et al., 2024). The improvement of this reputation will attract the attention of the government and environmental protection organizations, and promote them to increase the governance and protection of the wetland. Second, the increase of the reputation brought by the vegetation diversity per unit means that the natural resources of the wetland have better sustainable utilization potential. The government and environmental protection organizations realize the importance of wetland protection and sustainable development, and they will increase the management and planning of wetland resources to ensure that the ecological functions and economic benefits of the wetland can be sustained in the long term. Third, wetlands with high reputation often receive attention and recognition from experts and scholars at home and abroad. Governments and environmental protection organizations tend to carry out research, project cooperation and international exchanges on these wetlands to learn from advanced experience and enhance the international influence of the wetland. Fourth, the greater the reputation brought by the additional vegetation diversity per unit, the greater the public's attention to wetland ecological protection will be. Public opinions have an impact on the decision-making of governments and environmental protection organizations. Wetlands with high reputation often receive more attention and protection, and governments and environmental protection organizations will increase the governance efforts to meet public expectations. Therefore, the greater the reputation brought by the additional vegetation diversity per unit, the greater the governance efforts of governments and environmental protection organizations will be to protect the ecosystem function of wetlands and promote sustainable development.

To effectively manage wetlands based on carbon trading, according to conclusion 2, the following measures can be implemented. The government, in collaboration with media, industry associations, and other stakeholders, should establish a comprehensive reputation evaluation and dissemination system. Government departments and environmental organizations that have made outstanding contributions to wetland vegetation diversification should be officially recognized, and their achievements should be widely publicized through mainstream media. Special honorary awards, such as the "Wetland Vegetation Protection Pioneer Award," should be established and periodically awarded. Simultaneously, the government should increase funding for wetland vegetation diversification projects and provide policy support to environmental organizations, such as streamlining project approval processes and offering tax incentives (Bell-James et al., 2023). Environmental organizations, on their part, should actively leverage reputational incentives to attract more social donations and volunteer participation. They should intensify efforts in wetland vegetation planting, maintenance, and species introduction, while collaborating with research institutions to conduct studies on vegetation diversity. These actions will enhance the stability of wetland ecosystems and ultimately achieve effective wetland management (Bai et al., 2025).

According to conclusion 3, the greater the difficulty coefficient of controlling invasive species, the greater the degree of wetland governance by governments and environmental protection organizations. This is different from the study of Zhang B. et al. (2021). Zhang B. et al. (2021) proposed that under the condition of limited budget, it is more effective to prioritize the control effect on areas with high population density, and vice versa, it is better to implement balanced control effect on areas with high population density. Zhang B. et al. (2021) mainly considered the fund aspect, while this article mainly considered the difficulty of control. Specifically, the conclusion 3 is caused by the following reasons. First, invasive species may have a serious impact on the native biodiversity and ecological balance of wetlands. Invasive species that are difficult to control may rapidly reproduce and occupy the resources and habitats of wetland ecosystems, harming the native plant and animal populations. Aware of the destructiveness of invasive species, governments and environmental protection organizations will increase the efforts to govern wetlands to protect the ecological balance. Second, invasive species have a negative impact on the economic value and ecological service function of wetlands. The failure to effectively control invasive species will lead to the reduction of ecological functions of wetlands, such as water quality deterioration and reduction of fishery resources. Governments and environmental organizations will realize these losses and take measures to manage the wetlands to maintain their economic and ecological values. Third, the existence of invasive species may pose a threat to local ecosystems and communities. They may bring problems such as disease transmission, crop destruction, ecosystem degradation, and other problems, which have a negative impact on local life and health. Governments and environmental organizations will take action to mitigate these threats and protect the wetlands and their surrounding ecosystems and communities by controlling and managing invasive species. Fourth, the problem of invasive species usually crosses national boundaries, and transnational cooperation is one of the important means to solve the problem of invasive species. When the difficulty of management increases, governments and environmental organizations will tend to strengthen international cooperation and consensus, and solve the problem of invasive species through joint efforts to protect the ecological environment of wetlands. In reality, UNESCO is an international organization with extensive influence, playing a significant role in promoting global cooperation in culture, science, and education (Matias et al., 2025). In the field of wetland ecological conservation, especially in the face of increasing challenges in invasive species management, it facilitates international cooperation through various means. For instance, it organizes workshops, training programs, and other initiatives to provide a platform for governments and environmental organizations to exchange management experiences and technologies (Klaver et al., 2024). UNESCO has established a series of international conventions and guiding principles, which provide a framework and guidelines for cooperation among countries in related fields. In the context of invasive species management in wetlands, these conventions and principles can standardize the behavior of nations and foster consensus. For example, they may outline the responsibilities and obligations of countries in monitoring and controlling invasive species, as well as mechanisms for information sharing. In summary, the greater the difficulty of controlling invasive species, the more governments and environmental organizations will realize its destructiveness and challenge to wetlands, and thus increase the degree of management of wetlands to maintain the ecological balance, economic value, and community well-being of wetlands.

Based on conclusion 3, the following measures can be implemented to effectively manage wetlands based on carbon trading. The government should take the lead in forming a multidisciplinary expert team to conduct a comprehensive assessment of the current status, spread trends, and control difficulties of invasive species in wetlands. Based on the assessment results, a tiered management strategy should be formulated. For areas with high control difficulty, the government should increase funding and establish a dedicated management fund to purchase advanced monitoring equipment, control tools, and chemicals. Simultaneously, preferential policies should be introduced to encourage environmental organizations to participate in the management of high-difficulty invasive species, such as offering tax reductions and project subsidies. Environmental organizations, leveraging their professional expertise, should actively conduct research on high-difficulty invasive species and explore innovative management methods, such as biological control technologies and ecological restoration approaches (Duncan et al., 2023). Collaboration with communities and volunteers should be strengthened to expand the management team and improve efficiency. Additionally, the government and environmental organizations should jointly establish an information-sharing platform to promptly release relevant information and progress on invasive species management, attracting attention and support from all sectors of society. This will foster a positive atmosphere of collective participation in wetland management, using carbon trading as an economic incentive to drive the sustained and in-depth advancement of wetland management efforts (Bai et al., 2025).

Conclusion 4 has similarities with the research of Ranjan (2021). Ranjan (2021) established a payment mechanism for ecosystem services, where farmers could be compensated for discharging treated wastewater into streams flowing into natural wetlands. When the additional reputation gained by restoring the quantity of water resources per unit is small, the reasons for choosing the restoration of water quantity mode can achieve the maximum benefit are as follows. First, the focus is on water supply. In this case, the government pays more attention to the quantity and availability of water resources. Choosing the restoration of water quantity mode means that the government will prioritize increasing the quantity of water resources to meet the growing demand for water, such as drinking water, agricultural irrigation and industrial water. This can improve the efficiency of social development and economic growth. Second, economic benefits are the main consideration. When the additional reputation gained by restoring the quantity of water resources per unit is small, the government pays more attention to economic benefits. The restoration of water quantity mode can reduce the scarcity and cost of water resources by increasing the supply of water resources, improve the efficiency of water resource utilization, and thus promote the sustainable development of the economy (Li et al., 2021a). When the additional reputation gained by restoring the quantity of water resources per unit is large, the reasons for choosing the governance mode of diversifying vegetation to achieve the maximum benefit are as follows. First, ecological environment protection and improvement. In this case, the government pays more attention to protecting and improving the quality and sustainability of the ecological environment. By choosing the governance mode that diversify vegetation, the government can pay attention to the protection and increase of vegetation while restoring water resources. Vegetation diversity plays an important role in maintaining ecological balance, protecting soil and water resources, reducing water pollution and soil erosion. Second, enhancing reputation and sustainable development. When the additional reputation gained is large, the governance mode of diversifying vegetation can achieve remarkable achievements in environmental protection and increase the national reputation. Vegetation diversification can also provide better public landscape and ecotourism resources, which promote sustainable development and related economic activities. To sum up, according to the additional reputation gained by restoring the water resources per unit level, the government can choose different governance modes to obtain the maximum benefit. The mode of restoring water resources will focus on water resources supply and economic benefits, while the mode of diversifying vegetation will focus on ecological environment protection and improvement, enhancing reputation and sustainable development.

Based on conclusion 4, to effectively manage wetlands based on carbon trading, governments and environmental organizations can adopt different strategies depending on the additional reputation gained per unit of water resource restoration. The government should first establish a scientific reputation evaluation system to accurately measure the additional reputation derived from the restoration of a unit of water resources. If the assessment indicates that the additional reputation gained per unit of water resource restoration is minimal, the government should opt for a water resource restoration model. This involves increasing investment in wetland water supply projects, such as constructing water diversion channels, reservoirs, and other hydraulic facilities, while strengthening water resource supervision to prevent waste and pollution, thereby achieving effective water resource restoration. If the additional reputation gained per unit of water resource restoration is significant, the government should choose a vegetation diversification management model. This includes formulating vegetation planting plans, introducing native plant species suitable for wetland growth to enhance vegetation diversity, and establishing ecological compensation mechanisms to encourage local residents to participate in vegetation protection. Throughout this process, environmental organizations should actively collaborate with the government, conducting educational campaigns to raise public awareness of wetland conservation. Depending on the governments' chosen model, they should provide technical support in areas such as water resource monitoring and vegetation maintenance from a professional perspective, promoting the sustainable development of wetland management (Duncan et al., 2023).

According to conclusion 5 and conclusion 6, environmental organizations can achieve the maximum benefit by choosing the governance mode of controlling species invasion if the additional reputation gained by restoring water resources per unit level is small and the revenue gained by governing wetlands per unit level is large. This is different from the viewpoint of Fuentes et al. (2015). Fuentes et al. (2015) proposed that the population number is proportional to the degree of invasion of alien species. He started from the aspect of economic activities, while this article starts from the aspect of reputation and revenue.

The specific reasons for conclusion 5 and conclusion 6 are as follows. First, focus on wetland governance. In this case, environmental organizations pay more attention to wetland governance and protection. Wetlands are important ecosystems, which play an important role in water resource supply, water quality purification, biodiversity maintenance and other aspects. Choosing the governance mode of controlling means that environmental organizations will prioritize the control impact from invasive species and maintain the healthy ecosystem of wetlands. Second, revenue from wetland governance. Governing wetlands per unit level can bring a large revenue. By controlling, environmental organizations can protect the diversity and reproduction of local species, and maintain the stability and function of wetland ecosystems. This will bring direct benefits to society and local economy, such as ecotourism, fishing, medicinal plants and sustainable use of water resources (Ando and Getzner, 2006). On the other hand, if the additional reputation of restoring water resources per unit level is small, but the income of regulating wetlands per unit level is low, environmental organizations can choose the governance mode of diversifying vegetation to obtain the maximum benefit. This is because diversifying vegetation can provide a better ecological environment for wetlands, promote the stability of ecosystems and provide other ecological services, including soil protection, habitat and carbon absorption. In summary, environmental organizations can choose different governance modes to obtain the maximum benefit according to the additional reputation of restoring water resources per unit level and the income of regulating wetlands per unit level. The governance mode of controlling invasive species focuses on wetland governance and income sources, while the governance mode of diversifying vegetation focuses on providing a better ecological environment and additional ecological services.

Based on conclusions 5 and 6, to effectively manage wetlands based on carbon trading, and considering the revenue outcomes of environmental organizations under different conditions, the following operational plan can be implemented. The government needs to establish a precise evaluation mechanism to measure the additional reputation gained from unit water resource restoration and the benefits derived from unit wetland management. When the assessment indicates that the additional reputation from unit water resource restoration is low and the benefits from unit wetland management are also low, environmental organizations should opt for a vegetation diversification management model. In this scenario, environmental organizations can collaborate with research institutions to select diverse plant species suitable for local wetland conditions, develop detailed vegetation planting and maintenance plans, and conduct public education campaigns to encourage volunteer participation in vegetation planting. The government, through the carbon trading mechanism, should provide corresponding carbon credits to environmental organizations to compensate for their costs and incentivize their continued efforts (Pande, 2024). When the additional reputation from unit water resource restoration is low but the benefits from unit wetland management are high, environmental organizations should shift to an invasive species control management model. Environmental organizations can form specialized monitoring teams to track the distribution and spread of invasive species in real time, employing physical, chemical, or biological control methods for management. Similarly, the government, in accordance with carbon trading rules, should offer more carbon credit rewards to environmental organizations, ensuring that while they achieve positive social benefits, their economic interests are also safeguarded. This will motivate environmental organizations to participate more actively in wetland management.

Although this study employs a differential game model to explore wetland management issues based on carbon trading, with the players being the government and environmental organizations, it still has certain limitations. The decisions of both parties in the model (government and environmental organizations) can be objectively evaluated by the public and directly affect their reputation. However, in reality, the public's judgment of government behavior is often influenced by information asymmetry, media bias, or personal subjective tendencies, making it difficult to fully observe objectively. In addition, the model did not fully consider the complex social, economic, and political factors in the policy implementation process, such as local interest conflicts, uneven distribution of funds, or low implementation efficiency, which may weaken the actual effectiveness of wetland management policies. At the same time, the implementation of carbon trading mechanisms also faces challenges such as market volatility, inadequate regulation, and uncertainty in the value of carbon credits, which may affect the decisions and returns of both parties in the game. Therefore, the research results may be limited in practical applications and need to be further validated and adjusted in conjunction with specific contexts.

5 Conclusion

This article proposes three modes to manage wetland ecosystems: restore water resources, diversify vegetation and control invasive species. Considering the continuous change of wetland ecosystems over time, this article constructs a differential game model for the three control modes. The results show that if the additional reputation gained by restoring water resources per unit is small, the government can achieve the maximum benefit by choosing the restoration mode. If the additional reputation gained by restoring water resources per unit is large, the government can achieve the maximum benefit by choosing the diversification mode. Due to the existence of carbon trading, environmental organizations will take wetland ecosystem protection measures. If the additional reputation gained by restoring water resources per unit is small and the revenue gained by governing wetlands per unit is large, the environmental organizations can achieve the maximum benefit by choosing the control mode. Otherwise, the environmental organizations can achieve the maximum benefit by choosing the diversification mode.

The research in this article can also be extended. For example, it is assumed that the recovery of wetland water quantity can bring convenience to residents' water consumption, the vegetation diversification mode is beneficial to the reproduction of wetland vegetation, and the control of invasive species is difficult at the beginning but easy later. In future research, we can make the following assumptions for further study. Firstly, assume that the restoration of wetland water volume won't bring convenience to residents' water usage. Secondly, suppose that the vegetation diversification model has no impact on the reproduction of wetland vegetation. Additionally, assume that the difficulty of controlling invasive species remains unchanged. Meanwhile, some blanks in the research can also be solved in future research. Firstly, it is necessary to determine the specific standards adopted by the wetland ecosystem governance mode under different conditions. Secondly, under the carbon trading, the research results of wetland governance should be transformed into practical policy recommendations for the government and environmental protection organizations. Thirdly, the government and environmental protection organizations should determine the order of action of relevant research, rather than taking action at the same time.

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

BT: Data curation, Methodology, Investigation, Software, Supervision, Writing – original draft, Formal Analysis. YB: Validation, Methodology, Writing – original draft.

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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/fevo.2025.1699567/full#supplementary-material

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