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Bandwagon effect, free-rider effect, tragedy of the commons: collaborative governance of marine pollution

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The issue of marine pollution is becoming one of the core challenges in global environmental protection, particularly when it comes to coordinating governance among nations and stakeholders. Problems such as uneven distribution of responsibilities and low efficiency of cooperation are frequently encountered. Traditional governance models struggle to effectively address the complexity of trans-regional and cross-sectoral pollution sources. In response, this paper uses the bandwagon effect, free-rider effect, and tragedy of the commons as theoretical frameworks, drawing on models and a large body of statistical data to explore strategies for collaborative governance of marine pollution. The results show that when the reputation and benefits gained from managing marine pollution are low, the governance by countries most reflects the tragedy of the commons. Otherwise, their governance best exemplifies the bandwagon effect.

KEYWORDS

collaborative governance, differential games, marine pollution, maximum utility, developed countries, developing countries

1 Introduction

With the rapid development of the global economy and the advancement of industrialization, marine pollution has become increasingly severe, emerging as one of the urgent issues in global environmental protection. Pollutants such as plastic waste, chemical effluents, oil spills, and agricultural runoff continue to threaten the health of marine ecosystems, not only impacting the habitats of marine life but also posing significant risks to global climate regulation, fisheries resources, and the livelihoods of coastal populations (Sannigrahi et al., 2022). As the ocean serves as the core of the global ecosystem, the issue of marine pollution has surpassed the jurisdiction of any single country or region, necessitating international cooperation and coordination in marine pollution governance.

However, the collaborative governance of marine pollution faces complex governance structures and conflicting interests. Factors such as the economic interests of different countries, governance priorities, and the division of responsibilities create obstacles to

cooperation in governance. Against this backdrop, this paper introduces three major theories—the bandwagon effect, the free-rider effect, and the tragedy of the commons—to explore their application and implications in the context of collaborative marine pollution governance, aiming to provide a theoretical basis for optimizing global marine pollution governance mechanisms.

The bandwagon effect suggests that in the context of multi-stakeholder interest negotiations, individuals or groups tend to align with the stronger party to maximize their own interests. In the governance of marine pollution, this is reflected in the behavior of some countries and corporations, which, in order to avoid taking on governance responsibilities, often choose to side with dominant players or remain uninvolved (Eastman and Iyer, 2023). This alignment behavior during the governance process may exacerbate unequal resource allocation, leading to inefficiencies in governance. The free-rider Effect reflects a situation in collective action where some participants reduce or refrain from contributing because they can benefit from the efforts of others (Rivers and Shiell, 2014). In marine pollution governance, some countries or companies reduce their responsibilities and investments due to the efforts of others, engaging in "free riding" behavior, which further weakens the overall effectiveness of governance. The tragedy of the commons reveals the dilemma of over-exploitation of public resources. The ocean, as a global common resource, often becomes subject to overuse and pollution due to the lack of effective regulation and governance mechanisms.

Based on these theories, this study will explore how to establish a fair mechanism for responsibility-sharing, enhance international cooperation, and introduce incentive mechanisms and legal constraints to curb the free-rider effect and the tragedy of the commons, thereby promoting effective collaboration among all parties. It will also analyze how to address the power imbalances caused by the bandwagon effect, ensuring that different stakeholders can reach a consensus during the governance process and develop a more effective model for collaborative marine pollution governance (Bindra et al., 2022). This research aims to provide new policy recommendations and governance frameworks for global marine conservation, contributing to the achievement of a sustainable marine ecosystem.

In light of the severity of plastic pollution, various scholars have researched methods to address marine plastic waste. For instance, Skirtun et al. (2021) argue that identifying the sources of marine debris can help mitigate pollution. Helinski et al. (2021) designed specialized devices to capture plastic waste and reduce its environmental impact. Sannigrahi et al. (2022) utilized open remote sensing data alongside advanced machine learning techniques to identify marine debris. Additionally, Soares et al. (2021) emphasize the importance of environmental education in managing plastic waste. These researchers primarily focus on strategies for treating marine plastic waste through macro cooperation, waste traceability, technological innovation, and educational initiatives.

Some scholars have analyzed the free-rider effect. For example, Johnson (2011) explored the relationship between the free rider principle, the charitable market, and the economics of mood; Rivers and Shiell (2014) used the case of natural gas furnaces in Canada to introduce free riding on energy efficiency subsidies; McMillan (2010) analyzed the free rider problem through a survey; Kinnucan and Myrland (2010) used salmon as an example to examine the free-rider effect in generic advertising.

Some scholars have studied the bandwagon effect. For example, Nadeau et al. (2016) provided new evidence of the bandwagon effect during the process of opinion formation; Shaikh et al. (2017) analyzed the role of the bandwagon effect using the example of whether luxury brands can successfully attract consumers; Bindra et al. (2022) revisited the bandwagon effect through a systematic review aimed at developing a future research agenda; Farjam (2020) analyzed the bandwagon effect in an online voting experiment within a real political organization; Stolwijk et al. (2017) examined how anxiety and enthusiasm help explain the bandwagon effect; Eastman and Iyer (2023) developed a generalized bandwagon luxury motivation scale to measure the bandwagon effect; Hu et al. (2019) studied the bandwagon effect in the process of special dividend payments.

Previous research has primarily focused on the technical aspects, macro-level cooperation, and education related to marine plastic pollution governance. However, the role of behavioral economic phenomena such as the free-rider effect, the tragedy of the commons, and the bandwagon effect in decision-making and governance among multiple stakeholders has yet to be fully explored. To address these gaps, this study offers the following contributions and innovations. First, it introduces behavioral economic theories into the research framework for marine pollution governance. While existing studies mainly focus on technical solutions and macro-management, the roles of behavioral economic theories, such as the free-rider effect, the tragedy of the commons, and the bandwagon effect, in marine pollution governance have not been thoroughly examined. This study explores how certain countries or corporations benefit from the governance efforts of others without contributing proportionally, particularly in the context of global marine pollution governance, and designs incentive mechanisms to overcome this issue. It also analyzes the overuse and governance failures of the global high seas as a public resource, proposing innovative collaborative governance solutions to mitigate the over-exploitation and pollution of high seas resources by various nations. Furthermore, this study examines how certain countries or interest groups alter their environmental policies due to mainstream public opinion or external pressure in the context of multinational collaborative governance, and proposes how to leverage this effect to encourage more countries to participate in governance actions. The introduction of these theories enriches the existing research framework, providing a deeper understanding of the role of human behavior in governance.

Second, encouraging stakeholder participation in marine pollution governance through the bandwagon effect. The bandwagon effect suggests that individuals or organizations often make decisions influenced by mainstream opinions or behaviors. In the context of marine pollution governance, this implies that when certain countries or regions adopt strong environmental measures, other nations or organizations may follow suit due to international image concerns or pressure from public opinion. This study explores how to leverage this effect within the international

governance framework to guide more countries into joining marine pollution governance agreements, and how to use behavioral demonstration effects to encourage broader participation from global stakeholders.

Third, a collaborative governance mechanism to address the free-rider effect and the tragedy of the commons. The free-rider effect and the tragedy of the commons are particularly prominent in global issues, especially in the governance of public resources such as oceans. This study integrates these two effects and proposes new governance models or incentive mechanisms to address common issues in governance, such as unequal responsibility distribution and over-consumption of resources. For instance, it suggests designing a global responsibility-sharing mechanism or performance-based incentive models to prevent certain countries or corporations from free-riding, and resolving the tragedy of the commons through effective resource management strategies.

This study holds significant importance. Marine pollution is a global issue that requires the collaborative efforts of multiple countries, corporations, and organizations. From a management perspective, the governance of global public resources, such as oceans, often faces challenges like the tragedy of the commons and the free-rider effect, leading to unequal distribution of governance responsibilities and over-consumption of resources. By introducing the bandwagon effect, mainstream public opinion or policy pressures can be leveraged to motivate more countries and corporations to take action. Addressing these behavioral economic phenomena can help design fairer and more effective international cooperation mechanisms, enhancing participation and governance efficiency, and offering innovative governance models for global marine pollution governance.

2 Methodology

2.1 Problem description, hypothesis, and variable definition

2.1.1 Problem description

The collaborative governance of marine pollution between developed and developing countries is influenced by the bandwagon effect, free-rider effect, and tragedy of the commons, which shape their strategic interactions and governance outcomes.

(1) In the collaborative governance of marine pollution, developed and developing countries can apply the bandwagon effect to foster consensus and strengthen cooperation in addressing global marine pollution more effectively (Nadeau et al., 2016). The following are some specific applications. First, establish a common vision and goals. Through international conferences and consultations, developed and developing countries can jointly formulate a global framework for marine pollution governance, clearly defining long-term objectives for reducing marine pollution, such as decreasing plastic waste and protecting marine biodiversity. A shared vision encourages alignment in policies and actions among nations, creating a robust international cooperation network. Signing legally binding international agreements, akin to the Paris Agreement, can further unify the actions and commitments of countries in marine pollution governance. Such a legal framework ensures that countries work collectively towards achieving the stated goals.

Second, strengthening cooperation and support mechanisms. Developed countries can assist developing countries in enhancing their capacity for marine pollution governance through technology transfer and financial support. This cooperation not only promotes environmental efforts in developing countries but also strengthens the leadership role of developed countries in international governance, creating a bandwagon effect driven by aligned interests (Shaikh et al., 2017). Developed and developing countries can collaborate on marine pollution research and monitoring projects, sharing data and findings. Such collaboration helps establish a unified scientific foundation to guide governance actions across nations.

Third, promoting multi-stakeholder participation. Encouraging multinational corporations, non-governmental organizations (NGOs), and international organizations to participate in marine pollution governance can help form a global governance alliance involving diverse actors. Countries can apply the bandwagon effect to incorporate these stakeholders into a unified governance framework, ensuring consistency in their actions. Through international cooperation, developed and developing countries can jointly raise global public awareness of marine pollution and encourage public participation in governance efforts. Such global public involvement can reinforce the consistency of environmental policies across governments.

Fourth, harmonizing policies and standards. Through international consultations, a unified set of marine pollution prevention standards and regulations can be established, ensuring consistency between developed and developing countries within a legal framework. Such standardization can reduce policy divergences and promote coordinated actions across nations. Bilateral or multilateral agreements can facilitate mutual recognition and coordination of policies between countries, minimizing conflicts and frictions in the process of marine pollution governance. In this way, governance measures across countries can become more consistent, contributing to the formation of a global environmental bandwagon.

By applying the bandwagon effect, developed and developing countries can establish strong cooperative relationships in the process of marine pollution governance, ensuring alignment in policies, actions, and goals. This model of global coordinated governance not only helps address marine pollution more effectively but also provides a valuable example for global environmental governance.

(2) In the process of coordinated marine pollution governance, the free-rider effect refers to situations where some countries benefit from the governance efforts of others without contributing corresponding efforts or costs themselves, thereby diminishing the overall effectiveness of governance. This effect is particularly evident under the following circumstances (Rivers and Shiell, 2014). First, weak enforcement of international agreements. If international marine pollution governance agreements lack strong enforcement mechanisms, certain countries may choose not to fulfill their commitments, relying on the efforts of others to improve the global marine environment. In this case, these countries are "free-

riding" and failing to shoulder their fair share of responsibility. In some international agreements, even though consensus is reached, the agreements lack legally binding force, leading some countries to believe that strict adherence is unnecessary, as they assume they will not face penalties for non-compliance.

Second, unfair burden-sharing. The unequal distribution of responsibilities between developed and developing countries in marine pollution governance may lead some developing countries to refrain from actively participating, instead relying on the efforts of developed nations. For instance, if developed countries bear the majority of financial and technological support without corresponding obligations for developing countries, the latter may depend on the actions of the former without taking proactive measures themselves. Even within the group of developed countries, there may be instances where certain nations are unwilling to shoulder significant governance costs, instead relying on the advanced technologies and financial contributions of others. This internal imbalance can also give rise to the free-rider effect.

Third, lack of global oversight and transparency. In the absence of a transparent and effective global monitoring system, certain countries may conceal their pollution levels or the inadequacy of their governance efforts, relying on the actions of other nations to reduce global pollution. In such cases, free-riding behavior becomes more prevalent. Due to information asymmetry, some countries might exploit the international community's inability to fully grasp their actual pollution situation, reducing their own investment in governance while benefiting from the efforts of others to improve their own marine environment.

Fourth, national interests take precedence, and there is a lack of long-term planning. When countries prioritize short-term economic growth over long-term environmental protection, they may reduce their investments in pollution control, relying on the efforts of other countries. For example, some nations may continue to use highly polluting production methods while hoping that stricter environmental measures in other countries will mitigate the global pollution increase. In certain cases, the costs of marine pollution control may be too high, leading some countries to reduce their contributions or even opt out of international governance efforts, expecting to indirectly benefit from the actions of others. In such cases, the free-rider effect may weaken the overall effectiveness of the international community's marine pollution governance. To avoid this, there is a need for more equitable, transparent, and binding mechanisms in international cooperation to ensure that all countries contribute appropriately to the sustainable development of the marine environment.

In terms of environmental and situational constraints, the key difference between the free-rider effect and other collective action problems lies in the attributes of public goods. Environmental collective actions (such as climate change governance) typically involve global public goods that are non-excludable and non-rivalrous, meaning individuals can enjoy the benefits of emission reductions even without contributing, which strengthens the motivation to free-ride (Agénor and Silva, 2025). In contrast, localized collective actions (such as community clean-ups) have limited benefits and are subject to supervision, as geographical or social boundaries can partially curb free-riding behavior. For instance, international climate agreements face implementation challenges due to a lack of enforceability, whereas community rules can reduce the likelihood of shirking responsibilities through neighborhood oversight.

Furthermore, the temporal dimension and feedback delays exacerbate the complexity of free-riding in environmental issues. The consequences of environmental degradation often lag by decades, making it difficult for individuals to directly perceive the impact of their inaction, thereby weakening immediate constraints. In comparison, the outcomes of actions such as labor strikes or fundraising for schools are more directly observable, making it easier for participants to establish a link between contribution and reward. For example, overfishing fishermen may continue to deplete resources due to the long-term nature of fish stock depletion, whereas union members who shirk during a strike immediately face peer pressure. This delay effect highlights the need for institutional design (such as carbon quota trading) in the environmental domain to compensate for the inadequacy of situational constraints.

(3) In the collaborative governance of marine pollution, the tragedy of the commons often occurs or becomes particularly evident under the following circumstances. First, inadequate or mismanagement of resources. When marine resources, such as fisheries or marine minerals, lack effective governance mechanisms, countries may over-exploit them in pursuit of maximizing their own interests. This can lead to resource depletion and harm the long-term interests of all nations. If there is a lack of international oversight or if existing regulatory mechanisms are inadequate, countries and corporations may abuse marine resources and discharge pollutants. The absence of regulation makes "free-riding" behavior more prevalent, further exacerbating the occurrence of the tragedy of the commons (Rivers and Shiell, 2014).

Second, prioritization of short-term economic interests. Some developing countries may focus more on short-term economic growth, neglecting the sustainable use of marine resources. In their pursuit of rapid development, these nations might excessively rely on marine resources, leading to over-exploitation and environmental pollution. Developed countries, in an effort to reduce costs, may relocate highly polluting industries to developing countries with more lenient environmental regulations, exacerbating marine pollution in those regions. This outsourcing of pollution heightens the risk of the tragedy of the commons on a global scale.

Third, unequal distribution of benefits. If international rules or agreements fail to fairly allocate responsibilities and benefits, developing countries may feel deprived and thus less willing to cooperate. Developed countries, while enjoying more resources and benefits, may not assume a proportional share of governance responsibilities, leading to over-exploitation of resources and the occurrence of the "tragedy of the commons." When developing countries lack the necessary technology and funding for effective marine pollution control, they may be inclined to continue using environmentally harmful but economically more attractive practices, further exacerbating environmental degradation (Xiao et al., 2025).

Fourth, lack of international cooperation and trust. When developed and developing countries lack effective mechanisms for collaboration in marine pollution control, nations may tend to pursue their own interests rather than contributing adequately to the protection of common resources. The absence of cooperation can lead to independent actions by countries, exacerbating resource overuse. If there is a lack of mutual trust between countries, it can reduce the willingness to cooperate, particularly in the governance of shared or international waters. Nations may believe that other countries will not fulfill their commitments, thus becoming unwilling to assume greater responsibility themselves, leading to the unsustainable use of common resources.

The tragedy of the commons is widely manifested in marine pollution governance, including issues such as overfishing, oil spills, and the shirking of pollution responsibilities. Marine fishery resources are classic examples of "commons," lacking clear property rights, which leads fishermen to compete for short-term gains. For instance, Atlantic cod nearly collapsed in the late 20th century due to overfishing by fleets from various countries, despite scientists warning of the necessity of quota limits. Individual fishermen rationalized their actions by believing that "if I don't fish, someone else will," ultimately leading to ecological collapse (Monk et al., 2023). A similar situation has occurred in the East Asian seas, where competitive fishing by China, Japan, South Korea, and others has drastically reduced the fishery resources of the Yellow Sea, illustrating how individual rational choices can lead to collective disaster in the absence of effective international constraints.

In marine oil extraction and transportation, the tragedy of the commons often arises from the "externalization of costs." In the 2010 BP Gulf of Mexico oil spill, although BP bore primary responsibility, other oil companies had long lobbied for relaxed safety regulations, transferring pollution risks to public waters (Rotkin-Ellman et al., 2012). Similarly, ships illegally discharge waste oil into the open sea (e.g., through "magic pipes") due to the high difficulty of regulation and low penalties, incentivizing companies to shift cleaning costs to society at large. This "polluter profits, public pays" model is a classic manifestation of the tragedy of the commons in transnational marine governance.

These cases demonstrate that the fluidity of marine environments, the ambiguity of property rights, and the fragmentation of enforcement make the tragedy of the commons and the shirking of responsibilities more likely to occur. There is an urgent need to strengthen international agreements (such as the United Nations Convention on the Law of the Sea) and regional cooperation mechanisms (such as the EU fisheries quota system) to reconcile conflicts between individual interests and the public good.

These situations indicate that, in the absence of effective management, cooperation, trust, and fair distribution, both developed and developing countries are highly susceptible to the "tragedy of the commons" in the process of marine pollution governance. This necessitates that nations take these factors into full account when formulating policies and cooperation frameworks to prevent over-exploitation of resources and further environmental degradation.

The relationship between the three law or effect in the process of collaborative governance of marine pollution is shown in Figure 1.

2.1.2 Hypothesis

Hypothesis 1: Marine pollution control is long-term, dynamic and continuous

The governance of marine pollution by developed and developing countries is indeed a "long-term, dynamic, and continuous" process. This characterization reflects the global challenges of addressing marine pollution and the sustained efforts and adaptability required in the governance process. The following are specific explanations of these characteristics. First, marine pollution is a global issue that demands long-term

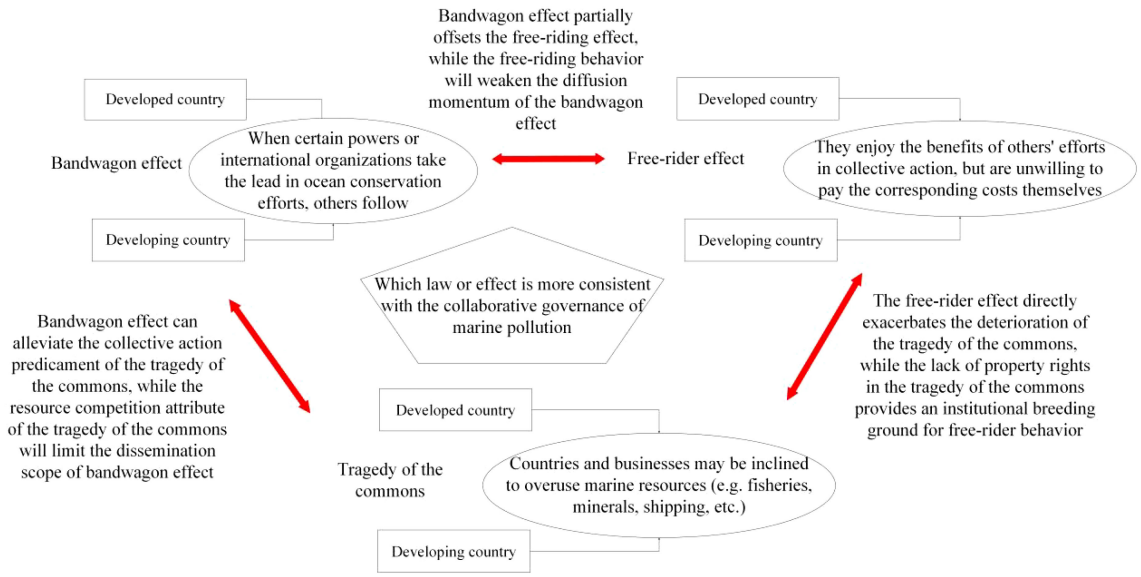

FIGURE 1
Relationship between three law or effect in the process of collaborative governance of marine pollution.

commitment and continuous effort. Both developed and developing countries must invest significant resources, formulate policies, and engage in international cooperation for effective marine pollution control. Given the widespread sources of marine pollution and the difficulties involved in its governance, long-term monitoring and continuous improvement are necessary to mitigate the impact of pollution and to restore already damaged marine ecosystems.

Second, the marine environment and sources of pollution are dynamic, and governance measures must be flexible enough to respond to these changes. Marine pollution originates from diverse and complex sources, including land-based discharges, ship waste, oil spills, plastic debris, among others. These sources may change over time due to factors such as economic activities and climate change (Sannigrahi et al., 2022). Therefore, when formulating and implementing governance measures, developed and developing countries must account for these changes and continuously adjust their strategies and technologies to ensure the effectiveness of pollution control efforts.

Third, marine pollution governance requires sustained efforts rather than one-off actions. Addressing marine pollution involves not only dealing with existing pollution but also implementing long-term preventive measures and policy support. Only through continuous monitoring, enforcement, and public education can new pollution be prevented, and the progress achieved in pollution control be maintained. Both developed and developing countries must ensure continuity in their marine pollution governance efforts, preventing any disruption in order to safeguard the health and sustainability of marine ecosystems.

Furthermore, this hypothesis aligns with empirical observations. For instance, the governance of marine pollution in the Mediterranean Sea is a long-term process, with its effects and impacts persisting over extended periods (López-Martínez et al., 2022). According to the latest report released by the World Wide Fund for Nature (WWF), as of 2024, 87% of the Mediterranean Sea is affected by pollution, primarily linked to toxic metals, industrial chemicals, and plastic waste. Over the past two decades, pollution-related deaths have increased by 66%, reaching 9 million annually, making pollution a leading environmental risk factor for global diseases and premature mortality. This underscores the long-term, dynamic, and persistent nature of marine pollution in the Mediterranean.

In conclusion, both developed and developing countries must adhere to long-term planning, dynamic responses, and continuous action when addressing marine pollution in order to effectively tackle the complex issues of the marine environment and protect the integrity of global marine ecosystems.

Hypothesis 2: Developed and developing countries are geographically close

Some developed and developing countries are geographically proximate. For example, the distance between Italy (a developed country) and Tunisia (a developing country) is only 145 kilometers (across the Strait of Sicily); similarly, the distance between Spain (a developed country) and Morocco (a developing country) is merely 14 kilometers (across the Strait of Gibraltar).

In the process of marine pollution governance, significant differences in governance approaches, priorities, and capacities may still exist between developed and developing countries, even if they are geographically close. This disparity can be attributed to several factors. First, there are economic and technological differences. Developed countries typically have access to more advanced pollution control technologies and greater financial resources to implement complex governance measures. In contrast, geographically proximate developing countries may not be able to invest as heavily in pollution control due to lower levels of economic development. Even when facing the same marine pollution challenges, differences in governance capacities and approaches can lead to variations in the effectiveness of pollution control efforts.

Second, differences in pollution sources. Even if developed and developing countries are geographically close, their sources of pollution may differ significantly. For instance, in developed countries, with higher levels of industrialization, marine pollution is more likely to stem from industrial wastewater, chemicals, and ship emissions. In contrast, developing countries may face pollution issues more related to household waste, agricultural runoff, and inadequate infrastructure. Consequently, even within the same geographical region, the nature of pollution and the methods of addressing it may vary (Skirtun et al., 2021).

Third, differences in governance priorities. When addressing marine pollution, the priorities of developed and developing countries may differ. Developed countries, having undergone longer environmental protection processes, often prioritize environmental protection as a high-level concern. In contrast, some developing countries, especially those experiencing rapid economic growth, may prioritize economic development, with environmental governance potentially being delayed or relegated to a secondary issue.

Fourth, the importance of international cooperation. Despite the aforementioned differences between developed and developing countries, international cooperation becomes particularly crucial due to the trans-boundary nature of marine pollution, especially when countries are geographically close. Pollutants can cross national borders through ocean currents, wind patterns, and biological migration, making regional cooperation essential for effective marine pollution governance (Soares et al., 2021). Both developed and developing countries must participate in international agreements, working together to formulate and implement marine protection policies. In conclusion, although developed and developing countries may be geographically close, differences in their economic capacities, technological advancements, and governance priorities lead to variations in their approaches and capabilities in addressing marine pollution. However, these differences also underscore the importance of international cooperation and coordination to achieve effective governance of shared marine areas.

However, this hypothesis also has certain limitations. For instance, the United States and Southeast Asian countries are geographically distant, yet pollutants such as plastic waste still reach their coastlines through ocean currents, indicating that geographical distance is not the sole determinant of pollution impact. Additionally, this hypothesis may overlook the complexity of political and economic factors in transnational pollution governance. For example, even when countries are

geographically close, differences in economic development levels, governance capacities, and political willingness can lead to difficulties in cooperation (Casas and Romera, 2011). Therefore, these hypotheses may fall short in explaining the diversity and complexity of global marine pollution governance.

2.1.3 Variable definition

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

However, these parameters are potentially influenced by unmeasured variables such as political instability or economic crises. Political instability can lead to a decline in national governance capacity, resulting in the failure to fulfill previously committed pollution control investments, thereby exacerbating the "free-rider effect" (Al-Tabbaa et al., 2023). Economic crises, on the other hand, may compel countries to prioritize short-term economic gains, cutting environmental protection budgets and further diminishing governance incentives. These unmeasured variables may also affect the stability of equilibrium outcomes by altering the strategic space and payoff functions of game participants. Consequently, neglecting these factors could lead to an overestimation of the likelihood of international cooperation or an underestimation of the difficulty in sharing governance costs, thereby compromising the accuracy of research conclusions and the applicability of policy recommendations.

2.2 Differential game of different scenarios

Differential game theory provides a dynamic and strategic framework uniquely suited to analyze the interplay of bandwagon effects, free-riding, and the tragedy of the commons in marine pollution governance. Unlike static models (e.g., classical game theory or cost-benefit analysis), differential games capture time-dependent decision-making, where nations continuously adjust their pollution control efforts based on others' actions and evolving environmental conditions (Petrosyan and Pankratova, 2023). This is critical because marine pollution is a cumulative, long-term problem—governance strategies must account for delayed feedback, stock pollutants (e.g., plastic accumulation), and shifting incentives over time.

In terms of dynamic free-rider analysis, traditional static games (e.g., Prisoner's Dilemma) treat free-riding as a one-time choice, but differential games reveal how delayed enforcement or gradual reputation gains can either exacerbate or mitigate free-riding. For instance, a nation may reduce cleanup efforts today if it expects others to compensate later—a behavior only detectable through dynamic modeling.

In terms of bandwagon effects as feedback loops, differential games formalize bandwagon effects as state-dependent strategies, where

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

Variables and parameters	Specific meaning
$Y=\{B,F,C\}$	Effect in the process of collaborative governance of marine pollution (bandwagon effect, free-rider effect, tragedy of the commons)
Independent variable	
$F_{Y1}(t)$	Developed countries' efforts to govern the marine pollution under the governance effect Y
$F_{Y2}(t)$	Developing countries' efforts to govern the marine pollution under the governance effect Y
$x_{Y1}(t)$	Reputation of developed countries in the governance process of the marine pollution under the governance effect Y
$x_{Y2}(t)$	Reputation of developing countries in the governance process of the marine pollution under the governance effect Y
Parameter	
ρ	The discount rate that occurs over time, $0\leq\rho\leq1$
δ	decay of reputation, $\delta>0$
l	The positive effects of reputation, $l>0$
a_1, a_2	The benefits that the developed countries or developing countries gain by governance of the marine pollution at a unit level, a_1, $a_2>0$
c_1,c_2	The cost to the developed countries or developing countries of governance of the marine pollution at a unit level, c_1, $c_2>0$
f_1, f_2	The reputation that the developed countries or developing countries gain by governance of the marine pollution at a unit level, f_1, $f_2>0$
p	Probability of ocean protection in developing countries, $p>0$
λ	Coefficient of impact of Marine protection in developing countries on developed countries, $\lambda>0$
a_{C1}, a_{C2}	Ecological damage caused by over-exploitation of Marine resources in developed or developing countries, a_{C1}, $a_{C2}>0$
b_1, b_2	The benefits of over-exploitation of Marine resources for developed or developing countries, b_1, $b_2>0$
f_C	The loss of reputation caused by ecological damage, $f_C>0$
T	The governance cycle of Marine pollution, $T>0$
Function	
$J_{Y1}(t)$	The social welfare function of developed countries under the governance effect Y
$J_{Y2}(t)$	The social welfare function of developing countries under the governance effect Y
$V_{Y1}(t)$	The social benefits of developed countries under the governance effect Y
$V_{Y2}(t)$	the social benefits of developing countries under the governance effect Y

nations increase participation only after a "critical mass" of others do so (e.g., via replicator dynamics). This explains why some regions (e.g., the EU) achieve rapid cooperation while others stagnate.

In terms of tragedy of the commons with stock externalities, unlike static models, differential games distinguish flow pollution (short-term emissions) from stock pollution (long-term degradation), showing how delayed consequences encourage over-exploitation. Policies like adaptive penalties (e.g., escalating fines as pollution stocks grow) can be rigorously tested.

Compared with other modeling methods (e.g., system dynamics, agent-based models and optimal control theory), differential games also have certain advantages. While system dynamics models feedback loops, they lack strategic interaction, while differential games explicitly model competitive/collaborative decision-making; agent-based models simulate heterogeneity but often lack analytical tractability, while differential games provide equilibrium solutions (e.g., Nash or cooperative equilibria) to guide policy design (Jia et al., 2023); optimal control theory assumes a single planner, whereas differential games internalize conflicts among multiple actors, aligning better with real-world governance fragmentation.

Differential game theory offers a rigorous yet flexible framework to dissect how strategic behaviors interact with environmental dynamics in marine pollution governance. By quantifying time-consistent policies, threshold effects for cooperation, and nonlinear penalties for free-riding, it advances theoretical depth beyond static or non-strategic models, providing actionable insights for international agreements (Plaksin and Kalev, 2024).

In the study of marine pollution governance under different scenarios, this paper employs differential game theory. The rationale behind using differential game theory lies in its ability to effectively analyze the interactive behaviors of multiple stakeholders in complex environments, particularly when issues such as resource sharing, benefit distribution, and cooperation failures are involved. Differential game theory helps address multiple aspects of these complex dynamic problems. Marine pollution is a continuously occurring and dynamically changing process, where issues such as pollutant diffusion and the gradual degradation of the ecological environment evolve over time. Differential game theory can assist in analyzing this dynamic evolution, modeling the strategic choices of multiple decision-makers at different time points, and assessing the long-term impacts of these decisions, thereby identifying optimized long-term solutions for pollution governance.

The bandwagon effect suggests that individuals tend to take sides in complex issues and act in accordance with the interests of the chosen side. Marine pollution governance often involves multiple stakeholders, such as national governments, environmental organizations, corporations, and the public, each of whom may adopt different positions based on their own interests. Differential game theory can analyze how different parties align and how various alignment strategies affect overall governance outcomes, thereby aiding in the design of cooperative mechanisms that reduce disagreements and encourage broader collaboration (Assarzadegan et al., 2024).

The free-rider effect refers to the phenomenon in collective actions where some participants may reduce their contributions or refrain from participating, expecting others to bear a greater share of the responsibility. Marine pollution governance is a typical example of a collective action problem, as all stakeholders share marine resources, but if certain countries or corporations adopt free-riding strategies, the effectiveness of governance may be significantly compromised. Differential game theory can help model this free-rider phenomenon in collective action and, through the design of appropriate incentive mechanisms, encourage all stakeholders to actively participate in governance and reduce free-rider behavior (Bai and Ma, 2023).

The tragedy of the commons refers to the scenario in which individuals, in the pursuit of maximizing their own interests, ultimately lead to the depletion of shared resources. In marine pollution governance, the ocean represents a "commons," where all nations and corporations may over-exploit or pollute, resulting in irreversible damage to the resources. Differential game theory, by analyzing the strategic interactions among participants competing for shared resources, aids in designing appropriate policies and governance mechanisms to prevent the tragedy of the commons and ensure the sustainable use of resources (Wei and Wang, 2021). Marine pollution governance requires long-term efforts, involving substantial investments of resources and funds. Different stakeholders may have varying expectations regarding the contributions and returns from governance, raising the issue of how to fairly distribute governance costs and maintain cooperation over time. Differential game theory, through analyzing the long-term interests of multiple parties, helps stakeholders identify sustainable cooperation models and effectively allocate costs and benefits throughout the governance process (Ji et al., 2024).

The bandwagon effect refers to the tendency of individuals or nations to follow the behavior or opinions of the majority. In marine pollution governance, this phenomenon may cause some countries or organizations to engage in governance only after observing other major nations or international organizations taking action. In other words, when certain major powers or international organizations lead efforts in marine conservation, other countries may follow suit, either due to pressure or in pursuit of benefits (Nadeau et al., 2016). This effect can promote global cooperation but may also lead to some countries becoming overly passive, waiting for others to act first.

If the developed countries and developing countries comply with the bandwagon effect in the process of collaborative governance of marine pollution, then their social welfare function can be expressed as Equations 1, 2:

$$J_{B1} = \int_0^T [(a_1 + \lambda p)F_{B1}(t) - \frac{c_1}{2}F_{B1}^2(t) + lx_{B1}(t)] \quad e^{-\rho t}dt \qquad (1)$$

$$J_{B2} = \int_0^T [pa_2F_{B2}(t) - p\frac{c_2}{2}F_{B2}^2(t) + \quad lx_{B2}(t)] \quad e^{-\rho t}dt \qquad (2)$$

In the above formula, $a_1F_{B1}(t)$ represents the benefits derived by developed countries from combating marine pollution. $\lambda pF_{B1}(t)$ indicates the positive impact of marine pollution in developing countries on the benefits to developed countries. $\frac{c_1}{2}F_{B1}^2(t)$ represents the costs incurred by developed countries in combating

marine pollution. $lx_{B1}(t)$ indicates the positive impact of reputation on the benefits of developed countries.

Among them, the cost is equal to the square of the effort level multiplied by a constant, reflecting a nonlinear relationship. This is primarily attributed to the following two reasons. First, the effect of increasing marginal costs. In the process of pollution control, initial investments may yield significant results through relatively simple measures, such as strengthening regulations or promoting basic technologies. However, as governance progresses, further pollution reduction requires more complex and costly technologies and resource inputs. For instance, transitioning from reducing industrial wastewater discharge to addressing microplastic pollution involves significantly higher technical challenges and costs. This characteristic of increasing marginal costs results in a nonlinear relationship between cost and effort level, and the square relationship effectively captures this accelerating trend.

Second, the characteristics of real-world governance costs. In practical pollution control, costs often exhibit an exponential relationship with the depth and breadth of governance (Soares et al., 2021). For example, developed countries may need to develop more advanced technologies or implement stricter policies when addressing marine pollution, leading to rapidly escalating costs. Developing countries face similar challenges, as increased governance efforts require multiplied investments in funding, technology, and human resources. Therefore, the square relationship better reflects these real-world cost characteristics. $pa_2F_{B2}(t)$ indicates the benefits that developing countries have gained from combating marine pollution. $p\frac{c_2}{2}F_{B2}^2(t)$ represents the costs incurred by developing countries in combating marine pollution. $lx_{B2}(t)$ indicates the positive impact of reputation on benefits to developing countries. $e^{-\rho t}$is a convolution. With this convolution, the integrals will begin to converge well before infinity.

It is noteworthy that marine pollution control in developing countries has a positive impact on developed countries, primarily because developing countries reduce pollution emissions through governance actions, thereby improving the quality of the global marine environment and directly alleviating the cross-border pollution pressure faced by developed countries. This "spillover effect" of environmental improvement allows developed countries to benefit without additional investment (Zhang and Xu, 2024).

On the other hand, the governance actions of developed countries have a relatively limited impact on developing countries. This is mainly because the pollution issues in developing countries are more often rooted in their own economic activities and insufficient governance capacity. The governance efforts of developed countries cannot directly address these fundamental issues, thus their influence remains relatively constrained.

$$\dot{x}_{B1}(t) = f_1F_{B1}(t) - \delta x_{B1}(t) \tag{3}$$

$$\dot{x}_{B2}(t) = pf_2F_{B2}(t) - \delta x_{B2}(t) \tag{4}$$

In the above formula (Equations 3, 4), $f_1F_{B1}(t)$ indicates the positive impact on the reputation of developed countries in combating marine pollution. $\delta x_{B1}(t)$ represents the erosion of the reputation of developed countries. $pf_2F_{B2}(t)$ indicates the positive impact on the reputation of developing countries for combating marine pollution. $\delta x_{B2}(t)$ represents a decline in the reputation of developing countries.

The free-rider effect refers to the phenomenon where individuals or nations benefit from the efforts of others in collective action without being willing to pay the corresponding costs. In marine pollution governance, some countries or corporations may choose not to take proactive measures, expecting others to address the issue, thus saving their own resources and costs (Rivers and Shiell, 2014). This effect can undermine the overall effectiveness of governance, as the lack of initiative from some participants may result in outcomes that fall short of expectations.

If the developed countries and developing countries comply with the free-rider effect in the process of collaborative governance of marine pollution, then their social welfare function can be expressed as Equations 5, 6:

$$J_{F1} = \int_0^T [a_1F_{F1}(t) - \frac{c_1}{2}F_{F1}^2(t) + lx_{F1}(t)] \quad e^{-\rho t}dt \tag{5}$$

$$J_{F2} = \int_0^T [a_2F_{F2}(t) - \frac{c_2}{2}F_{F2}^2(t) + lx_{F2}(t)]e^{-\rho t}dt \tag{6}$$

In the above formula, $a_1F_{F1}(t)$ represents the benefits gained by developed countries in combating marine pollution. $\frac{c_1}{2}F_{F1}^2(t)$ indicates the costs incurred by developed countries in combating marine pollution. $lx_{F1}(t)$ represents the positive impact of reputation on the gains of developed countries. $a_2F_{F2}(t)$ indicates the gains made by developing countries in combating marine pollution. $\frac{c_2}{2}F_{F2}^2(t)$ represents the costs incurred by developing countries in combating marine pollution. $lx_{F2}(t)$ indicates the positive impact of reputation on the earnings of developing countries.

It is noteworthy that pollution control efforts in developed and developing countries do not mutually influence each other, primarily because both sides tend to rely on the other's governance efforts to improve the marine environment while reducing their own investments. Developed countries may believe that the governance actions of developing countries are sufficient to mitigate global pollution issues, thus they are unwilling to bear additional governance costs. Meanwhile, developing countries may argue that the technological and financial advantages of developed countries oblige them to take on greater responsibility, thereby reducing their own governance investments. This "free-rider" behavior results in a lack of synergistic effects between the governance actions of both sides, failing to establish a mutually reinforcing mechanism. Consequently, the impact of each side's pollution control efforts on the other is weakened or even neutralized (Johnson, 2011).

Under the bandwagon effect scenario, developing countries reduce pollution emissions through governance actions, improving the quality of the global marine environment and directly alleviating the cross-border pollution pressure faced by developed countries. However, under the free-rider effect scenario,

this outcome does not occur, primarily because the "free-rider" behavior leads to a lack of proactive governance motivation on both sides. Developing countries may believe that developed countries should bear the primary responsibility, thus their governance investments are limited and fail to significantly reduce pollution emissions. Similarly, developed countries may rely on the governance actions of developing countries, thereby reducing their own efforts (Kinnucan and Myrland, 2010). This mutual dependence and evasion result in weak governance outcomes on both sides, failing to achieve significant global environmental improvement. Therefore, the cross-border pollution pressure is not substantially alleviated.

$$\dot{x}_{F1}(t) = f_1 F_{F1}(t) - \delta x_{F1}(t) \tag{7}$$

$$\dot{x}_{F2}(t) = f_2 F_{F2}(t) - \delta x_{F2}(t) \tag{8}$$

In the above formula (Equations 7, 8), $f_1 F_{F1}(t)$ indicates the positive impact on the reputation of developed countries in combating marine pollution. $\delta x_{F1}(t)$ represents the erosion of the reputation of developed countries. $f_2 F_{F2}(t)$ indicates the positive impact on the reputation of developing countries for combating marine pollution. $\delta x_{F2}(t)$ represents a decline in the reputation of developing countries.

The tragedy of the commons refers to the over-exploitation of shared resources (such as oceans, air, etc.) by individuals seeking to maximize personal gain, ultimately leading to the depletion or damage of those resources. In the context of marine pollution, countries and corporations may be inclined to overuse marine resources (such as fisheries, minerals, and shipping), believing that if they do not do so, others will (Xiao et al., 2024a). This mindset results in the over-exploitation of marine resources and the exacerbation of pollution. The tragedy of the commons illustrates that without effective governance mechanisms, shared resources are easily overused and damaged.

If the developed countries and developing countries comply with the tragedy of the commons in the process of collaborative governance of marine pollution, then their social welfare function can be expressed as Equations 9, 10:

$$J_{C1} = \int_0^T [(a_1 - a_{C1})F_{C1}(t) - \frac{c_1}{2}F_{C1}^2(t) + b_1 + lx_{C1}(t)]e^{-\rho t}dt \tag{9}$$

$$J_{C2} = \int_0^T [(a_2 - a_{C2})F_{C2}(t) - \frac{c_2}{2}F_{C2}^2(t) + b_2 + lx_{C2}(t)]e^{-\rho t}dt \tag{10}$$

In the above formula, $a_1 F_{C1}(t)$ represents the gains made by developed countries in combating marine pollution. $a_{C1}F_{C1}(t)$ indicates the ecological damage caused by over-exploitation of marine resources. $\frac{c_1}{2}F_{C1}^2(t)$ represents the costs incurred by developed countries in combating marine pollution. b_1 represents the benefits to developed countries of over-exploitation of marine resources. $lx_{C1}(t)$ represents the positive impact of reputation on the gains of developed countries. $a_2 F_{F2}(t)$ represents the benefits to developing countries of combating marine pollution. $a_{C2}F_{C2}(t)$ indicates the ecological damage caused by over-exploitation of marine resources. $\frac{c_2}{2}F_{C2}^2(t)$ represents the costs incurred by developing countries in combating marine pollution. b_2 indicates the benefits to developing countries from the over-exploitation of marine resources. $lx_{C2}(t)$ represents the positive impact of reputation on the gains of developing countries.

$$\dot{x}_{C1}(t) = (f_1 - f_C)F_{C1}(t) - \delta x_{C1}(t) \tag{11}$$

$$\dot{x}_{C2}(t) = (f_2 - f_C)F_{C2}(t) - \delta x_{C2}(t) \tag{12}$$

In the above formula (Equations 11, 12), $f_1 F_{C1}(t)$ represents the positive impact on the reputation of developed countries in combating marine pollution. $f_C F_{C1}(t)$ indicates a decline in the reputation of developed countries as a result of ecological damage. $\delta x_{C1}(t)$ represents a decline in the reputation of developed countries. $f_2 F_{C2}(t)$ indicates the positive impact on the reputation of developing countries in combating marine pollution. $f_C F_{C2}(t)$ represents a decline in the reputation of developing countries as a result of ecological damage. $\delta x_{C2}(t)$ indicates a decline in the reputation of developing countries.

3 Results

In the differential game, the developed countries and developing countries in the process of collaborative governance of marine pollution are not only affected by control variables and parameters, but also change over time. In order to better calculate the control benefits 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 condition that the bandwagon effect is satisfied, the HJB equation of the social welfare function of the developed countries and developing countries are as Equations 13, 14:

$$\rho V_{B1} = \max_{F_{B1}(t)} \left\{ \begin{array}{l} [(a_1 + \lambda p)F_{B1}(t) - \frac{c_1}{2}F_{B1}^2(t) + lx_{B1}(t)] \\ \qquad + \frac{\partial V_{B1}}{\partial x_{B1}}[f_1 F_{B1}(t) - \delta x_{B1}(t)] \end{array} \right\} \tag{13}$$

$$\rho V_{B2} = \max_{F_{B2}(t)} \left\{ \begin{array}{l} [pa_2 F_{B2}(t) - p\frac{c_2}{2}F_{B2}^2(t) \\ \qquad + lx_{B2}(t)] + \frac{\partial V_{B2}}{\partial x_{B2}}[pf_2 F_{B2}(t) - \delta x_{B2}(t)] \end{array} \right\} \tag{14}$$

Under the condition that the free-rider effect is satisfied, the HJB equation of the social welfare function of the developed countries and developing countries are as Equations 15, 16:

$$\rho V_{F1} = \max_{F_{F1}(t)} \left\{ \begin{array}{l} [a_1 F_{F1}(t) - \frac{c_1}{2} F_{F1}^2(t) \\ \qquad + l x_{F1}(t)] + \frac{\partial V_{F1}}{\partial x_{F1}} [f_1 F_{F1}(t) - \delta x_{F1}(t)] \end{array} \right\} \tag{15}$$

$$\rho V_{F2} = \max_{F_{F2}(t)} \left\{ \begin{array}{l} [a_2 F_{F2}(t) - \frac{c_2}{2} F_{F2}^2(t) + l x_{F2}(t)] \\ \qquad + \frac{\partial V_{F2}}{\partial x_{F2}} [f_2 F_{F2}(t) - \delta x_{F2}(t)] \end{array} \right\} \tag{16}$$

Under the condition that the tragedy of the commons is satisfied, the HJB equation of the social welfare function of the developed countries and developing countries are as Equations 17, 18:

$$\rho V_{C1} = \max_{F_{C1}(t)} \left\{ \begin{array}{l} [(a_1 - a_{C1}) F_{C1}(t) - \frac{c_1}{2} F_{C1}^2(t) + b_1 + l x_{C1}(t)] \\ \qquad + \frac{\partial V_{C1}}{\partial x_{C1}} [(f_1 - f_C) F_{C1}(t) - \delta x_{C1}(t)] \end{array} \right\} \tag{17}$$

$$\rho V_{C2} = \max_{F_{C2}(t)} \left\{ \begin{array}{l} [(a_2 - a_{C2}) F_{C2}(t) - \frac{c_2}{2} F_{C2}^2(t) + b_2 + l x_{C2}(t)] \\ \qquad + \frac{\partial V_{C2}}{\partial x_{C2}} [(f_2 - f_C) F_{C2}(t) - \delta x_{C2}(t)] \end{array} \right\} \tag{18}$$

3.2 Result of equilibrium

Proposition 1: Under the condition that the bandwagon effect is satisfied, the extent of efforts to govern the marine pollution, and social benefits of developed countries and developing countries are respectively Equations 19-22 (the specific solving procedure is shown in Appendix 1):

$$F_{B1}^{\star}(t) = \frac{a_1 + \lambda p}{c_1} + \frac{f_1}{c_1} \frac{l}{\rho + \delta} \tag{19}$$

$$F_{B2}^{\star}(t) = \frac{a_2}{c_2} + \frac{f_2}{c_2} \frac{l}{\rho + \delta} \tag{20}$$

$$V_{B1}^{\star} = \frac{l}{\rho+\delta} x_{B1} + \frac{1}{\rho}(a_1 + \lambda p)\left(\frac{a_1+\lambda p}{c_1} + \frac{f_1}{c_1}\frac{l}{\rho+\delta}\right) - \frac{c_1}{2}\frac{1}{\rho}\left(\frac{a_1+\lambda p}{c_1} + \frac{f_1}{c_1}\frac{l}{\rho+\delta}\right)^2 + \frac{l}{\rho+\delta}\frac{1}{\rho} f_1 \left(\frac{a_1+\lambda p}{c_1} + \frac{f_1}{c_1}\frac{l}{\rho+\delta}\right) \tag{21}$$

$$V_{B2}^{\star} = \frac{l}{\rho+\delta} x_{B2} + \frac{1}{\rho} p a_2 \left(\frac{a_2}{c_2} + \frac{f_2}{c_2}\frac{l}{\rho+\delta}\right) - \frac{1}{\rho} p \frac{c_2}{2}\left(\frac{a_2}{c_2} + \frac{f_2}{c_2}\frac{l}{\rho+\delta}\right)^2 + \frac{1}{\rho}\frac{l}{\rho+\delta} p f_2 \left(\frac{a_2}{c_2} + \frac{f_2}{c_2}\frac{l}{\rho+\delta}\right) \tag{22}$$

Conclusion 1: Under the conditions of the bandwagon effect, the greater the impact of marine governance efforts by developing countries on developed nations, the more intensive the marine governance efforts of developed nations will become.

Proposition 2: Under the condition that the free-rider effect is satisfied, the extent of efforts to govern the marine pollution, and social benefits of developed countries and developing countries are respectively Equations 23-26 (the specific solving procedure is shown in Appendix 2):

$$F_{F1}^{\star}(t) = \frac{a_1}{c_1} + \frac{f_1}{c_1}\frac{l}{\rho+\delta} \tag{23}$$

$$F_{F2}^{\star}(t) = \frac{a_2}{c_2} + \frac{f_2}{c_2}\frac{l}{\rho+\delta} \tag{24}$$

$$V_{F1}^{\star} = \frac{l}{\rho+\delta} x_{F1} + \frac{1}{\rho} a_1 \left(\frac{a_1}{c_1} + \frac{f_1}{c_1}\frac{l}{\rho+\delta}\right) - \frac{c_1}{2}\frac{1}{\rho}\left(\frac{a_1}{c_1} + \frac{f_1}{c_1}\frac{l}{\rho+\delta}\right)^2 + \frac{1}{\rho}\frac{l}{\rho+\delta} f_1 \left(\frac{a_1}{c_1} + \frac{f_1}{c_1}\frac{l}{\rho+\delta}\right) \tag{25}$$

$$V_{F2}^{\star} = \frac{l}{\rho+\delta} x_{F2} + \frac{1}{\rho} a_2 \left(\frac{a_2}{c_2} + \frac{f_2}{c_2}\frac{l}{\rho+\delta}\right) - \frac{c_2}{2}\frac{1}{\rho}\left(\frac{a_2}{c_2} + \frac{f_2}{c_2}\frac{l}{\rho+\delta}\right)^2 + \frac{1}{\rho}\frac{l}{\rho+\delta} f_2 \left(\frac{a_2}{c_2} + \frac{f_2}{c_2}\frac{l}{\rho+\delta}\right) \tag{26}$$

Proposition 3: Under the condition that the tragedy of the commons is satisfied, the extent of efforts to govern the marine pollution, and social benefits of developed countries and developing countries are respectively Equations 27-30 (the specific solving procedure is shown in Appendix 3):

$$F_{C1}^{\star}(t) = \frac{a_1 - a_{C1}}{c_1} + \frac{f_1 - f_C}{c_1}\frac{l}{\rho+\delta} \tag{27}$$

$$F_{C2}^{\star}(t) = \frac{a_2 - a_{C2}}{c_2} + \frac{f_2 - f_C}{c_2}\frac{l}{\rho+\delta} \tag{28}$$

$$V_{C1}^{\star} = \frac{l}{\rho+\delta} x_{C1} + \frac{1}{\rho}(a_1 - a_{C1})\left(\frac{a_1-a_{C1}}{c_1} + \frac{f_1-f_C}{c_1}\frac{l}{\rho+\delta}\right) - \frac{c_1}{2}\frac{1}{\rho}\left(\frac{a_1-a_{C1}}{c_1} + \frac{f_1-f_C}{c_1}\frac{l}{\rho+\delta}\right)^2 + \frac{1}{\rho} b_1 + \frac{l}{\rho+\delta}\frac{1}{\rho}(f_1 - f_C)\left(\frac{a_1-a_{C1}}{c_1} + \frac{f_1-f_C}{c_1}\frac{l}{\rho+\delta}\right) \tag{29}$$

$$V_{C2}^{\star} = \frac{l}{\rho+\delta} x_{C2} + \frac{1}{\rho}(a_2 - a_{C2})\left(\frac{a_2-a_{C2}}{c_2} + \frac{f_2-f_C}{c_2}\frac{l}{\rho+\delta}\right) - \frac{c_2}{2}\frac{1}{\rho}\left(\frac{a_2-a_{C2}}{c_2} + \frac{f_2-f_C}{c_2}\frac{l}{\rho+\delta}\right)^2 + \frac{1}{\rho} b_2 + \frac{l}{\rho+\delta}\frac{1}{\rho}(f_2 - f_C)\left(\frac{a_2-a_{C2}}{c_2} + \frac{f_2-f_C}{c_2}\frac{l}{\rho+\delta}\right) \tag{30}$$

TABLE 2 The expenditure amounts of each country.

Countries	Total expenditure (million USD)	Tourism expenditure (million USD)	Hovernment expenditure (million USD)	The expenditure fisheries and aquaculture (million USD)
France	56	38.17	12.23	5.7
Italy	150	126.055	22.375	4.73
Spain	87	49.735	22.49	14.825
Algeria	15	3.1	12.15	0
Libya	0.75	0.625	0.065	0.06
Tunisia	2.9	1.45	0.82	0.67
Egypt	14	6.64	1.05	6.23
Turkey	99	19.405	73.13	6.065

Conclusion 2: Under the conditions of the tragedy of the commons, the greater the ecological loss caused by the over-exploitation of marine resources, the less effort will be made by both developed and developing countries in marine governance.

3.3 Case analysis

In order to describe in more detail the changes in social utility of developed countries and developing countries in the process of collaborative governance of marine pollution, this paper adopts the method of case analysis. The following assumptions are made for relevant parameters:

This paper uses plastic pollution in the Mediterranean Basin as an example to illustrate how developed and developing countries manage plastic pollution. The developed countries include France, Italy, and Spain, while the developing countries include Algeria, Libya, Tunisia, Egypt, and Turkey. According to data from the website (https://theoceancleanup.com/the-price-tag-of-plastic-pollution/), the annual expenditure amounts of each country are shown in the following Table 2.

According to the above data calculation, it can be concluded that $a_{C1}=b_1=(38170000 + 5700000 + 14825000 + 49735000 + 126055000 + 4730000)/(56000000 + 87000000 + 150000000)$ is approximately equal to 0.8;$a_{C2}=b_2=(3100000 + 625000 + 60000 + 1450000 + 670000 + 6640000 + 6230000 + 19405000 + 6065000)/(15000000 + 750000000 + 2900000 + 14000000 + 99000000)=0.34$; $\lambda=(15000000 + 750000000 + 2900000 + 14000000 + 99000000)/(56000000 + 87000000 + 150000000)=0.45$.

Some data could not be obtained from the relevant website; therefore, this paper uses questionnaires to gather missing information. The questionnaire survey helps to understand the level of awareness and attitudes of local residents toward marine pollution governance. For this purpose, the study selected 500 local male residents and 500 local female residents to complete the questionnaire, assessing the satisfaction levels with marine pollution governance in both developed and developing countries. Based on the data from the questionnaire (see Supplementary Material for detailed data), the proportion of reputational loss caused by ecological damage to the reputational gain caused by marine pollution control is 0.5676. In this paper, the above data is rounded, i.e. $f_C=0.57f$.

The discount factor reflects the preferences of game participants for current versus future benefits or costs. Typically, individuals tend to favor immediate benefits over future ones, so future benefits or costs need to be "discounted" to their present value. A discount factor closer to 1 indicates that a country places greater emphasis on future benefits or costs, while a value closer to 0 suggests a stronger focus on current benefits or costs. In the context of marine pollution control in the Mediterranean Sea, environmental issues are characterized by long-term and cumulative effects. For instance, reducing plastic pollution or restoring marine ecosystems may require years or even decades (Pusker et al., 2024). Moreover, both developed and developing countries generally attach significant importance to future environmental costs and benefits. Therefore, the discount factor in this study is set closer to 1. For convenience, this article assumes that the discount rate ρ that occurs over time is 0.9.

Reputation is a form of long-term accumulated social capital, the formation of which requires time and sustained effort. Once established, it typically does not dissipate quickly. For instance, the reputation gained by developed or developing countries in addressing marine pollution in the Mediterranean Sea is recognized and remembered by the international community for an extended period. Therefore, a low decay rate of reputation (close to 0) reflects its enduring nature. The governance of marine pollution in the Mediterranean Sea is a long-term process, with its effects and impacts persisting over a considerable duration (López-Martínez et al., 2022). The reputation acquired by game participants through governance actions is often linked to their long-term environmental contributions. If the decay rate of reputation is too high (close to 1), it fails to accurately capture these long-term effects. A lower decay rate better characterizes the persistence of reputation and the long-term value of governance actions. For convenience, this article assumes that decay δ of reputation is 0.1.

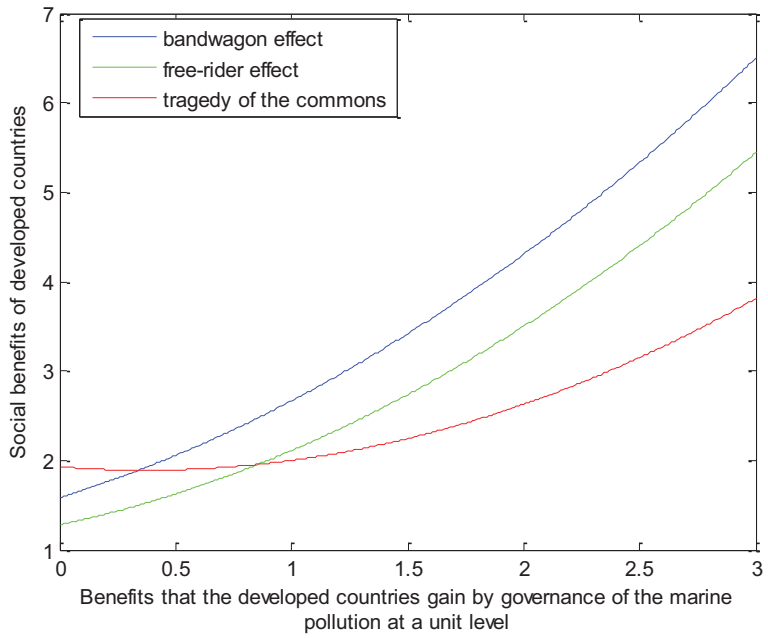

FIGURE 2
Impact of benefits of developed countries on social welfare.

When the reputation that developed countries gain by governance of the marine pollution at a unit level is 1, this article can calculate the social benefits of developed countries as Equations 31-33:

$$V_{B1}^{\star} = 1 + 1.111(0.5a_1 + 0.725)^2 \quad (31)$$

$$V_{F1}^{\star} = 1 + 1.111(0.5a_1 + 0.5)^2 \quad (32)$$

$$V_{C1}^{\star} = 1.89 + 1.111(0.5a_1 - 0.185)^2 \quad (33)$$

The following graph (named Figure 2) can also be produced:

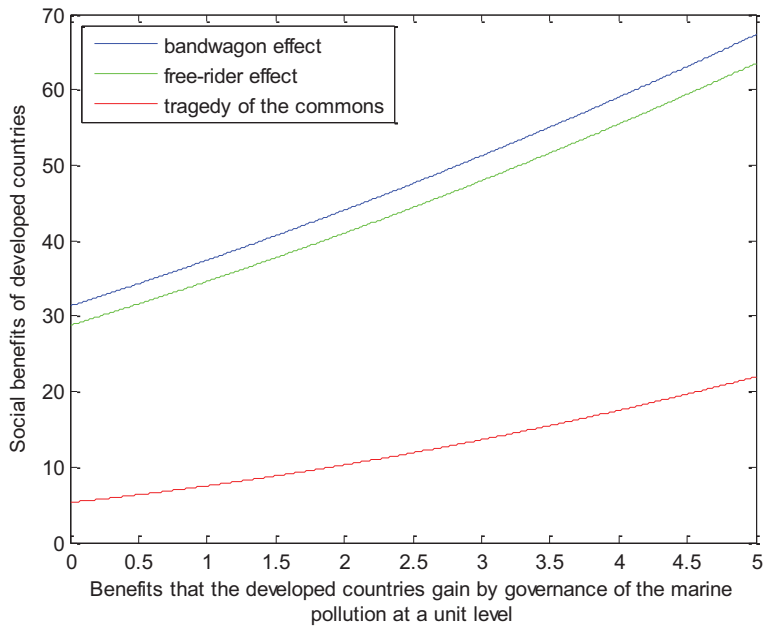

FIGURE 3
Impact of benefits of developed countries on social welfare.

When the reputation that developed countries gain by governance of the marine pollution at a unit level is 10, this article can calculate the social benefits of developed countries as Equations 34-36:

$$V_{B1}^{\star} = 1 + 1.111(0.5a_1 + 5.225)^2 \tag{34}$$

$$V_{F1}^{\star} = 1 + 1.111(0.5a_1 + 5)^2 \tag{35}$$

$$V_{C1}^{\star} = 1.89 + 1.111(0.5a_1 + 1.75)^2 \tag{36}$$

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

Conclusion 3: When the reputation and benefits gained from managing marine pollution are relatively small, the governance of marine pollution by developed countries most clearly reflects the tragedy of the commons. Otherwise, the governance of marine pollution by developed countries most clearly reflects the bandwagon effect.

When the reputation that developing countries gain by governance of the marine pollution at a unit level is 1, this article can calculate the social benefits of developing countries as Equations 37-39:

$$V_{B2}^{\star} = 1 + 1.111 \times (0.5a_2 + 0.5)^2 \tag{37}$$

$$V_{F2}^{\star} = 1 + 1.111(0.5a_2 + 0.5)^2 \tag{38}$$

$$V_{C2}^{\star} = 1.38 + 1.111(0.5a_2 + 0.045)^2 \tag{39}$$

In the context of marine pollution governance, developing countries typically do not exhibit the free-rider effect, as they often face more immediate environmental and survival pressures (e.g., depletion of fishery resources, health risks for coastal populations) and lack sufficient technology and financial resources to independently address pollution issues. Consequently, they are compelled to actively participate in governance efforts. In contrast, developed countries are more prone to the free-rider effect, as their geographical locations (e.g., being distant from pollution sources) and economic strength enable them to withstand certain environmental risks. Additionally, they can leverage technology transfers or financial aid to shift the primary governance costs to developing countries, thereby enjoying the benefits of governance without direct investment. This asymmetry reflects an imbalance in the distribution of power and responsibility. Therefore, when comparing the three effects, this study excludes the scenario of the free-rider effect for developing countries.

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

When the reputation that developing countries gain by governance of the marine pollution at a unit level is 10, this article can calculate the social benefits of developing countries as Equations 40-42:

$$V_{B2}^{\star} = 1 + 1.111(0.5a_2 + 5)^2 \tag{40}$$

$$V_{F2}^{\star} = 1 + 1.111(0.5a_2 + 5)^2 \tag{41}$$

$$V_{C2}^{\star} = 1.38 + 1.111(0.5a_2 + 1.98)^2 \tag{42}$$

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

Conclusion 4: When the reputation and benefits gained from managing marine pollution are relatively small, the governance of marine pollution by developing countries most clearly reflects the

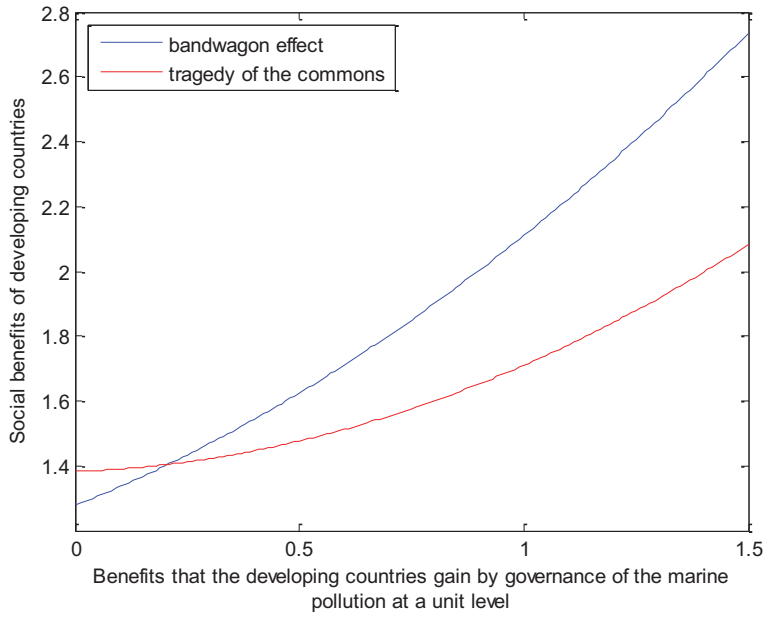

FIGURE 4
Impact of benefits of developing countries on social welfare.

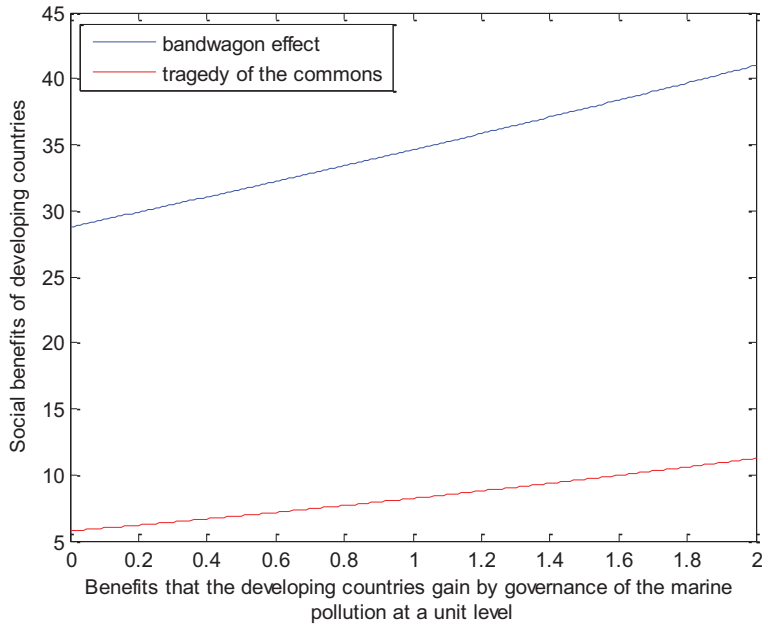

FIGURE 5
Impact of benefits of developing countries on social welfare.

tragedy of the commons. Otherwise, the governance of marine pollution by developing countries most clearly reflects the bandwagon effect.

4 Discussion

Although this study uses models and a large amount of data to obtain certain results, it still has specific regional applicability. First, it applies to areas of multinational shared seas, where the tragedy of the commons is particularly prominent in marine pollution governance, especially in international shared waters. This research is applicable to sea areas jointly used by multiple countries, such as the South China Sea, the Mediterranean Sea, and the Baltic Sea. These regions often face issues of over-exploitation, resource abuse, and inadequate pollution control due to difficulties in coordinating the interests of different countries, leading to the occurrence of the "tragedy of the commons."

Second, coastal areas with high levels of industrialization and population density. The free-rider effect is common in situations where the responsibility for marine pollution governance is unclear. This research is applicable to highly industrialized and densely populated coastal regions, such as the eastern coast of China, India, Southeast Asia, and coastal cities in the United States. In these areas, pollution-producing enterprises or stakeholders often evade responsibility or reduce governance costs, relying on the efforts of others to take action in pollution control.

Third, regions with conflicts of interest among multiple parties. The bandwagon effect indicates that stakeholders often choose sides in the face of conflicts of interest. This applies to areas where the development of marine resources and pollution governance are entangled with the interests of various parties, such as in regions with developed industries like fisheries, oil and gas extraction, and tourism. Pollution control in such areas requires multi-party coordination, interest balancing, and the establishment of fair governance mechanisms.

Conclusion 1 explores the impact of developing countries' marine governance on developed countries and the response of developed countries under the conditions that satisfy the "bandwagon effect." The following is a detailed explanation of Conclusion 1. When developing countries take action in marine governance, especially when these actions have significant effects on the global marine environment, resource allocation, or international shipping, developed countries will feel the impact of these changes. The more significant the actions taken by developing countries, the greater the impact, and the more developed countries need to respond to protect their own interests. According to the bandwagon effect, the greater the impact of developing countries' marine governance on developed countries, the more pressure or threats are felt by developed countries (Nadeau et al., 2016). In response to this impact, developed countries will have to increase their efforts and investments in marine governance to ensure that their interests are not compromised or that they can maintain their dominance in international marine affairs. The efforts of developed countries may manifest in the form of stricter marine governance policies, stronger international cooperation, or greater resource allocation to ensure their influence and voice in marine affairs. Under the conditions that satisfy the bandwagon effect, the greater the impact of developing countries' marine governance on developed countries, the more efforts and investments developed countries will make in marine governance to counter this impact. This phenomenon indicates that the behavior of developed

countries is a response to the actions of developing countries, aimed at maintaining their interests and status in international marine affairs.

Conclusion 2 discusses the changes in governance efforts by developed or developing countries in response to ecological losses caused by the overexploitation of marine resources under the conditions of the "tragedy of the commons." The following is a detailed explanation. Under the tragedy of the commons, each participant tends to overuse resources, as they believe that refraining from using them would allow others to benefit, thereby exacerbating resource depletion. Over-exploitation of the oceans refers to the excessive use of marine resources, such as overfishing, pollution discharge, and over-extraction of marine minerals, leading to the destruction of marine ecosystems. These ecological losses may include the depletion of fishery resources, a decline in marine biodiversity, and an increase in marine pollution. Within the framework of the tragedy of the commons, as ecological losses intensify, individual countries (whether developed or developing) may perceive their governance efforts as having a limited impact on the overall ecological recovery or protection, as other countries may continue to over-exploit resources (Helinski et al., 2021). In this scenario, countries may develop a sense of "ineffective governance," believing that even if they reduce exploitation and strengthen governance, the actions of others will offset these efforts, ultimately leading to a reduction in their willingness and investment in governance. In summary, as ecological losses increase and the effects of the tragedy of the commons become more apparent, trust and cooperation between countries become more difficult to establish, and countries may reduce their governance efforts, believing that their individual actions will not significantly change the overall trend. Therefore, under the conditions of the tragedy of the commons, the more severe the ecological losses caused by over-exploitation of marine resources, the more countries (whether developed or developing) may view their governance efforts as ineffective, and thus tend to reduce their investment. This situation highlights how the tragedy of the commons hampers international cooperation, weakening governance efforts due to a lack of trust and coordination.

Conclusion 3 discusses how developed countries exhibit different behavioral patterns in marine pollution governance depending on the reputation and benefits they gain, manifesting the dynamics of both the tragedy of the commons and the bandwagon effect. When developed countries realize that their efforts to control marine pollution result in limited improvements in international reputation and economic benefits, it indicates that the returns on their environmental efforts are relatively low. In such cases, developed countries are more likely to reduce their investments and efforts in marine pollution governance. Conversely, if developed countries gain significant boosts in international reputation and substantial economic benefits through marine pollution control, their behavioral patterns change (Shaikh et al., 2017). The greater the reputation and rewards, the more developed countries are incentivized to take further action to manage marine pollution, thereby maintaining or enhancing their position and influence in the international community. In such cases, the behavior of developed countries aligns more closely with the bandwagon effect. The bandwagon effect refers to the tendency of nations to align their actions or positions in international relations based on their interests and political stance (Bindra et al., 2022). When developed countries gain significant reputation and benefits from marine pollution governance, they become more proactive in taking governance measures to solidify and elevate their international standing. This proactive governance behavior can be seen as a form of "bandwagoning," where developed countries secure their place and pursue benefits in international affairs through environmental actions. Therefore, when the perceived reputation and benefits are small, developed countries may view the returns from marine pollution governance as insufficient and reduce their governance efforts, displaying characteristics of the tragedy of the commons, where the pursuit of self-interest leads to the neglect of overall environmental protection. However, when the perceived reputation and benefits are substantial, developed countries will increase their governance efforts, demonstrating the bandwagon effect, where they seek to secure international reputation and economic gains through active governance, thereby consolidating their position in international affairs.

However, the "low reputation and low returns" mentioned in Conclusion 3 are subject to specific conditions. From a political economy perspective, the phenomenon of low reputation and returns in marine pollution governance fundamentally reflects the structural contradictions in the provision of global public goods.

At the political level, the willingness of developed countries to participate is significantly constrained by domestic interest group dynamics. For instance, industries such as shipping and oil, which possess strong political lobbying power, often oppose stringent environmental regulations because governance measures may increase their operational costs (Xiao et al., 2024b). Simultaneously, the short-sightedness induced by electoral cycles leads governments to prioritize immediate economic issues over long-term environmental benefits. This domestic political-economic landscape makes it difficult for environmental policies to garner sufficient support, thereby undermining the credibility of international commitments.

On the economic dimension, market failures and externalities are particularly pronounced. The value of marine ecosystem services is difficult to monetize through traditional market mechanisms, resulting in a lack of clear economic returns on governance investments. Notably, marine pollution exhibits significant spatial externalities—the benefits of upstream countries' governance efforts spill over to downstream countries, yet current international institutions lack effective compensation mechanisms (Tzannatos, 2010). For example, in the governance of marine debris in the Northwest Pacific region, China, Japan, and South Korea have long faced disputes over cost-sharing. This inability to internalize positive externalities, coupled with the pollution displacement effects driven by the industrialization of developing countries, has led to diminishing marginal returns on governance investments, further reducing the motivation for participation.

To enhance the effectiveness of collaborative marine pollution governance, policymakers should leverage the bandwagon effect

while mitigating the tragedy of the commons and free-rider problems. Since developed countries are more likely to engage in collective action when reputational and economic benefits are significant, international agreements should amplify incentives for participation. For instance, green branding initiatives (e.g., "Blue Economy" certifications) and financial rewards (e.g., preferential trade access for compliant nations) can motivate developed countries to lead by example, triggering a positive spillover effect where others follow suit (Carlson et al., 2024).

Additionally, stronger enforcement mechanisms are needed to prevent free-riding and ensure equitable contributions. This could include transparency measures (e.g., public rankings of national pollution control efforts) and penalties for non-compliance (e.g., sanctions or loss of access to international marine conservation funds). For developing nations, capacity-building support (e.g., technology transfer and funding for waste management) can reduce reliance on developed countries' efforts, ensuring a more balanced and sustainable governance framework. By combining reputational incentives, economic benefits, and accountability measures, global marine pollution governance can shift from a tragedy of the commons to a collective success story.

Conclusion 4 explores the behavioral patterns of developing countries in marine pollution governance under different circumstances, incorporating the theories of the tragedy of the commons, the bandwagon effect, and the free-rider effect. The following is a detailed explanation. When developing countries engage in marine pollution governance and find that the gains in international reputation and economic benefits are relatively small, it indicates that their returns on environmental efforts are low. Due to high governance costs and low returns, developing countries may be inclined to reduce their investment in pollution control. In this context, developing countries may exhibit behavioral patterns consistent with the tragedy of the commons. Since the perceived reputation and benefits from governance are limited, developing countries may believe that even if they reduce pollution, other nations, particularly developed ones, may continue to pollute the oceans, resulting in no overall environmental improvement. As a result, these countries may choose to reduce their governance efforts or even continue polluting, displaying the classic characteristics of the tragedy of the commons, where short-term interests are prioritized at the expense of long-term environmental protection.

If marine pollution governance can bring significant improvements in international reputation and economic benefits to developing countries, it will incentivize them to adopt more proactive governance measures. In this case, they will not only consider the direct environmental benefits but also the international standing and potential economic returns resulting from active governance. When marine pollution control yields substantial reputation and benefits, developing countries may exhibit characteristics of the bandwagon effect. This means they will choose to actively govern pollution based on their interests and international relations to gain more international recognition and economic support, thereby positioning themselves advantageously in global environmental governance (Bindra et al., 2022). This behavior is a strategic choice aimed at aligning with the international community or gaining greater influence. Therefore, when reputation and benefits are small, developing countries tend to exhibit the tragedy of the commons, reducing their governance efforts due to insufficient returns. When reputation and benefits are substantial, developing countries demonstrate the bandwagon effect, actively governing pollution to gain international reputation and economic benefits.

To address the tragedy of the commons in marine pollution governance among developing countries—where weak incentives lead to unsustainable exploitation—international frameworks should prioritize capacity-building and direct benefits. Financial and technological support, such as grants for waste management infrastructure and clean-up technologies, can reduce the short-term economic burdens that drive over-exploitation. Additionally, localized incentive systems, such as payments for ecosystem services (PES) or community-based monitoring programs, can align national interests with long-term conservation goals, transforming passive resource depletion into active stewardship (Nobakht et al., 2024).

When reputational or economic gains are sufficient, developing countries may exhibit bandwagon effects (following successful regional models). To maximize cooperation while minimizing exploitation, global agreements should link participation to tangible rewards, such as preferential trade access or climate finance eligibility (Tennant et al., 2024). By combining targeted support, conditional incentives, and accountability measures, international governance can shift developing countries from passive beneficiaries to proactive partners in marine pollution control.

Although the findings of this study are based on models and extensive data, there are still certain limitations. First, there is the challenge of transnational coordination. The limitation of the tragedy of the commons lies in the extreme complexity of coordinating governance across international waters. Different countries have varying environmental policies, economic interests, and stages of development, making it difficult to reach a consensus on governance agreements. Therefore, the feasibility of such collaborative governance in international waters is severely constrained.

Second, the prevalence of the free-rider effect. In marine pollution governance, the free-rider effect often results in some countries or corporations being unwilling to bear their fair share of the costs in governance actions. This issue is more pronounced in developing countries or underdeveloped regions, where governance capacity is limited, and there is often an expectation that developed nations should take on greater responsibility. Consequently, the unequal distribution of governance costs may hinder the effective implementation of collaborative governance.

Third, the divergence of interests caused by the bandwagon effect. The limitation of the bandwagon effect is evident in marine pollution governance, where different stakeholders often align based on their own interests, complicating and delaying the decision-making process during governance. For instance, certain countries or industries (such as fisheries or marine mining) may be hesitant to support stringent environmental governance measures, exacerbating divisions among stakeholders and weakening the effectiveness of governance actions.

In the collaborative governance of marine pollution, cultural, political, and economic factors profoundly influence the manifestations of the bandwagon effect, free-rider effect, and tragedy of the commons. In regions dominated by collectivist cultures (e.g., East Asia, Northern Europe), social norms can reinforce the bandwagon effect, encouraging parties to follow mainstream environmental actions while curbing free-riding behavior and mitigating the tragedy of the commons (Kantorowicz-Reznichenko and Kantorowicz, 2021). For instance, Japan's shame culture and Norway's sense of community honor drive active participation in governance. In contrast, in regions where individualism prevails (e.g., North America), environmental actions rely more on economic incentives, free-riding is more prevalent, and the tragedy of the commons is more pronounced, often necessitating mandatory regulations or privatization to constrain polluting behaviors.

Political systems also shape the functioning of these effects. In regions with strong government leadership (e.g., China, the European Union), policy guidance can steer the bandwagon effect, legal measures can reduce free-riding, and centralized governance can alleviate the tragedy of the commons. However, in regions with weaker governance capacity (e.g., Southeast Asia, Africa), transnational cooperation often falters due to disparities in enforcement, leading to rampant free-riding and worsening the tragedy of the commons (Nguyen, 2024). For example, countries in the Mekong River region have been evading responsibility in plastic pollution governance, while conflict zones like Somalia suffer from ongoing marine ecological destruction due to a lack of effective regulation.

Economic development levels also determine governance outcomes across regions. High-income economies (e.g., Norway, Singapore) have the capacity to invest in environmental technologies, leverage market mechanisms (e.g., fishing quotas, carbon taxes) to reduce free-riding risks, and transform public resources into controlled property rights. However, in developing economies (e.g., India, Brazil), the prioritization of economic growth weakens the willingness to follow environmental actions, and impoverished communities often rely on marine resources for survival, leading to widespread free-riding and the intractability of the tragedy of the commons. For instance, coastal industrial zones in India frequently relax emission standards for economic reasons, while Brazilian fishermen illegally discard fishing nets due to livelihood pressures (Neves et al., 2024).

The interplay of these factors creates a complex landscape for global marine pollution governance. In developed regions like the North Sea, political and economic cooperation can effectively foster transnational governance networks, though events like Brexit may still introduce free-riding risks. In tourism-dependent regions like the Caribbean, economic interests drive small nations to collaborate, but illegal dumping and other behaviors undermine governance efforts. In regions with well-preserved traditional cultures, such as the South Pacific, indigenous taboos have locally protected marine resources, but the impacts of globalization are accelerating the tragedy of the commons. Therefore, effective collaborative governance requires integrating cultural mobilization, institutional innovation, and economic incentives, tailoring differentiated strategies to regional characteristics to systematically mitigate the compounding of negative effects.

5 Conclusion and policy suggestions

Marine pollution has become one of the core challenges in global environmental protection, particularly when it comes to coordinating governance among countries and stakeholders, where issues such as unequal responsibility distribution and inefficiencies in cooperation frequently arise. Traditional governance models struggle to effectively address the cross-regional and cross-sectoral complexity of pollution sources. Therefore, this paper, using the theoretical frameworks of the "bandwagon effect," the "free-rider effect," and the "tragedy of the commons," explores countermeasures for collaborative marine pollution governance based on models and extensive statistical data. When the reputational benefits and returns from marine pollution governance are low, developed countries most clearly manifest the tragedy of the commons in their governance efforts. Conversely, when these benefits and returns are high, the bandwagon effect is more evident in the governance actions of developed countries. Similarly, when the reputational benefits and returns are low, developing countries tend to exhibit the tragedy of the commons in their pollution governance. In contrast, when these benefits and returns increase, developing countries exhibit the bandwagon effect.

In global marine pollution governance, attention should be paid to the distribution of responsibilities and the coordination of interests between developed and developing countries. First, for developed countries, when the reputational benefits and returns from marine pollution governance are low, the tragedy of the commons is likely to occur. Developed countries may tend to neglect their responsibilities, overly relying on the use of public resources while being unwilling to bear the corresponding governance costs. Therefore, it is recommended that international agreements strengthen the accountability of developed countries, setting specific pollution control targets and penalties to prevent the overuse of resources and the evasion of governance responsibilities. When reputational and economic returns increase, developed countries may exhibit the bandwagon effect, aligning with high-reputation coalitions in international cooperation. Thus, promoting globally reputable governance platforms and initiatives can encourage developed countries to proactively assume greater responsibility.

Developing countries should establish a dual-driven governance mechanism based on "reputation and returns." By participating in international marine governance certification systems (e.g., blue economy certification), they can enhance their national image. Simultaneously, they should negotiate with developed countries to establish green technology transfer and carbon credit trading

systems linked to pollution governance performance. When governance outcomes meet regional standards, these agreements should automatically trigger technical assistance and market access incentives. This approach transforms short-term governance costs into long-term revenue streams, effectively steering national behavior from the "tragedy of the commons" toward a virtuous cycle of the "bandwagon effect."

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

YG: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

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

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2025.1549424/full#supplementary-material

References

Agénor, P., and Silva, L. A. P. D. (2025). Global public goods, fiscal policy coordination, and welfare in the world economy. *Eur. Econ. Rev.* 172, 104914. doi: 10.1016/j.euroecorev.2024.104914

Al-Tabbaa, O., Nasr, A., Zahoor, N., and De Silva, M. (2023). Socio-emotional wealth preservation and alliance success in family firms: the role of political instability and alliance management capability. *Brit. J. Manage.* 34, 915–941. doi: 10.1111/1467-8551.12626

Assarzadegan, P., Hejazi, S. R., and Rasti-Barzoki, M. (2024). A stackelberg differential game theoretic approach for analyzing coordination strategies in a supply chain with retailer's premium store brand. *Ann. Oper. Res.* 336, 1519–1549. doi: 10.1007/s10479-023-05372-9

Bai, Y., and Ma, S. (2023). From depression to wellbeing: How to protect the mental health of isolated people under the "dynamic clearance" of patients with COVID-19. *Front. Psychol.* 14, 1124063. doi: 10.3389/fpsyg.2023.1124063

Bindra, S., Sharma, D., Parameswar, N., Dhir, S., and Paul, J. (2022). Bandwagon effect revisited: a systematic review to develop future research agenda. *J. Bus. Res.* 143, 305–317. doi: 10.1016/j.jbusres.2022.01.085

Carlson, A. K., Leonard, N. J., Munawar, M., and Taylor, W. W. (2024). Assessing and implementing the concept of blue economy in laurentian great lakes fisheries: lessons from coupled human and natural systems. *Aquat. Ecosyst. Health* 27, 74–84. doi: 10.14321/aehm.027.02.74

Casas, O. J., and Romera, R. (2011). A stochastic model for the environmental transnational pollution control problem. *Environmetrics* 22, 541–552. doi: 10.1002/env.v22.4

Eastman, J. K., and Iyer, R. (2023). Measuring the bandwagon effect: development of a generalized bandwagon luxury motivation scale. *J. Consum. Behav.* 22, 801–817. doi: 10.1002/cb.v22.4

Farjam, M. (2020). The bandwagon effect in an online voting experiment with real political organizations. *Int. J. Public Opin. R.* 33, 412–421. doi: 10.1093/ijpor/edaa008

Helinski, O. K., Poor, C. J., and Wolfand, J. M. (2021). Ridding our rivers of plastic: a framework for plastic pollution capture device selection. *Mar. pollut. Bull.* 165, 112095. doi: 10.1016/j.marpolbul.2021.112095

Hu, M., Tuilautala, M., and Kang, Y. (2019). Bandwagon effect: special dividend payments. *Int. Rev. Econ. Financ.* 63, 339–363. doi: 10.1016/j.iref.2019.04.002

Ji, W., Zamir, S., Krishna, V., and Stengel, B. V. (2024). Closed-loop and open-loop equilibrium of a class time-inconsistent linear-quadratic differential games. *Int. J. Game Theory* 53, 635–651. doi: 10.1007/s00182-024-00895-2

Jia, K., Hong, S., and Yue, J. (2023). Ordering stability of nash equilibria for a class of differential games. *Open Math.* 21, 20230132. doi: 10.1515/math-2023-0132

Johnson, D. B. (2011). The free-rider principle, the charity market and the economics of mood. *Brit. J. Soc Psychol.* 2, 93–106. doi: 10.1111/j.2044-8309.1982.tb00519.x

Kantorowicz-Reznichenko, E., and Kantorowicz, J. (2021). To follow or not to follow the herd? transparency and social norm nudges. *Kyklos* 74, 362–377. doi: 10.1111/kykl.12274

Kinnucan, H. W., and Myrland, Ø. (2010). Free-rider effects of generic advertising: the case of salmon. *Agribusiness* 19, 315–324. doi: 10.1002/agr.10061

López-Martínez, S., Perez-Rubín, C., Gavara, R., Handcock, R. N., and Rivas, M. L. (2022). Presence and implications of plastics in wild commercial fishes in the alboran sea (mediterranean sea). *Sci. Total Environ.* 850, 158025. doi: 10.1016/j.scitotenv.2022.158025

McMillan, J. (2010). The free-rider problem: a survey. *Econ. Rec.* 55, 95–107. doi: 10.1111/j.1475-4932.1979.tb02209.x

Monk, C. T., Power, M., Freitas, C., Harrison, P. M., Heupel, M., Kuparinen, A., et al. (2023). Atlantic cod individual spatial behaviour and stable isotope associations in a no-take marine reserve. *J. Anim. Ecol.* 92, 2333–2347. doi: 10.1111/1365-2656.14014

Nadeau, R., Cloutier, E., and Guay, J. H. (2016). New evidence about the existence of a bandwagon effect in the opinion formation process. *Int. Polit. Sci. Rev.* 14, 203–213. doi: 10.1177/019251219301400204

Neves, R. A. F., Rodrigues, N., Luca, G. D., Oliveira, M. A. A., Carvalho, T. F., Santos, N. S., et al. (2024). Evidence of plastics contamination and sewage-derived residues in a Brazilian hope spot for conservation of marine biodiversity - cagarras islands and surrounding waters. *Mar. pollut. Bull.* 203, 116407. doi: 10.1016/j.marpolbul.2024.116407

Nguyen, T. H. (2024). A review of marine debris research in Vietnam. *J. Coast. Res.* 40, 588–597. doi: 10.2112/JCOASTRES-D-23-00085.1

Nobakht, M., Zahraie, B., Dolatabadi, N., and Rezazadeh, H. (2024). Application of payments for ecosystem services and nexus modeling for agriculture land use management. *Arab. J. Geosci.* 17, 64. doi: 10.1007/s12517-024-11860-4

Petrosyan, L. A., and Pankratova, Y. B. (2023). Solutions of cooperative differential games with partner sets. *Dokl. Math.* 108, S92–S99. doi: 10.1134/S1064562423600719

Plaksin, A., and Kalev, V. (2024). "Zero-sum positional differential games as a framework for robust reinforcement learning: deep q-learning approach," in *Proceedings of the 41st International Conference on Machine Learning*, vol. 1660. , 40869–40885.

Pusker, S. M., DeBie, K. A., Clark, M. L., Neophytou, A. M., Keller, K. P., Gutilla, M. J., et al. (2024). Environmental justice and sustainable development: cumulative environmental exposures and all-cause mortality in Colorado counties. *Sustainability* 16, 9147. doi: 10.3390/su16219147

Rivers, N., and Shiell, L. (2014). Free-riding on energy efficiency subsidies: the case of natural gas furnaces in Canada. *Energ. J.* 37, 239–266.

Rotkin-Ellman, M., Wong, K. K., and Solomon, G. M. (2012). Seafood contamination after the bp gulf oil spill and risks to vulnerable populations: a critique of the fda risk assessment. *Environ. Health Persp.* 120, 157–161. doi: 10.1289/ehp.1103695

Sannigrahi, S., Basu, B., Basu, A. S., and Pilla, F. (2022). Development of automated marine floating plastic detection system using sentinel-2 imagery and machine learning models. *Mar. pollut. Bull.* 178, 113527. doi: 10.1016/j.marpolbul.2022.113527

Shaikh, S., Malik, A., Akram, M. S., and Chakrabarti, R. (2017). Do luxury brands successfully entice consumers? the role of bandwagon effect. *Int. Market. Rev.* 34, 498–513. doi: 10.1108/IMR-09-2014-0302

Skirtun, M., Sandra, M., Strietman, W., Burg, S., Raedemaecker, F. D., and Devriese, L. (2021). Plastic pollution pathways from marine aquaculture practices and potential solutions for the north-east atlantic region. *Mar. pollut. Bull.* 174, 113178. doi: 10.1016/j.marpolbul.2021.113178

Soares, J., Miguel, I., Venncio, C., Lopes, I., and Oliveira, M. (2021). On the path to minimize plastic pollution: the perceived importance of education and knowledge dissemination strategies. *Mar. pollut. Bull.* 171, 112890. doi: 10.1016/j.marpolbul.2021.112890

Stolwijk, S. B., Schuck, A. R., and Vreese, C. H. (2017). How anxiety and enthusiasm help explain the bandwagon effect. *Int. J. Public Opin. R.* 29, 554–574. doi: 10.1093/ijpor/edw018

Tennant, D., Davies, S., and Tennant, S. (2024). Determinants of access to climate finance: nuanced insights for sids and other vulnerable economies. *World Dev.* 180, 106623. doi: 10.1016/j.worlddev.2024.106623

Tzannatos, E. (2010). Ship emissions and their externalities for the port of piraeus – Greece. *Atmos. Environ.* 44, 400–407. doi: 10.1016/j.atmosenv.2009.10.024

Wei, J., and Wang, C. (2021). Improving interaction mechanism of carbon reduction technology innovation between supply chain enterprises and government by means of differential game. *J. Clean. Prod.* 296, 126578. doi: 10.1016/j.jclepro.2021.126578

Xiao, G., Pan, L., and Lai, F. (2025). Application, opportunities, and challenges of digital technologies in the decarbonizing shipping industry: a bibliometric analysis. *Front. Mar. Sci.* 12, 1523267. doi: 10.3389/fmars.2025.1523267

Xiao, G., Wang, T., Shang, W., Shu, Y., Biancardo, S. A., and Jiang, Z. (2024a). Exploring the factors affecting the performance of shipping companies based on a panel data model: A perspective of antitrust exemption and shipping alliances. *Ocean Coast. Manage.* 253, 107162. doi: 10.1016/j.ocecoaman.2024.107162

Xiao, G., Xiao, Y., Shu, Y., Ni, A., and Jiang, Z. (2024b). Technical and economic analysis of battery electric buses with different charging rates. *Transport. Res. D-Tr. E.* 132, 104254. doi: 10.1016/j.trd.2024.104254

Zhang, F., and Xu, K. (2024). Can China's ecologically civilized environmental policy (ecep) have a positive spillover effect on pro-environmental behavior? evidence from the chinese general social survey, (2021) data. *Pol. J. Environ. Stud.* 33, 927–937. doi: 10.15244/pjoes/172025