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Evolutionary game analysis of Arctic shipping black carbon emission reduction strategies based on government regulation and port fee differential policies

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The issue of black carbon (BC) emissions from Arctic shipping has garnered significant attention from the international community. Promoting action among key stakeholders is particularly critical at this juncture. This study constructed a BC emissions governance model for Arctic shipping based on government regulation and differential port fee policies, and established an evolutionary game model of Arctic coastal governments, ports and shipping companies, analyzing the impact of evolutionary steady state and various parameter variables on the choice of stakeholder behavioral strategies. The results show that $E_8(1, 1, 1)$ is the optimal steady-state case for the system, which means active government regulation along the Arctic, implementation of port fee differential policies by port, and active emission reductions by shipping companies. During the game process, each participant's strategy is influenced by the initial choices made by other participants. Among them, the coastal government's first supervision is the key factor in promoting the emission reduction behavior of the shipping industry. At the same time, appropriate coastal government reward and punishment mechanisms and differential port fee policies play a decisive role in emission control. If the policy intensity is too low, shipping companies may lack action for a long time. Excessive policy intensity may affect the long-term sustainability of the policy. In addition, lower emission reduction technology costs help to enhance the willingness of shipping companies to reduce emissions. On the contrary, high technology costs will weaken their enthusiasm and may cause the government to turn to passive regulation due to regulatory costs and delayed market response. Overall, to achieve the desired stabilization strategy for BC emission reductions in Arctic shipping, collective action is essential.

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Introduction

In recent years, the extended navigable season in the Arctic has raised concerns about the environmental impacts of shipping activities, particularly black carbon (BC) emissions (Corbett et al. 2010). Between 2015 and 2021, the number of Arctic navigation vessels increased by 24.46%, and the sailing distance grew by 48.10% (Arctic Council, 2024), while BC emissions rose by 113.99% (ICCT, 2023). BC is particulate matter produced by the incomplete combustion of carbon-containing substances (IPCC, 2007), which is causing irreversible impacts on the Arctic (Browse et al. 2013; Messner, 2019), including reducing the albedo of ice and snow (Messner, 2020) and inducing a local greenhouse effect (Koch et al. 2011). Approximately 20% of the loss of Arctic ice and snow cover during the 20th century is attributed to the effects of BC (Koch et al. 2011). Additionally, BC has a 20-year global warming potential in the Arctic that is 6,200 times greater than that of CO₂ (IPCC, 2014). Moreover, BC threatens the ecological environment along the route (Koch and Del Genio, 2010) and local residents' health and life expectancy (Janssen et al. 2012; Li et al. 2016). Fortunately, BC is a short-lived climate pollutant (atmospheric lifetime is about a few days to a few weeks), meaning that simple regulatory measures can quickly yield climate benefits, making it politically appealing (Aakre et al. 2017).

Since 2008, the International Maritime Organization (IMO) has been paying attention to this issue. In recent years, IMO has reviewed and adopted several resolutions, including the non-mandatory resolution "Protecting the Arctic from Black Carbon Emissions" (MEPC.342 (77)), the "HFO Ban", and the "Goal-based Practical Recommendations for Ship Black Carbon Emission Reduction" (MEPC.393 (82)). While these efforts demonstrate IMO's commitment to addressing this issue, progress in Arctic shipping BC emission reduction governance has been slow, and the current measures lack substantive and mandatory elements (Qi et al. 2024). Specifically, the IMO clearly pointed out that the "HFO Ban" cannot replace BC control measures (IMO, 2022). Similarly, resolution MEPC.393(82), considered and adopted at the 82nd meeting of the Marine Environment Protection Committee (MEPC) in 2024, also implies that the current IMO puts the responsibility of whether to act or not in the hands of the ship operator or the company (IMO, 2024b). However, adopting new emission reduction measures will increase shipping companies' operating costs. Carbon neutrality and desulphurization initiatives in the shipping industry have also proved that shipping companies tend not to reduce emissions voluntarily, because they face operational benefit decisions (Qi et al. 2024). There is still a lack of relevant incentives and regulatory measures in the Arctic region.

Ship activities provide significant economic benefits to ports, but their air pollutant emissions can harm society. Therefore, maritime stakeholders and communities hope that ports will take measures to improve their environmental reputation (Anas S. Alamoush et al. 2022). Many ports respond to this problem through incentive policies and fee adjustments, often as a response to the slow progress of IMO environmental management (Christodoulou et al. 2019). This is a "polluter pays principle", which internalizes the negative external environmental emissions costs by requiring polluters to bear the costs (Mjelde et al. 2019). Currently, some ports in Singapore, Sweden, the Netherlands, and other countries have formulated differentiated policies to reduce air pollutant emissions (Appendix A). Among them, as early as 1999, 23 and 15 ports in Sweden introduced differentiated fairway fees for SO_x and NO_x emissions, respectively, offering partial waterway fee discounts to ships equipped with specific emission reduction technologies. Research indicates that the social value generated by Swedish port policies far exceeds the associated costs, with benefits potentially reaching

3–17 times and 6–9 times the costs (Lindé et al. 2019). This also offers new insights and strategies for reducing BC emissions in Arctic shipping.

It is worth noting that the Swedish analysis report pointed out that past fairway charging systems lacked sufficient incentives for shipping operators to invest in technologies to reduce nitrogen oxide emissions, primarily because the rebates received only covered a small portion of the cost of the emissions reduction equipment (Transport Analysis, 2017). Therefore, based on past experience, uniting stakeholders and promoting cooperation between Arctic coastal governments and ports may be an effective way to enhance the emission reduction effect of the port fee differential policy (Anas S. Alamoush et al. 2022; Masodzadeh et al. 2024). However, the dynamic evolution of the interaction between the current main stakeholders (Arctic coastal governments, ports, and shipping companies) has not been discussed. In particular, the various participating entities will be affected by different interests.

For coastal governments, the direct environmental impacts of BC emissions provide them with an incentive, to encourage all parties to participate in the management and reduction of BC emissions. However, coastal governments need to weigh the regulatory costs (L. Xu et al. 2021a, 2021b), and choose appropriate action strategies. It is necessary to integrate the needs of various stakeholders, formulate scientific and reasonable regulatory policies, and design effective incentive and punishment mechanisms (Jiang et al. 2020), to provide a strong impetus for port policy formulation and shipping companies to take action. For ports, there are two key issues. First, whether or not to develop a policy on port fee differentials. Improving the green image and port competitiveness are the main motivations for policy formulation, but high administrative burdens and management economic challenges are obstacles to decision-making (Masodzadeh et al. 2024). Second, how to effectively implement these policies. Too low incentives cannot encourage shipowners to invest in emission reduction technologies, and too high incentive costs make it difficult for ports to bear. Inappropriate punishment measures may also weaken competitiveness (Anas S. Alamoush et al. 2022; Transport Analysis, 2017). For shipping companies, as the direct implementers of emission reduction measures, there is a trade-off between operating costs and investments in emission reduction (Wu et al. 2022). Government and port policies directly influence the investment costs of shipping companies (through adjustments in coastal government subsidies and port fee policies), which in turn impact their decision-making. Therefore, exploring how Arctic coastal governments and ports regulate and incentivize shipping companies to reduce BC emissions is crucial for Arctic sea ice protection and coastal sustainable development.

This study aims to construct a three-party evolutionary game model involving Arctic coastal governments, ports, and shipping companies. It examines the decision-making processes and dynamic adjustments of the three parties and explores how to encourage the Arctic shipping industry to adopt BC emission reduction technologies under various regulatory decisions and port fee differential policies, along with the differing effects of these strategies. This will help identify effective coastal government reward and punishment mechanisms and port fee differential mechanisms to reduce BC emissions in Arctic shipping. It is important to note that the current port fee differential policy addresses multiple aspects, including CO₂, NO_x, SO_x, sewage, and chemical substances (see Appendix A for details). The port's policy objectives primarily determine these specific emission reduction targets. This study will specifically focus on BC emission reduction. Overall, this study aims to explore the following issues, determine

the evolutionary and stable strategies of BC emission reduction for Arctic coastal governments, ports, and shipping companies, and explain the impact on the emission reduction behavior of shipping companies under different scenarios:

- (1) Should Arctic coastal governments adopt a proactive or reactive approach to regulation when developing Arctic shipping?
- (2) When facing pressure to reduce BC emissions, should Arctic ports passively respond to Arctic coastal governments or actively implement port fee differential policies? Additionally, should ports reduce fees for shipping companies that adopt emission reduction technologies, increase fees for those that passively reduce emissions, or adopt a combination of both?
- (3) Under what conditions will relevant factors affect shipping companies' adoption of BC emission reduction measures? How do these factors work?

The contributions of this study are summarized as follows: (1) It provides an experimental case supporting a broader theory: that is, the feasibility of reducing emissions of short-lived climate pollutants (SLCPs), such as BC, in shipping through port fee differential policies. This study supplements IMO regulations on BC emission reductions and enriches theoretical research on both port fee differential policies and Arctic shipping BC emission reduction. It also offers valuable management insights for Arctic coastal governments and ports in formulating more scientifically grounded emission reduction policies, and for shipping companies in implementing effective reduction plans; (2) Considering the completeness, dynamics and rationality, this study establishes a three-party evolutionary game model of Arctic coastal governments, ports and shipping companies, to help the three parties determine the behavioral strategies for jointly promoting Arctic shipping BC emission reduction under different regulatory decisions and port fee differential policies, which enriches the application of evolutionary games in shipping emission reduction; (3) Numerical simulations were used to analyze the impacts and dynamic evolutionary trajectories of various factors on the emission reduction strategies of Arctic shipping BC emissions. This further clarifies the factors and mechanisms that influence these emission reduction behaviors.

Literature review

Arctic shipping governance primarily depends on a three-tier system involving global, regional, and national levels (Qi et al. 2024). At the international level, the United Nations Convention on the Law of the Sea (UNCLOS), as one of the key international treaties, stipulates in its special protection clause for “ice-covered areas” (Article 234) that “coastal states have the right to adopt and implement non-discriminatory laws and regulations to prevent, reduce and control marine pollution from ice-covered areas within the exclusive economic zone”. This clause grants Arctic coastal states strict authority to prevent and control ship pollution, providing a legal foundation for regional governance (Gavrilov et al. 2019). In addition, IMO's governance evolution trajectory for the issue of BC emissions from Arctic shipping has gone through the following steps: “Definition of the nature of BC emissions (Pollution Prevention and Response, PPR 2nd session, 2015) → Standardization of measurement methods (PPR 5th session, 2018) → Identification of possible emission reduction measures (PPR 6th session, 2019) → Introduction of the ‘HFO Ban’ (MEPC 76th session, 2021) → Formulation of non-mandatory resolutions (MEPC.342 (77) resolution, 2021) → Issuance of recommended guidelines for emission reduction practices (MEPC.393 (82), 2024)” (IMO, 2015, 2018, 2019, 2021a, 2021b, 2024b).

At the regional governance level, the Arctic Council is the primary high-level intergovernmental forum, composed of representatives from the eight Arctic countries and six Arctic indigenous communities. Although it does not have legal status and the power to make international law, it provides member states with an important cooperation and negotiation platform. It has facilitated a number of multilateral agreements related to maritime activities, such as the Arctic Search and Rescue Agreement signed in 2011. At the same time, it has a substantial impact on Arctic BC governance through two paths: On one hand, it fosters a scientific consensus mechanism, such as the establishment of the Expert Group on Short-Lived Climate Pollutants (2010) and the release of the “Impacts on Arctic Climate” report (2011) (Quinn et al. 2011); On the other hand, it advances the process of policy institutionalization. For instance, the “Framework for Action on Enhanced Black Carbon and Methane Emissions Reductions” (2015) set a collective goal for Arctic countries to reduce BC emissions by 25–33% by 2025, compared to 2013 levels (Arctic Council Secretariat, 2015). Furthermore, it has released three Arctic BC progress reports (2017, 2019, 2021) (Arctic Council, 2017, 2019, 2021). At the national level, BC governance measures in Arctic countries mainly focus on international cooperation, emission inventory development, project funding, and scientific research (Qi et al. 2024). Additionally, Canada and Norway plan to establish Emission Control Areas (ECAs) in their Arctic waters to reduce SO_x, NO_x, and BC emissions (IMO, 2024a).

Research on BC emissions from Arctic shipping primarily focuses on assessment (Q. Chen et al. 2021b), observation (Marelle et al. 2016) and impact (Li et al. 2021), while a small number of scholars have discussed possible control measures (Zhang et al. 2019), as well as their economics (Corbett et al. 2014) and economic impact (Kong et al. 2021). Additionally, some scholars have focused on the governance and regulation of BC emissions from Arctic shipping (Qi et al. 2024). The study suggests that to mitigate irreversible damage to the Arctic environment, Arctic coastal countries and ports should take the initiative to implement emission reduction requirements for ships operating in the Arctic, ahead of the IMO negotiation process (Qi et al. 2024). However, existing research has yet to address the critical question of how to incentivize stakeholders to take action on emission reductions.

In addition to global and regional regulations, many ports are adopting market-based policy tools to reduce the negative impacts of shipping activities (specific port policies are shown in Appendix A), such as the Clean Shipping Index (CSI), the Environmental Ship Index (ESI), and the Environmental Port Index (EPI). Existing research has also extensively studied the impact of port (fairway) fee differentiation policies (Lindé et al. 2019; Merkel and Lindgren, 2022; Mjelde et al. 2019; Vierth and Johansson, 2020). Taking Sweden's policy as an example, Merkel and Lindgren (2022) analyzed the impact of fairway fees on ship deployment and utilization, which affects the supply structure of short-sea shipping by inducing ship owners to mitigate increased costs by adjusting their deployment strategies. Lindé et al. (2019) analyzed the impact of Sweden's environmentally differentiated fairway fees on ship emission reduction decisions, and explored the interaction between waterway fees. Vierth and Johansson, (2020) note that fairway fee differential policies can accelerate the implementation of new technologies, promote fuel switching, encourage more efficient operations, and facilitate other actions beyond the scope of existing regulations.

Evolutionary game theory provides a powerful tool for analyzing shipping emission reduction stakeholders' complex and diverse interactions (Sheng et al. 2023). Based on the concept of limited profit for decision-makers (Aumann, 1997), it achieves

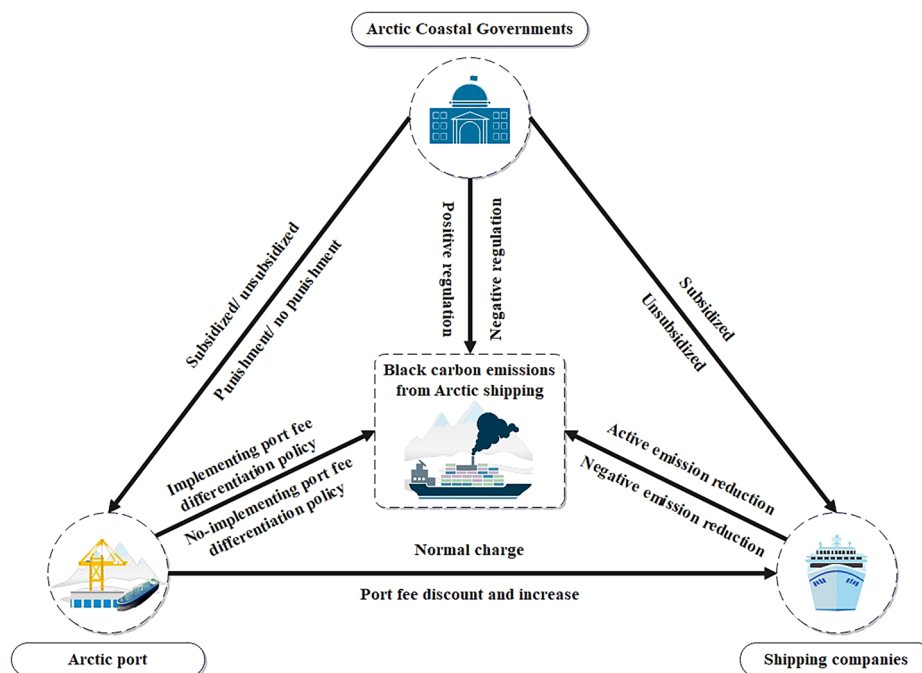


Fig. 1 Tripartite participant relationship diagram. This figure illustrates the interaction among Arctic coastal governments, Arctic ports and shipping companies in reducing BC emissions in Arctic shipping. The Arctic coastal governments (top) choose to actively or passively regulate for Arctic ports and shipping companies. Arctic ports (lower left) choose whether to implement a differential port fee policy for shipping companies. Shipping companies (lower right) choose to actively or passively reduce BC emissions.

game equilibrium through the imitation and variation of the players' strategies. Currently, scholars widely apply evolutionary game theory in the shipping sector, analyzing the behaviors of various stakeholders from three perspectives: emission reduction strategies (Huang et al. 2023; Meng et al. 2022), emission control areas and government supervision (Jiang et al. 2020; L. Xu et al. 2021a, 2021b), and emission reduction measure selection (J. Chen et al. 2021a; Lang Xu et al. 2021a, 2021b), aiming to identify the optimal solutions for shipping emission reductions. Related research has laid a theoretical foundation for this study. However, existing scholars have focused on issues such as shipping carbon peaking and SO_x emission reduction, and the measures are mostly port emission reduction subsidy policies and carbon taxes, without exploring port fee differential policies and how to deal with Arctic shipping BC emission reductions from the perspective of an evolutionary game.

Increasingly, ports are adopting port fee differential policies as a supplementary measure to emission reduction strategies. The port fee differential policy forces shipping companies to implement emission reduction measures by adjusting port charging standards and establishing a reduction and surcharge mechanism. This fundamentally differs from the implementation method of general port emission reduction incentive policies. Additionally, compared with the formation of a CO₂ knowledge community around the IPCC work, the advocacy of BC policy-related knowledge and the knowledge system related to mitigation still need to be further consolidated and supplemented (Corbera et al. 2016; Yamineva et al. 2023).

Evolutionary game model of Arctic coastal governments, Arctic ports and shipping companies

Problem description. The interaction behavior strategies among the Arctic coastal governments, Arctic ports and shipping companies are shown in Fig. 1. Reducing BC emissions from Arctic shipping involves three key stakeholders: Arctic coastal governments, ports, and shipping companies, with complex interactions

between them. Due to the direct negative impacts of BC emissions on the region, Arctic coastal governments are more likely to prioritize social and environmental benefits, motivating them to actively involve other stakeholders in emission management. In the IMO's efforts to promote BC control in Arctic shipping, countries such as Norway and Finland, as pioneers, have proposed several initiatives and supported stronger oversight of Arctic shipping BC emissions. If Arctic coastal governments take proactive regulatory measures and implement effective and reasonable policies, it will help enhance the willingness of all parties to act. However, this also requires governments to bear higher regulatory costs, such as establishing monitoring systems, training personnel, and addressing violations. Arctic ports and shipping companies can also take the initiative to assume social responsibility and take emission reduction actions, but this also requires increased investment. If Arctic coastal governments choose passive regulation, although relevant standards may be established. However, due to the low frequency of supervision, more responsibilities will rely on ports and shipping companies to manage themselves to meet IMO's BC emission reduction initiatives. Since each of the three parties has different goals and priorities, they make distinct strategic choices and adjust their decisions based on the actions of other participants. Therefore, finding a stable strategic equilibrium for reducing BC emissions from Arctic shipping is crucial, and this can be achieved through evolutionary game models.

Overall, this study attempts to construct a new Arctic shipping BC emission reduction model, which is mainly based on the regulatory behavior of Arctic coastal governments and Arctic ports' port fee differential policy.

Basic assumptions. Based on the above three players' dynamic game relationship, we propose the following model assumptions:

Assumption 1: When aiming to reduce Arctic shipping BC emissions, only the Arctic coastal government, ports, and shipping companies participate in this shipping system, and their

behaviors are all limited and rational. At the same time, the three parties can be regarded as large and infinite groups. Among them, the participants will be in a state of information asymmetry during the game process, and their initial behavior strategies may not be the optimal strategy choices. They will maximize their interests through learning and adjusting strategies until they reach the Evolutionarily Stable Strategy (ESS).

Assumption 2: The strategies of the three participating entities are as follows, the behavioral strategy set of the Arctic coastal government (G) is [active regulation (G_1), passive regulation (G_2)], with selection probabilities of [x and $1 - x$]; The behavioral strategy set of the Arctic port (P) is [implementation of port fee difference policy (P_1), non-implementation of port fee difference policy (P_2)], and with selection probabilities of [y and $1 - y$]; The behavioral strategy set of the shipping company (S) is [active emission reduction (S_1), passive emission reduction (S_2)], and with selection probabilities of [z and $1 - z$].

Assumption 3: The initial social welfare of the Arctic coastal government is W_{g0} . When the shipping company adopts the strategy S_1 , it will bring environmental and social welfare (W_{g1}) to the Arctic coastal government. When the Arctic port adopts the strategy P_2 , it will bring environmental and social welfare (W_{g2} , assuming that no matter what strategy the port chooses, it will take measures such as improving the collection and distribution system to reduce emissions). When the Arctic coastal government chooses the strategy G_1 , it needs to pay additional regulatory costs (C_{g1} , establishment of inspection/audit mechanisms, tracking and monitoring of emissions, creation of specialized agencies or teams, etc), and subsidizing ports and shipping companies that adopt strategies P_1 and S_1 (S_p and S_s), and impose fines (F_p) on ports that choose the strategy P_2 . At the same time, Arctic coastal government will also obtain reputation benefits (B_1). When the Arctic coastal government conducts G_1 and the shipping company chooses S_1 , it means that effective supervision is carried out, and the social evaluation obtained will be improved (B_2). In addition, when the shipping company chooses to adopt the strategy S_2 , it will bring environmental damage (E). When the Arctic coastal government conducts G_2 , it pays additional regulatory costs C_{g2} , which is less than C_{g1} . At the same time, if ports choose the P_2 strategy, Arctic coastal governments will be accused of inaction, damaging their image and incurring reputation costs (C_{g3}).

Assumption 4: The initial income of the port is I_p . It is assumed that when ports choose P_1 and P_2 strategies, they will both take measures such as improving the collection and distribution system, and they need to pay an initial cost (C_{p1}).

At the same time, when the port chooses the P_1 strategy, it will implement the “port fee difference policy” (providing port fee discounts to shipping companies that choose the S_1 strategy, and charging additional fees on the contrary) to encourage ships to apply technical measures to reduce BC emissions. It will pay additional costs (C_{p2} , construction and maintenance of related system costs, labor costs, management costs, etc.), and obtain socially recognized benefits (E_p) by improving the external image of the port (including enhancing corporate social responsibility and external trust in the port, improving green reputation and image, etc.). Among them, part of the port fee is T (including terminal fees, safety fees, pilotage preparation fees, etc., and the port fee difference policy often does not cover all port fees), γ is the port tax and fee discount strength ($0 < \gamma \leq 1$), and λ is the port fee surcharge strength ($0 < \lambda \leq 1$). When the Arctic coastal government adopts the strategy G_1 , the ports will receive subsidies (S_p) for implementing the port fee differential policy, otherwise they will receive penalties (F_p). When shipping companies choose the strategy S_2 , ports will face worker welfare losses (W_p , such as increased health and life loss risks).

Assumption 5: The initial income of the shipping company is I_s , and part of the port fee collected by the port of call is T . When the shipping company chooses the S_1 strategy, it will invest in BC emission reduction technology (installing Diesel particulate filters or using Water-in-fuel emulsion, etc.) and incur additional costs C_s (including installation costs, transformation costs, maintenance costs, operating costs, etc.). In addition, it will receive subsidies from Arctic coastal governments that choose the G_1 strategy (S_s), as well as port fee discounts (γT) for shipping companies that choose the S_1 strategy. When the shipping company chooses the S_2 strategy, it will pay more port fees (λT).

Appendix B summarizes the symbols and definitions of model parameters and variables.

Evolutionary Game Profit Matrix. Based on the above assumptions, this study constructs the profit matrix of Arctic coastal governments, ports, and shipping companies, as shown in Table 1.

Three players replication the dynamic equation and stability analysis

Replication dynamic equation. The expected benefits of active and passive government regulation by Arctic coastal governments are U_{G1} and U_{G2} respectively; The expected benefits of Arctic ports implementing the port fee differential policy and not implementing the port fee differential policy are U_{P1} and U_{P2}

Table 1 The profit matrix of Arctic coastal governments, Arctic ports and shipping companies.

		Arctic coastal government	
		$G_1 (x)$	$G_2 (1-x)$
Arctic port $P_1 (y)$	Shipping company $S_1 (z)$	$W_{g0} + W_{g1} + W_{g2} + B_1 + B_2 - C_{g1} - S_p - S_s$ $I_p + T + E_p + S_p - C_{p1} - C_{p2} - \gamma T$ $I_s + E_s + S_s + \gamma T - C_s - T$	$W_{g0} + W_{g1} + W_{g2} - C_{g2}$ $I_p + T + E_p - C_{p1} - C_{p2} - \gamma T$ $I_s + E_s + \gamma T - C_s - T$
	Shipping company $S_2 (1-z)$	$W_{g0} + W_{g2} + B_1 - C_{g1} - S_p - E$ $I_p + T + \lambda T + E_p + S_p - C_{p1} - C_{p2} - W_p$ $I_s - T - \lambda T$	$W_{g0} + W_{g2} - C_{g2} - E$ $I_p + T + \lambda T + E_p - C_{p1} - C_{p2} - W_p$ $I_s - T - \lambda T$
Arctic port $P_2 (1-y)$	Shipping company $S_1 (z)$	$W_{g0} + W_{g1} + W_{g2} + B_1 + B_2 + F_p - C_{g1} - S_s$ $I_p + T - C_{p1} - F_p$ $I_s + E_s + S_s - C_s - T$	$W_{g0} + W_{g1} + W_{g2} - C_{g2} - C_{g3}$ $I_p + T + C_{p1}$ $I_s + E_s - C_s - T$
	Shipping company $S_2 (1-z)$	$W_{g0} + W_{g2} + B_1 + F_p - C_{g1} - E$ $I_p + T - C_{p1} - F_p - W_p$ $I_s - T$	$W_{g0} + W_{g2} - C_{g2} - C_{g3} - E$ $I_p + T - C_{p1} - W_p$ $I_s - T$

Table 2 Jacobian matrix eigenvalues corresponding to equilibrium points.

Equilibrium point	Jacobian Matrix Eigenvalues		
	λ^1	λ^2	λ^3
$E_1(0, 0, 0)$	$E_s - C_s$	$E_p + \lambda T - C_{p2}$	$B_1 - C_{g1} + C_{g3} + C_{g2} + F_p$
$E_2(1, 0, 0)$	$E_s - C_s + S_s$	$E_p + F_p + S_p + \lambda T - C_{p2}$	$C_{g1} - C_{g2} - C_{g3} - F_p - B_1$
$E_3(0, 1, 0)$	$C_{p2} - E_p - \lambda T$	$B_1 + C_{g2} - C_{g1} - S_p$	$E_s + \lambda T + \gamma T - C_s$
$E_4(0, 0, 1)$	$C_s - E_s$	$E_p - \gamma T - C_{p2}$	$B_1 + B_2 + C_{g2} + C_{g3} + F_p - S_s - C_{g1}$
$E_5(1, 1, 0)$	$C_{g1} + S_p - B_1 - C_{g2}$	$C_{p2} - E_p - F_p - S_p - \lambda T$	$E_s + \lambda T + \gamma T + S_s - C_s$
$E_6(1, 0, 1)$	$C_s - E_s - S_s$	$E_p + F_p + S_p - \gamma T - C_{p2}$	$C_{g1} + S_s - C_{g2} - C_{g3} - F_p - B_1 - B_2$
$E_7(0, 1, 1)$	$C_{p2} - E_p + \gamma T$	$C_s - E_s - \gamma T - \lambda T$	$C_{g2} + B_1 + B_2 - C_{g1} - S_p - S_s$
$E_8(1, 1, 1)$	$C_s - S_s - E_s - \gamma T - \lambda T$	$C_{p2} - E_p - F_p - S_p + \gamma T$	$C_{g1} + S_p + S_s - B_1 - B_2 - C_{g2}$

respectively; The expected benefits of active and passive emission reduction by shipping companies are U_{S1} and v respectively.

According to Table 2, the expected benefits and average expected ($U_{G1}, U_{G2}, \overline{U}_G$) benefits of active or passive regulation by Arctic coastal governments are:

$$\begin{aligned}
 U_{G1} = & yz[W_{g0} + W_{g1} + W_{g2} + B_1 + B_2 - C_{g1} - S_p - S_s] \\
 & + y(1-z)[W_{g0} + W_{g2} + B_1 - C_{g1} - S_p - E] \\
 & + (1-y)z[W_{g0} + W_{g1} + W_{g2} + B_1 + B_2 + F_p - C_{g1} - S_s] \\
 & + (1-y)(1-z)[W_{g0} + W_{g2} + B_1 + F_p - C_{g1} - E]
 \end{aligned} \quad (1)$$

$$\begin{aligned}
 U_{G2} = & yz[W_{g0} + W_{g1} + W_{g2} - C_{g2}] + y(1-z)[W_{g0} + W_{g2} - C_{g2} - E] \\
 & + (1-y)z[W_{g0} + W_{g1} + W_{g2} - C_{g2} - C_{g3}] \\
 & + (1-y)(1-z)[W_{g0} + W_{g2} - C_{g2} - C_{g3} - E]
 \end{aligned} \quad (2)$$

$$\overline{U}_G = xU_{G1} + (1-x)U_{G2} \quad (3)$$

In evolutionary games, the strategy selection process of the participants is called a replication dynamic system, which is a dynamic differential equation that describes the probability of the participants choosing a certain strategy (Friedman, 1991). According to the Malthusian equation, combining Eqs. (1) to (3) can derive the replication dynamic equation of Arctic coastal governments:

$$\begin{aligned}
 F(x) = \frac{dx}{dt} = & x(U_{G1} - \overline{U}_G) = x(1-x)(U_{G1} - U_{G2}) \\
 = & x(1-x)[B_1 + C_{g2} + C_{g3} - C_{g1} + F_p - y(S_p + F_p + C_{g3}) - z(S_s - B_2)]
 \end{aligned} \quad (4)$$

Similarly, the expected benefits and average expected ($U_{P1}, U_{P2}, \overline{U}_P$) benefits of Arctic ports implementing or not

implementing the port fee differential policy are:

$$\begin{aligned}
 U_{P1} = & xz[I_p + T + E_p + S_p - C_{p1} - C_{p2} - \gamma T] \\
 & + (1-x)z[I_p + T + E_p - C_{p1} - C_{p2} - \gamma T] \\
 & + x(1-z)[I_p + T + \lambda T + E_p + S_p - C_{p1} - C_{p2} - W_p] \\
 & + (1-x)(1-z)[I_p + T + \lambda T + E_p - C_{p1} - C_{p2} - W_p]
 \end{aligned} \quad (5)$$

$$\begin{aligned}
 U_{P2} = & xz[I_p + T - C_{p1} - F_p] + (1-x)z[I_p + T - C_{p1}] \\
 & + x(1-z)[I_p + T - C_{p1} - F_p - W_p] \\
 & + (1-x)(1-z)[I_p + T - C_{p1} - W_p]
 \end{aligned} \quad (6)$$

$$\overline{U}_P = xU_{P1} + (1-x)U_{P2} \quad (7)$$

Based on Eqs. (5)–(7), the replication dynamics equation of Arctic ports can be expressed as:

$$\begin{aligned}
 F(y) = \frac{dy}{dt} = & y(U_{P1} - \overline{U}_P) = y(1-y)(U_{P1} - U_{P2}) \\
 = & y(1-y)[E_p + \lambda T - C_{p2} + x(F_p + S_p) - zT(\gamma + \lambda)]
 \end{aligned} \quad (8)$$

The expected benefits and average expected ($U_{S1}, U_{S2}, \overline{U}_S$) benefits of shipping companies' active or passive emission reduction are:

$$\begin{aligned}
 U_{S1} = & xy[I_s + E_s + S_s + \gamma T - C_s - T] \\
 & + (1-x)y[I_s + E_s + \gamma T - C_s - T] \\
 & + x(1-y)[I_s + E_s + S_s - C_s - T] \\
 & + (1-x)(1-y)[I_s + E_s - C_s - T]
 \end{aligned} \quad (9)$$

$$\begin{aligned}
 U_{S2} = & xy[I_s - T - \lambda T] + (1-x)y[I_s - T - \lambda T] \\
 & + x(1-y)[I_s - T] + (1-x)(1-y)[I_s - T]
 \end{aligned} \quad (10)$$

$$\overline{U}_S = xU_{S1} + (1-x)U_{S2} \quad (11)$$

Based on Eqs. (9)–(11), the replication dynamic equation of the shipping company can be expressed as:

$$\begin{aligned}
 F(z) = \frac{dz}{dt} = & z(U_{S1} - \overline{U}_S) \\
 = & z(1-z)[E_s - C_s + xS_s + yT(\gamma + \lambda)]
 \end{aligned} \quad (12)$$

Therefore, according to Eqs. (4), (8), and (12), a three-dimensional dynamic system of Arctic coastal governments, Arctic ports, and shipping companies can be constructed:

$$\begin{cases}
 F(x) = \frac{dx}{dt} = x(1-x)[B_1 + C_{g2} + C_{g3} - C_{g1} + F_p - y(S_p + F_p + C_{g3}) - z(S_s - B_2)] \\
 F(y) = \frac{dy}{dt} = y(1-y)[E_p + \lambda T - C_{p2} + x(F_p + S_p) - zT(\gamma + \lambda)] \\
 F(z) = \frac{dz}{dt} = z(1-z)[E_s - C_s + xS_s + yT(\gamma + \lambda)]
 \end{cases} \quad (13)$$

Table 3 Stability analysis of E_7 and E_8 .

Equilibrium point	Scenario 1: $C_{g2} + B_1 + B_2 < C_{g1} + S_p + S_s$					Scenario 2: $C_{g2} + B_1 + B_2 > C_{g1} + S_p + S_s$				
	λ_1	λ_2	λ_3	Stability	Conditions	λ_1	λ_2	λ_3	Stability	Conditions
$E_1(0, 0, 0)$	/	/	+	Non- ESS	①	/	/	+	Non- ESS	②
$E_2(1, 0, 0)$	/	+	/	Non- ESS		/	+	/	Non- ESS	
$E_3(0, 1, 0)$	/	/	+	Non- ESS		/	+	/	Non- ESS	
$E_4(0, 0, 1)$	/	+	/	Non- ESS		/	/	+	Non- ESS	
$E_5(1, 1, 0)$	/	/	+	Non- ESS		/	/	+	Non- ESS	
$E_6(1, 0, 1)$	/	+	/	Non- ESS		/	+	/	Non- ESS	
$E_7(0, 1, 1)$	—	—	—	ESS		/	/	+	Non- ESS	
$E_8(1, 1, 1)$	/	/	+	Non- ESS		—	—	—	ESS	

① $C_{g2} + B_1 + B_2 < C_{g1} + S_p + S_s, E_p > \gamma T + C_{p2}, E_s + \gamma T + \lambda T > C_s$; ② $C_{g2} + B_1 + B_2 > C_{g1} + S_p + S_s, S_s + E_s + \gamma T + \lambda T > C_s, E_p + F_p + S_p > \gamma T + C_{p2}, C_{g3} + F_p > S_p$ and S_s and B_2 .

The tripartite evolution path and stability analysis are detailed in Appendix C.

System evolution stability analysis. According to Lyapunov's stability theorem, an equilibrium point can be considered asymptotically stable, only if all eigenvalues of the Jacobi matrix have negative real parts. Based on formula (13), let $F(x) = 0$, $F(y) = 0$, $F(z) = 0$, we can get the system equilibrium points: $E_1(0, 0, 0)$, $E_2(1, 0, 0)$, $E_3(0, 1, 0)$, $E_4(0, 0, 1)$, $E_5(1, 1, 0)$, $E_6(1, 0, 1)$, $E_7(0, 1, 1)$, $E_8(1, 1, 1)$, $E_9((C_s - E_s - \gamma T - \lambda T)/S_s, 1, (C_{g2} + B_1 - C_{g1} - S_p)/(B_2 - S_s))$, $E_{10}((C_s - E_s)/S_s, 0, (C_{g1} - C_{g2} - C_{g3} - F_p - B_1)/S_s)$, $E_{11}(1, (C_s - E_s - S_s)/(\gamma T + \lambda T), (E_p + F_p + S_p + \lambda T - C_{p2})/(\gamma T + \lambda T))$, $E_{12}((\gamma T + C_{p2} - E_p)/(F_p + S_p), (B_1 - C_{g1} + C_{g2} + C_{g3} + F_p)/(S_p + F_p + C_{g3}), 1)$, $E_{13}((C_{p2} - E_p - \lambda T)/(S_p + F_p), (B_1 - C_{g1} + C_{g2} + C_{g3} + F_p)/(S_p + F_p + C_{g3}), 0)$, $E_{14}(0, (C_s - E_s)/(\gamma T + \lambda T), (E_p + \lambda T - C_{p2})/(\gamma T + \lambda T))$.

Among them, $E_1 - E_8$ are pure strategy equilibrium points, and $E_9 - E_{14}$ are mixed strategy equilibrium points in this asymmetric dynamic game, there are eigenvalues with different signs, and they are definitely not evolutionary stable points.

For the eight pure strategy equilibrium points ($E_1 - E_8$), this study uses Lyapunov's first method to determine the stability of the evolutionary game system. Based on formula (13), the Jacobian matrix of the three-party evolutionary game system is shown in formula (14):

$$J = \begin{bmatrix} J_1 & J_2 & J_3 \\ J_4 & J_5 & J_6 \\ J_7 & J_8 & J_9 \end{bmatrix} = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix}$$

$$= \begin{bmatrix} (1-2x)[B_1 + C_{g2} + C_{g3} - C_{g1} + F_p - \gamma a - zb] & -x(1-x)a & -x(1-x)b \\ \gamma(1-y)c & (1-2y)[E_p + \lambda T - C_{p2} + xc - zTd] & -y(1-y)Td \\ z(1-z)S_s & z(1-z)Td & (1-2z)[E_s - C_s + xS_s + \gamma Td] \end{bmatrix}$$

Note: Among them, let $(S_p + F_p + C_{g3})$ be a ; $(S_s - B_2)$ be b ; $(S_p + F_p)$ be c ; $(\gamma + \lambda)$ be d .

Furthermore, the eigenvalues of the Jacobian matrix corresponding to the eight equilibrium points are shown in Table 2.

According to the Lyapunov stability theorem, an equilibrium point is asymptotically stable only if all eigenvalues of the Jacobian matrix have negative real parts. Among them, in the $E_7(0, 1, 1)$ and $E_8(1, 1, 1)$ strategies, the eigenvalue $\lambda_7^3 (C_{g2} + B_1 + B_2 - C_{g1} - S_p - S_s)$ and the eigenvalue $\lambda_8^3 (C_{g1} + S_p + S_s - B_1 - B_2 - C_{g2})$ must have opposite signs, which should be determined based on the actual situation. Therefore, we considered two different scenarios in our analysis: (1) $C_{g2} + B_1 + B_2 < C_{g1} + S_p + S_s$; (2) $C_{g2} + B_1 + B_2 > C_{g1} + S_p + S_s$. Ideally, Arctic coastal governments would adjust their strategies to a state of equilibrium, where no shipping company would passively reduce emissions, and any Arctic port would implement a differentiated port fee policy to actively guide shipping companies to reduce emissions. This ideal situation means that $Y = 1$ and $Z = 1$ are satisfied at an equilibrium point, which shows that E_7 and E_8 are ideal ESS points. The stability of E_7 and E_8 under the two scenarios is shown in Table 3. Additionally, the evolutionary stability of each equilibrium point under the two scenarios is illustrated in Appendix D, while the transition from the initial ESS to the ideal stable points E_7 and E_8 is shown in Appendix E.

Based on Table 3, the following two propositions can be obtained:

Proposition 1

When $C_{g2} + B_1 + B_2 < C_{g1} + S_p + S_s, E_p > \gamma T + C_{p2}, E_s + \gamma T + \lambda T > C_s$, $E_7(0, 1, 1)$ is the only ESS, that is, the Arctic coastal government passively regulates, and shipping companies actively reduce emissions under the policy guidance of Arctic ports.

Proposition 1 shows that when the sum of the cost of the G_1 strategy of the Arctic coastal government and the subsidies to all

parties, is greater than the sum of the cost of the G_2 strategy, the potential reputation benefits, and social evaluation improvement, the Arctic coastal government tends to regulate passively. Furthermore, reducing BC emissions around the port will enhance the working environment for port workers and reduce

Table 4 Parameter value settings.														
C_{g1}	C_{g2}	C_{g3}	B_1	B_2	S_s	S_p	F_p	E_p	C_{p2}	T	γ	λ	C_s	E_s
3.0	1.2	5.0	2.5	1.5	1.2	0.8	1.2	0.8	1.2	2.5	0.15	0.30	2.6	0.6

welfare losses, such as health damage caused by BC emissions. In the absence of government subsidies, when the external benefits to Arctic ports surpass the combined value of the port fee discount and the additional costs associated with the P_1 strategy, ports are more inclined to implement the port fee difference policy. When the sum of the benefits of the shipping company S_1 strategy and the penalty for passive emission reduction is greater than the cost, the stable evolution strategy of the system is [passive supervision, implementation of port fee difference policy, active emission reduction].

Proposition 2
When $C_{g2} + B_1 + B_2 > C_{g1} + S_s + S_s, S_s + E_s + \gamma T + \lambda T > C_s, E_p + F_p + S_p > \gamma T + C_{p2}, C_{g3} + F_p > S_p$ and S_s and $B_2, E_8(1, 1, 1)$ is the only ESS, that is, the Arctic coastal government actively regulates, and shipping companies actively reduce emissions under the guidance of the policies of the Arctic coastal government and ports.

Proposition 2 shows that when the sum of the external benefits of the P_1 strategy of the Arctic port, government subsidies and potential fines, is greater than the sum of the additional costs of the P_2 strategy and port fee concessions, it will choose to implement the port fee differential policy. Additionally, when the cost for shipping companies to adopt BC emission reduction technology is lower than the external benefits, government subsidies, port tax concessions, and potential fines they can receive, it becomes advantageous for the shipping companies to act. When Arctic port and shipping companies are actively reducing BC emissions, the sum of the Arctic coastal government's subsidies to ports and shipping and the G_1 strategy cost, is less than the sum of the G_2 strategy cost and the improvement of reputation and social evaluation. Therefore, the Arctic coastal government is more inclined to take the initiative to regulate now. Meanwhile, the stable evolution strategy of the system is [active supervision, implementation of port fee differential policy, active emission reduction].

Furthermore, we further analyze the above scenario, which are $C_{g1} + S_p + S_s - (C_{g2} + B_1 + B_2)$. In the context of the international community's high attention to the reduction of Arctic shipping BC emissions, and the increasingly urgent environmental problems caused, $(B_1 + B_2)$ is the government reputation benefits and social evaluation improvement obtained by the Arctic coastal governments for taking the lead in taking action and effectively governing. $(C_{g1} + S_p + S_s)$ represents the regulatory costs of Arctic coastal governments under active supervision, as well as the incentive costs for ports and shipping companies to take action, such as subsidy policies, and the human and material resources consumed in formulating BC emission reduction policies. Among other things, BC emissions in the Arctic have significant environmental impacts, including a far more regional greenhouse effect and loss of snow and ice cover (Comer et al. 2017b; Koch et al. 2011), which will have a direct social and environmental impact on Arctic coastal governments, and which the international community has all called upon to act despite. Therefore, according to the actual situation, it can be inferred that $C_{g1} + S_p + S_s - (C_{g2} + B_1 + B_2) < 0$. In scenario 1, the eigenvalue 3 of the equilibrium point $E_7(0, 1, 1)$ is positive, which does not meet the basic requirements for system evolution and stable strategy. In the equilibrium point $E_8(1, 1, 1)$, all eigenvalues are

negative, so the system will eventually evolve to this equilibrium point. The corresponding evolutionary strategy is [active supervision, implementation of the port fee differential policy, and active emission reduction].

Parameter setting. Container ships are a primary mode of transport in modern shipping. As the most efficient form of maritime transport, their share in Arctic shipping is expected to keep growing (Zhu et al. 2018). Technical measures for reducing BC emissions in Arctic shipping mainly include diesel particulate filters (DPF), scrubbers, and water-in-fuel emulsions (WiFE), etc. Among these, DPFs are costly for large vessels, while scrubbers face controversy due to wastewater disposal issues. WiFE is a fuel emulsification technology that forms a stable emulsion by adding water and mixing evenly. This technology improves fuel combustion performance, enhances combustion efficiency, is easy to install, and can be integrated with other emission reduction technologies (Aquametro, 2024). Currently, companies such as Aquametro and IPCO Power can provide the installation of this equipment. Studies have shown that WiFE (30%) is expected to reduce BC emissions by 50–90%, and has a reduction effect on various ship pollutants such as SO_2, NO_x, PM_{10} , etc (Corbett et al. 2014; Kornienko et al. 2021; Zhang et al. 2019). Additionally, better fuel selection combined with the use of technology will reduce most BC emissions for ships operating in the Arctic.

This study selects container ships and WiFE (30%) technology as simulation objects. Assume a container ship with a main engine power of 12000Kw and a remaining life of 10 years. Based on the investigation, the installation cost of WiFE (30%) on this container ship is approximately \$300,000 (including the anti-freeze system), with an annual operation and maintenance cost of about \$99,804. In the scenario of a 5-month Arctic navigation period, assuming that the ship has been transporting between Arctic ports during the navigation period, the average monthly shipping company's active emission reduction cost $C_s = 2.60$. Among them, the port fees in Norway are used as a reference (Mjelde et al. 2019). The external benefits of ports implementing port fee differential policies, and shipping companies actively reducing emissions are (Jiang et al. 2020; Meng et al. 2022; L. Xu et al. 2021a, 2021b); Reputational costs, reputational welfare, and social evaluation enhancement for Arctic coastal governments are referenced in (Aakre et al. 2017; Meng et al. 2022), and regulatory costs are referenced in (Jiang et al. 2020; Zhou et al. 2022); The discount and surcharge of port fees are based on the EPI policy of the Norwegian Port of Tromsø havn (Tromsø havn, 2024), as well as the port fee differential policies of countries such as Sweden. Additionally, an information survey of ports and shipping companies was carried out to correct some of the parameters (see Appendix F for details). The above values only represent general proportions and are mainly used to verify the Arctic shipping BC emission reduction strategy model. Specific parameter settings are detailed in Table 4.

Simulation analysis and discussion

We used MATLAB R2024a to perform numerical simulations on the model based on the optimal steady-state case $E_8(1, 1, 1)$, and analyzed the impact of various factors on Arctic shipping BC emission reduction behavior. This will help to reveal the dynamics of the strategy evolution of each subject under different

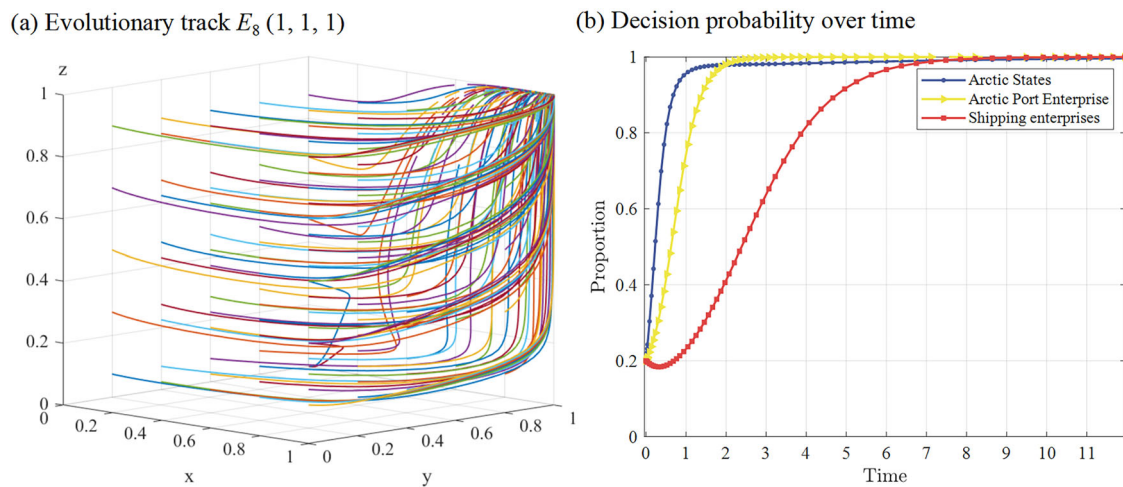


Fig. 2 Evolution trajectory of $E_8(1, 1, 1)$. **a** Imulation results of parameter studies around the equilibrium point $E_8(1, 1, 1)$. The three-dimensional graph illustrates the trajectories of various parameters that affect the system behavior in the x , y , and z dimensions; **b** When the initial probabilities of x , y , and z are 0.2, the simulation results of the equilibrium point $E_8(1, 1, 1)$ based on the parameter settings in Table 4.

parameter conditions, and intuitively present the degree of influence trend between variables, thereby providing a theoretical reference for BC emission reduction in Arctic shipping.

Evolution trajectory of ESSs of $E_8(1, 1, 1)$. Figure 2a shows the evolution trajectory of the random initial strategy combination after 50 evolutions. Although different initial strategy selection probabilities lead to different evolution rates, their final evolutionary stability converges to a point $(1, 1, 1)$. As Arctic coastal governments and ports realize the necessity of shipping BC emission reduction and the synergistic environmental and social benefits of the belt, they will actively participate in the investment of emission reduction policies and port tax concessions, thereby promoting shipping companies to invest in BC emission reduction technologies actively. The entire system is in an ideal stable decision-making state. Furthermore, the three-party evolutionary stable strategy is obtained by setting the initial strategy selection probability of Arctic coastal governments, ports, and shipping companies $[x = y = z = 0.2]$, as shown in Fig. 2b.

It can be seen that although the evolution rates of the three parties are different, they all tend to be 1 in the end. Among them, the strategy of the Arctic coastal government evolves the fastest and will converge first, followed by ports. At the same time, shipping companies evolve slowly, and the evolution path is a “U” curve. On the one hand, shipping companies need to consider the installation cost of BC emission reduction technology and potential funding opportunities in the early stage. On the other hand, when the current situation is unclear, shipping companies will observe the actions of other companies and adopt conservative strategies, showing a willingness to reduce active emission reduction in the short term during the evolution process. As the evolution time progresses, the tendency of Arctic coastal governments to actively supervise and ports to implement port fee difference policies is increasing. After comprehensive consideration, shipping companies find that taking active emission reduction measures will bring more benefits, such as increasing the attractiveness to sustainable development customers, enhancing the image of shipping companies, building public trust, obtaining incentives and avoiding fines. Therefore, the probability of shipping companies actively reducing emissions gradually increases. As the game deepened, all parties gradually realized the possibility of cooperative reduction of BC emissions

from Arctic shipping, further strengthening their willingness and ultimately achieving an ideal stable situation.

The impact of an initial strategy on evolution. To study the correlation between the initial strategy selection probabilities of the three parties, we will further analyze their influence on each other. Specifically, the initial strategy selection probability of one party is fixed at 0.2, and the initial strategy selection probabilities of the other two parties are taken as 0.2 and 0.8, respectively, thus generating 4 sets of data to analyze the impact of the probability selection of two parties on the other party. The results are shown in Fig. 3.

When shipping companies choose the initial strategy with high probability, or when both Arctic ports and shipping companies choose the initial strategy with low probability, the regulatory pressure on Arctic coastal governments increases, and the probability of choosing active regulation will evolve to 1 (Fig. 3a). On the one hand, this reflects that when shipping companies have a high initial willingness to reduce BC emissions, Arctic coastal governments will increase their regulatory efforts to prevent the “rebound” phenomenon in the strategic evolution of shipping companies. On the other hand, when Arctic ports and shipping companies tend not to implement the port fee difference policy and passively reduce emissions, the government will have to actively regulate to prevent environmental damage caused by shipping BC. However, when Arctic ports choose the initial strategy with high probability and shipping companies choose the strategy with low initial probability, the probability of Arctic coastal governments choosing active regulation initially shows an upward trend, but then evolves to 0. This evolutionary process reflects the government’s game thinking and dynamic adjustment mechanism in market regulation. It reveals the cost-benefit trade-off of regulatory behavior and the dynamic adjustment strategy between market expectations. That is, coastal governments need to balance environmental protection, economic development, and financial resources. In the early stages of Arctic port implementing emission reduction policies, coastal governments may take active emission reduction measures for policy consistency and reputation. However, suppose shipping companies remain passive or fail to respond in a timely manner despite multiple policy guidance. In that case, coastal governments may tend to make strategic concessions due to high administrative costs and delayed market response.

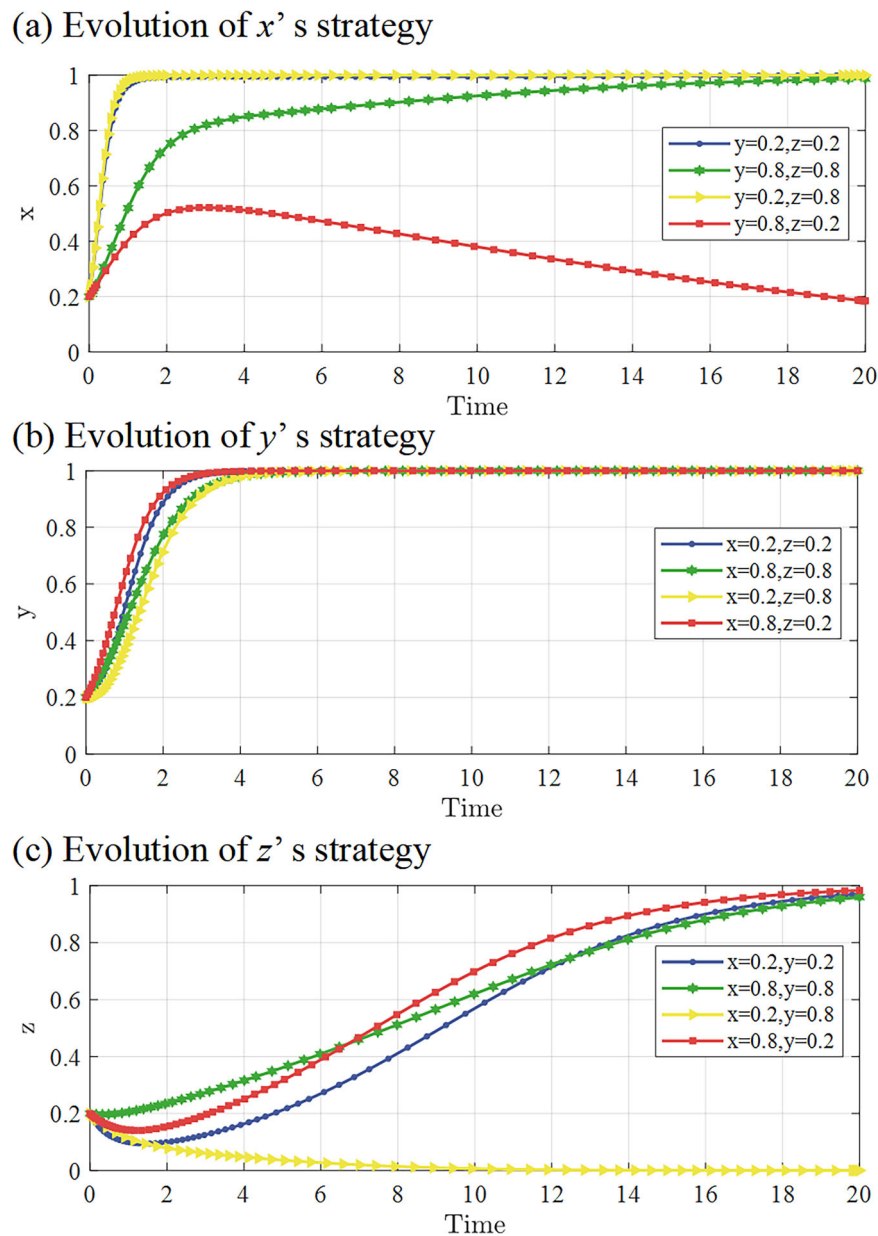


Fig. 3 The impact of initial probabilities of x , y and z on the evolution trajectory of $E_g(1, 1, 1)$. **a** The influence of the initial probability changes of y and z on the evolution of the x strategy; **b** The influence of the initial probability changes of x and z on the evolution of the y strategy; **c** The influence of the initial probability changes of x and y on the evolution of the z strategy.

Secondly, under the three initial strategy selection probabilities, the probability of Arctic ports implementing port fee differential policies always gradually tends to 1. Still, the evolution rate will be affected by the initial willingness of Arctic coastal governments and shipping companies (Fig. 3b). Specifically, it is positively correlated with the initial probability of Arctic coastal governments, which reflects the guiding and incentive role of Arctic coastal governments in the process of Arctic shipping BC emission reduction, and policy constraints can prompt Arctic ports to adopt emission reduction strategies more quickly. At the same time, it is negatively correlated with the initial probability of shipping companies, which shows that the active emission reduction of shipping companies has alleviated the emission reduction pressure of port to a certain extent, weakened the motivation of port to take immediate emission reduction actions, and made them show greater delay or flexibility in strategy selection.

Finally, when $x = y = 0.2$, the shipping company evolution strategy shows an obvious “U” curve in the early stage (Fig. 3c). This shows that in a weakly constrained environment, shipping companies are more likely to have a “fluke” avoidance mentality and are more inclined to behave speculatively to maximize their own interests. In addition, if the Arctic coastal government chooses an initial strategy with a high probability, the shipping company’s active emission reduction strategy will evolve faster. Meanwhile, if the Arctic coastal government chooses an initial strategy with a low probability, and the shipping company chooses an initial strategy with a high probability, the probability of the shipping company choosing active emission reduction will evolve to 0. This phenomenon shows that, although the initial Arctic ports have shown a strong motivation for emission reduction, in the absence of government regulatory support and the current reference port fee differential policy, these behaviors are difficult to form sufficient market incentives and pressure on

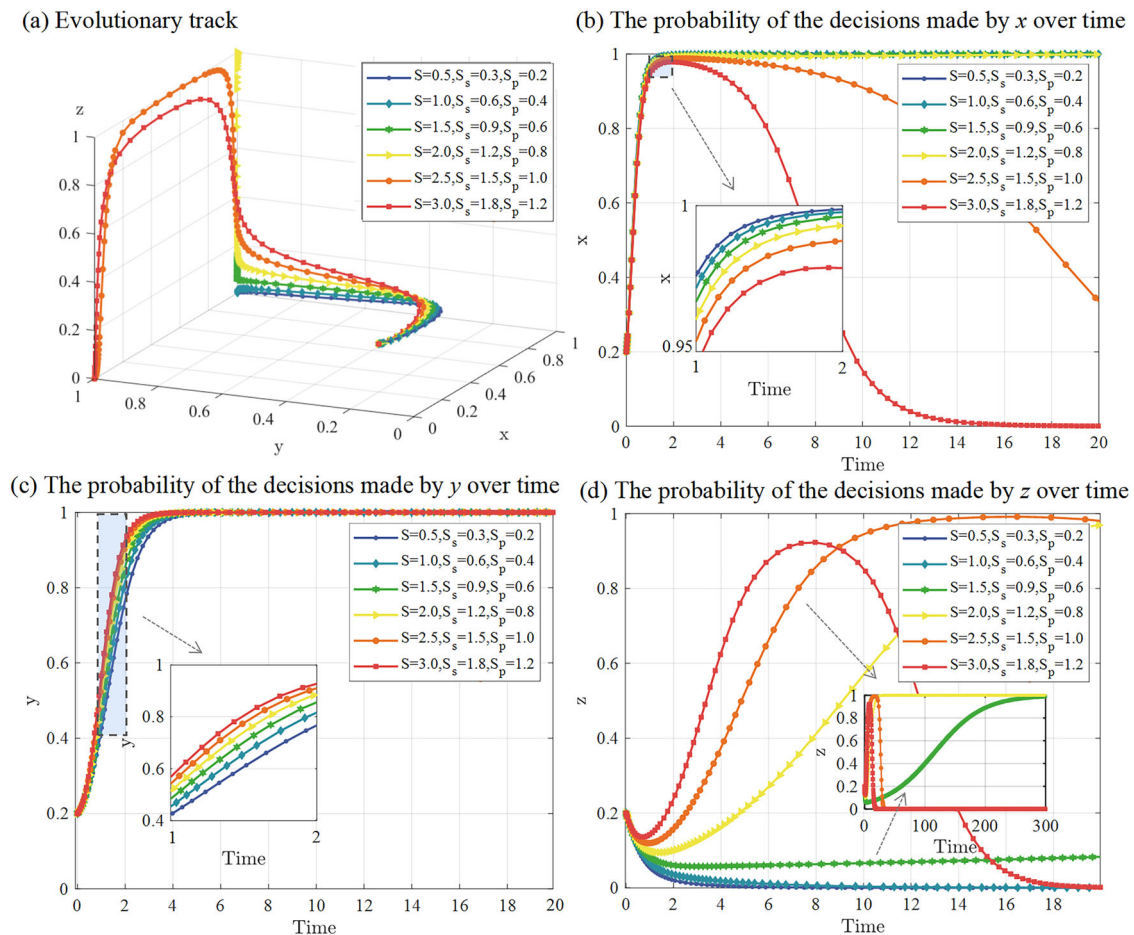


Fig. 4 The impact of government incentive policies along the Arctic on the evolutionary strategies of all parties. **a** The impact of Arctic coastal government incentive policies ($S = 0.5, S = 1.0, S = 1.5, S = 2.0, S = 2.5, S = 3.0$) on the evolution process; **b** the impact of Arctic coastal government incentive policies on the probability of x making a decision over time; **c** the impact of Arctic coastal government incentive policies on the probability of y making a decision over time; **d** the impact of Arctic coastal government incentive policies on the probability of z making a decision over time.

shipping companies. This finding is consistent with the results of Sweden's research on the differential policy practices of fairway fees (Transport Analysis, 2017). That is, the independent port fee differential policy of the port is difficult to affect the long-term strategy of the entire shipping industry chain.

At the same time, the analysis report of European Commission, (2017) also pointed out, that the current differences in port fees may not significantly change the behavior of shipowners. Considering competitiveness and costs, the incentives of ports in the past may have been too low. However, cooperative projects between port authorities and other responsible agencies usually bring the most cost-effective and comprehensive results, and help share or clarify common responsibilities. Considering that improved air quality will directly benefit citizens, the possible loss of revenue for port authorities can be balanced by the compensation mechanism of local governments. The simulation results of this study show that to effectively reduce BC emissions from Arctic shipping, Arctic coastal governments should first take action and form a linkage mechanism with ports to form a more consistent policy signal and improve policy effectiveness.

Impact of key parameters

Subsidies and penalties of Arctic coastal governments. The changes in incentive parameters S , S_s and S_p in the regulatory strategy of Arctic coastal governments are set to analyze their impact on the evolutionary equilibrium of Arctic ports and

shipping companies. Among them, $S = 2.0, S_s = 1.2, S_p = 0.8$ is used as the benchmark (Assuming that $S_s : S_p = 1.5 : 1.0$). On this basis, five situations are set, and the system evolution results are shown in Fig. 4. It can be seen that the evolutionary stability of the Arctic ports implementing the port fee difference policy and the shipping companies' active emission reduction strategy, is affected by the subsidy intensity of the Arctic coastal governments, and the convergence rate of the strategy is positively proportional to the subsidy intensity. However, under low-intensity subsidies from Arctic coastal governments ($S = 0.5$ or 1), although Arctic ports may still choose to implement the port fee differential policy, due to insufficient overall strength and weak policy guidance, it is impossible to effectively attract ships to adopt emission reduction technology investments, and the probability of shipping companies choosing active emission reduction strategies gradually converges to 0. This shows that inappropriate subsidy measures do not help promote corporate emission reduction, and may even cause shipping companies to degenerate into long-term inaction.

When the subsidy intensity is moderate ($S = 1.5$ or 2), Arctic ports and shipping companies can achieve a relatively ideal policy implementation effect, and the system is in a long-term stable state. In this case, ports can more effectively implement the port fee differential policy, attract more ships that meet environmental standards, and maintain the competitiveness and green image of ports. Shipping companies can also benefit from government

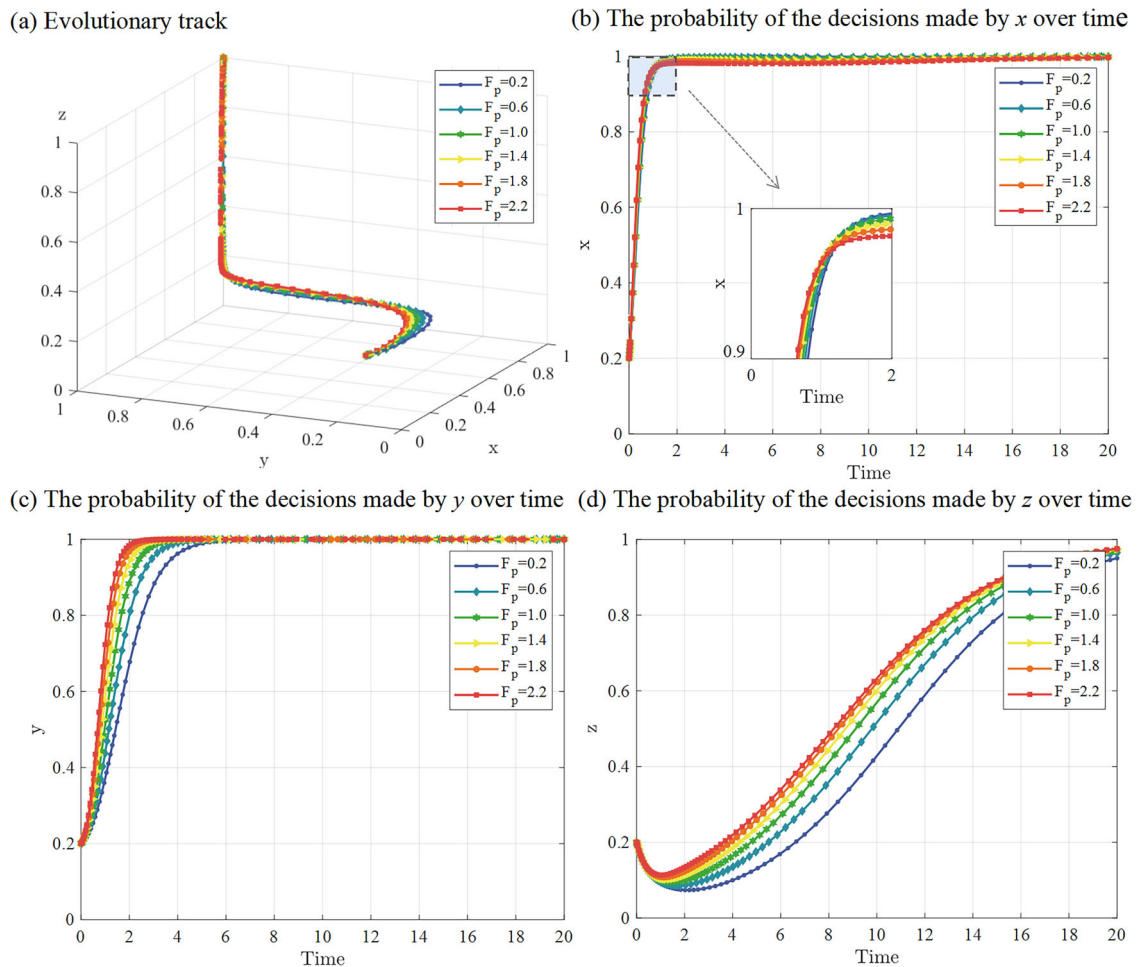


Fig. 5 The impact of Arctic coastal government punitive policies on the evolutionary strategies of the parties. **a** The impact of Arctic coastal government punishment policies ($F_p = 0.2$, $F_p = 0.6$, $F_p = 1.0$, $F_p = 1.4$, $F_p = 1.8$, $F_p = 2.2$) on the evolution process; **b** the impact of Arctic coastal government punishment policies on the probability of x making a decision over time; **c** the impact of government punishment policies on the probability of y making a decision over time; **d** the impact of Arctic coastal government punishment policies on the probability of z making a decision over time.

subsidies and port fee reductions, which encourages them to invest in BC emission reduction technologies and green fleet renewal.

At the same time, the study shows that under a high-intensity subsidy policy ($S = 2.5$ or 3.0), the entire system will rapidly evolve toward $E_8(1, 1, 1)$. However, although this strategy can effectively motivate ports and shipping companies in the short term, the government will find it difficult to bear the high subsidy costs in the long term, leading to a gradual shift to passive regulation. Among them, shipping companies tend to choose active emission reduction in the early stage, but due to the operation and update costs of BC emission reduction technology, their enthusiasm for emission reduction will weaken in the long run. Therefore, although the high-intensity subsidy policy can produce good results in the short term, its long-term sustainability faces great challenges. The government needs to balance fiscal pressure with emission reduction targets to ensure the long-term successful implementation of the policy. Based on the previous experience of shipping industry decarbonization and sulfur emission reduction, the policy effect will change over time (Anas S. Alamoush et al. 2022). Subsidy intensity and regulatory measures need to be monitored and adjusted promptly to avoid excessive economic burden and policy failure (Meng et al. 2022). In addition, the Arctic route crosses multiple coastal countries, and independent supervision by coastal governments is costly and

prone to regulatory blind spots. Therefore, in the future, a transnational cooperation mechanism can be established through the Arctic Council to share data and resources and reduce regulatory costs.

In addition, this study changes the ratio of $S_c : S_p = 1.0:1.5$ (see Appendix G). Under the same total subsidy amount, the coastal government's subsidy policies of various intensities failed to encourage shipping companies to take emission reduction measures successfully. This result can be explained by the findings of Wang et al. (2022) study addressing the optimization of the structure of government subsidies for shore power, which found that subsidies to ships should be prioritized over subsidies to ports.

Keeping other parameters unchanged, the penalty parameter F_p in the Arctic coastal government regulatory strategy is set to change, so as to analyze its impact on the evolutionary equilibrium of ports and shipping companies. Among them, five cases are set on the basis of $F_p = 1.0$, and the evolution results of Arctic ports and shipping companies are shown in Fig. 5. It can be seen that the penalty intensity F_p has an impact on the convergence rate of action taken by ports and shipping companies, and is positively correlated. This shows that the penalty measures of the Arctic coastal government can not only accelerate the convergence of the emission reduction strategy of

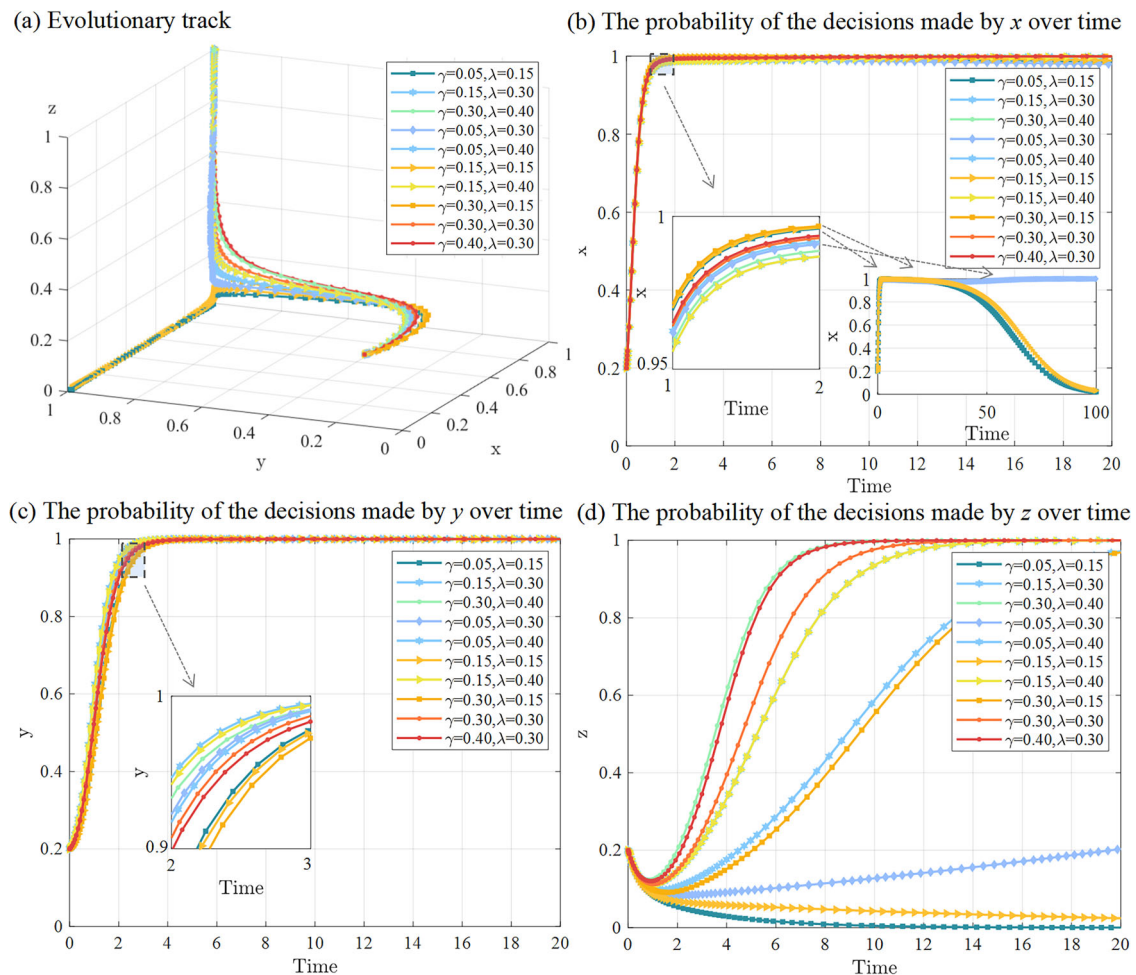


Fig. 6 The impact of the intensity of the port fee difference policy combination on the evolutionary strategies of all parties. **a** The impact of port fee difference policy combination on the evolution process; **b** the impact of port fee difference policy combination on the probability of x making a decision over time; **c** the impact of port fee difference combination on the probability of y making a decision over time; **d** the impact of port fee difference policy combination on the probability of z making a decision over time.

ports to a steady state. At the same time, in the context of more and more Arctic ports implementing port fee difference policies, shipping companies will face higher operating costs and market barriers. Adopting BC emission reduction technology has become necessary for the company to maintain its competitiveness in the Arctic shipping market in the long term. This synergy also accelerates the convergence of shipping companies' strategy evolution. However, overall the penalty policy has little impact on the three-party behavioral strategies.

Preferential and punitive strength of the port fee differential policy. Further, the impact on the system evolution equilibrium is analysed according to the changes in preferential strength (γ) and punitive strength (λ) in the Arctic ports' port fee differential policy. To this end, we set 9 different policy scenarios and show the corresponding results in Fig. 6. It can be found that there are significant differences in the regulations of Arctic coastal governments and emission reduction behaviors of shipping companies, under different combinations of port fee differential policies. Among them, when $\gamma = 0.30, \lambda = 0.40$ and $\gamma = 0.40, \lambda = 0.30$, it will prompt shipping companies to apply BC emission reduction technology more quickly. The evolution speed of " $\gamma = 0.40, \lambda = 0.30$ " is faster than that of " $\gamma = 0.30, \lambda = 0.40$ ", which shows that punishment can promote emission reduction behavior more than incentives. At the same time, the

combination of low preferential and low penalty ($\gamma = 0.05, \lambda = 0.15$) and medium preferential and low penalty ($\gamma = 0.15, \lambda = 0.15$) will not lead shipping companies to reduce emissions actively.

At the same time, in the early stage of different port fee differential policy combinations, Arctic coastal governments tend to choose active regulatory strategies (Fig. 6b). Among them, in the high-incentive differential policy combination (such as the $\gamma = 0.30, \lambda = 0.40$), Arctic coastal governments will converge to active regulatory strategies more quickly. This reflects that combined with strong port fee differential policies, Arctic coastal governments are willing to pay higher regulatory costs to ensure that ports and shipping companies meet BC emission reduction targets. However, under the low-incentive differential policy combination, although the probability of Arctic coastal governments choosing active regulatory strategies will also converge quickly to 1 in the early stage, due to the failure of effective linkage between ports and government policies, the continuous stimulation of shipping companies' BC active emission reduction behavior will gradually turn to passive regulation, and the system will eventually converge to $E_3(0, 1, 0)$. This reflects the limitations of the port fee differentiation policy, which needs to work in synergy with the country's or region's larger environmental policy plans to form a more powerful incentive and penalty mechanism, to ensure that ports and

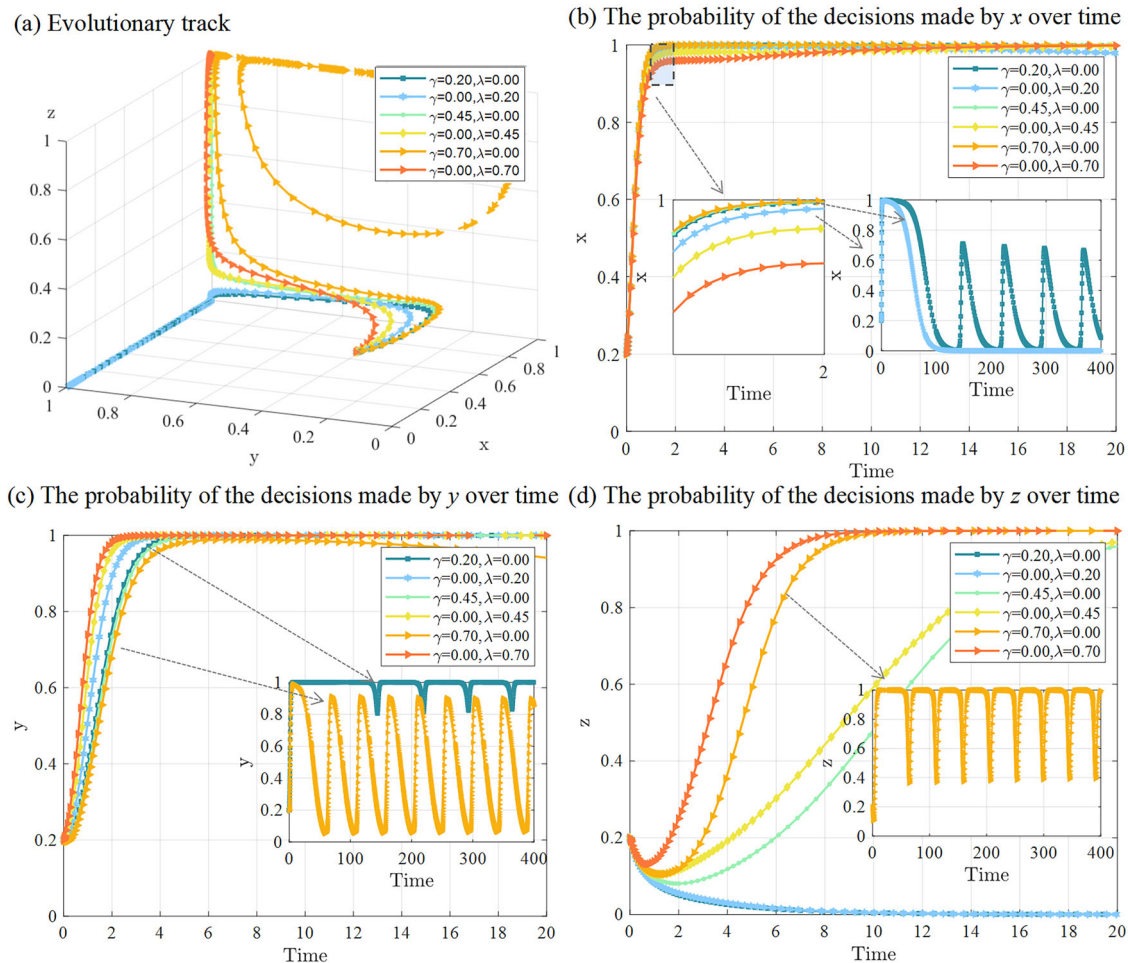


Fig. 7 The impact of the single port fee difference policy on the evolutionary strategies of the parties. **a** The impact of the single port fee difference policy on the evolution process; **b** the impact of the single port fee difference policy on the probability of x making a decision over time; **c** the impact of the single port fee difference on the probability of y making a decision over time; **d** the impact of the single port fee difference policy on the probability of z making a decision over time.

shipping companies promote emission reduction behaviors in the long term and continuously.

In addition, the current port fee differential policies can be mainly divided into two categories: one is only to provide port fee concessions for ship emission reduction (such as port fee differential policies based on CSI and ESI). The other is to expand the cost difference between less polluting ships and more polluting ships through a combination of concessions and surcharges (such as port fee differential policies based on EPI), thus becoming a penalty for ships that do not make green investments. Therefore, we further compared the policy combination and single policy (Fig. 7).

It can be seen that when $\gamma = 0.20$ and $\lambda = 0.20$, there will be no incentive for shipping companies to take emission reduction measures, which will affect the strategic choices of Arctic coastal governments. At the same time, if the port adopts an excess incentive policy (when $\gamma = 0.70$), the high incentive cost of the port will cause its decision-making choices to be volatile (Fig. 7c). From the perspective of the speed of the system equilibrium state, the convergence rate of Arctic coastal governments to active regulation is inversely proportional to the degree of port fee increase and proportional to the degree of exemption (Fig. 7b), and ports expressive in the opposite way to Arctic coastal governments. At the same time, for the convergence rate of shipping companies to active emission reduction, in the case of

$\gamma + \lambda = 70$, $\gamma = 0.00 - \lambda = 0.70 > \gamma = 0.30 - \lambda = 0.40$ (Appendix H), but the difference in evolution speed is small. However, in the case of $\gamma + \lambda = 45$, $\gamma = 0.15 - \lambda = 0.30$ will reach equilibrium faster than $\gamma = 0.00 - \lambda = 0.45$.

Cost of BC emission reduction technology for Arctic shipping.

To describe the changes in the emission reduction decision-making of the system caused by the cost of BC emission reduction technology for Arctic shipping, we set the change of the emission reduction technology cost parameter C_s to analyze its impact on the system evolution equilibrium. Among them, taking $C_s = 2.6$ as the benchmark, five cases are set on this basis, and the system evolution results are shown in Fig. 8. It can be found that when $C_s \leq 2.6$, the probability of shipping companies actively reducing emissions shows a trend of first decreasing and then increasing (Fig. 8d). Among them, the probability reduction of initial active emission reduction is negatively correlated with the C_s value. This shows that lower BC emission reduction technology costs can help promote shipping companies' willingness to reduce emissions in the long term, but in the early stages, shipping companies may temporarily reduce their active emission reduction tendencies due to increased costs in the short term. Over time, shipping companies gradually increase emission reduction actions under policy incentives, eventually converging to 1. In addition, when

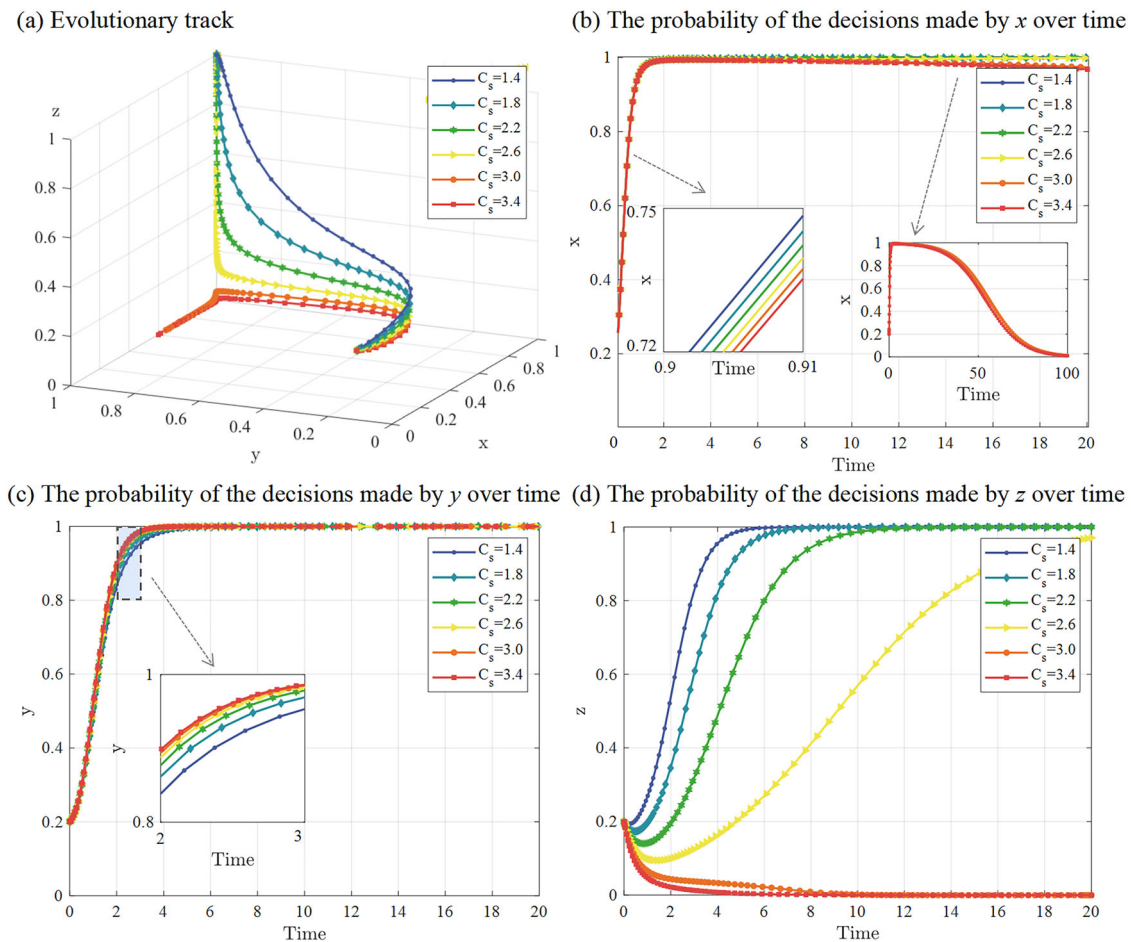


Fig. 8 The impact of emission reduction technology costs on the evolution strategies of each party. **a** The impact of emission reduction technology costs on the evolution process; **b** the impact of emission reduction technology costs on the probability of x making a decision over time; **c** the impact of emission reduction technology costs on the probability of y making a decision over time; **d** the impact of emission reduction technology costs on the probability of z making a decision over time.

$C_s \geq 2.6$, the probability of active regulation of Arctic coastal policies will gradually converge to 1, and then slowly decrease and converge to 0 (Fig. 8b). This shows that higher technology costs may lead to a decline in corporate willingness to reduce emissions, and government supervision may also be weakened. Therefore, how to reduce emission reduction technology is also particularly important.

Latapi et al. (2023) investigated the drivers and barriers to large-scale adoption of hydrogen fuel cells by Nordic shipping companies through interviews. The results show that high technology-related costs are the main barrier, and all costs of using hydrogen fuel cells (including capital expenditures, operating expenses and total cost of ownership) are higher than other fuels and technologies, making it difficult for shipping companies to adopt. The study pointed out that the EU has pledged to increase investment in green hydrogen production, which will help reduce costs and accelerate the popularization of hydrogen technology. At the same time, Mjelde et al. (2019) pointed out that port fee differential policies may become an additional driving force for cruise ship owners to invest in green technology. Their case study shows that if 50% of the world's ports implement the same port fee differential policy as Norway (with the same rebate scale), each LNG cruise ship will achieve a cost benefit of more than 700,000 euros per year, which will shorten the investment payback period of LNG technology to less than one year.

Discussion. The unique nature of the BC problem is that it is both a regional air pollutant and a contributor to climate change.

It is estimated that reducing SLCP emissions (especially methane and BC) can slow global warming by 0.5 °C by 2040 (Amann et al. 2011). The 2012 amendment to the Gothenburg Protocol was the first international agreement to set binding emission reduction targets for $PM_{2.5}$. Although BC was included in the control framework as a component of $PM_{2.5}$, but BC-related emission reduction commitments are still mainly voluntary. Port fee differential policies can be consistent with the broader environmental and regulatory framework by encouraging ships to adopt BC emission reduction measures. In particular, if ships adopt technology-based BC emission reduction measures, it will bring about synergistic emission reductions of multiple pollutants. For example, studies have shown that WiFE technology can simultaneously reduce SO_x (7%–24%), PM_x (40–88%) and CO_2 (12–17%) emissions while achieving BC reduction (Comer et al. 2017a; Corbett et al. 2014; Kornienko et al. 2021; Lack et al. 2012; Zhang et al. 2019).

Currently, BC emission reduction has been gradually integrated into the corporate governance system. The Norwegian Shipowners Association encourages its members (shipping companies) to include BC-related emission data in their climate reports (Idha and Jens, 2022). In particular, during Norway's chairmanship of the Arctic Council, it also expressed a desire to see progress in reducing BC emissions from ships in the Arctic

(Ship and Bunker News Team, 2024). However, to ensure the effectiveness of the policy, the implementation of the port fee differential policy needs to establish a dynamic adjustment mechanism, regularly evaluate the relevance of the charging standards to the emission reduction effect and economic impact, and adjust them according to the evaluation results to ensure that they are consistent with broader environmental goals. Additionally, coastal governments and ports should involve local, regional, and international stakeholders in the policy-making process to ensure fairness and inclusiveness (European Commission, 2017). Based on this, the port fee differential policy is expected to support the realization of the 1.5 °C temperature control target of the Paris Agreement, and provide strong support for improving regional air quality and the melting of Arctic ice and snow, thereby achieving a win-win situation for economic and environmental benefits.

It is worth noting that port fee differential policies have been implemented in many countries and present diversified models, such as CSI, ESI, EPI, Green Award, and Green Flag Incentive Program. The EPI of the Port of Gothenburg in Sweden provides port fee reductions for ships with SO_x, NO_x, and CO₂ emissions below the average level (Port of Gothenburg, 2024). The “Green Flag Incentive Program” of the Ports of Los Angeles and Long Beach provides discounts for ships that slow down. The Port of Vancouver adopts a more complex scoring mechanism, which comprehensively rates ships (Base, Bronze, Silver, Gold, Platinum) based on more than ten standards, such as ESI, Green Award, and CSI, and adjusts port fees according to the level (Vancouver Fraser Port Authority, 2025). This paper proposes a BC emission governance model for Arctic shipping based on government supervision and port fee differential policies, which can be used in combination with existing policies.

Conclusions and limitations

Conclusions. Currently, Arctic countries and ports have deeply realized the significant environmental impact of shipping BC emissions on the Arctic region, but the governance process is still in the monitoring and evaluation stage, and there is still a lack of effective multi-level regulatory policies (Qi et al. 2024). Although some Arctic countries have taken control measures (such as the new emission control areas in Canadian Arctic waters and the Norwegian Sea) to alleviate the problem, there is no policy specifically targeting shipping BC emissions. This study focuses on the strategic interaction process of Arctic coastal governments, ports and shipping companies in BC governance, and constructs a game model of three stakeholders to analyze the impact of government regulation and port fee differential policies on shipping companies' investment in BC emission reduction technologies.

The results of this study show that it is crucial for the evolutionary game system to transition from the initial state $E_1(0, 0, 0)$ to the desired state $E_8(1, 1, 1)$. Among them, the success of BC emissions governance in Arctic shipping relies on the collaboration of multiple stakeholders, including coastal governments, ports, and shipping companies. Coastal governments play a leading role in policy formulation (subsidy and penalty mechanisms) and supervision. Ports jointly encourage shipping companies to reduce emissions through port fee differential policies, while shipping companies achieve emission reduction targets by investing in BC emission reduction technologies. The balance of policy incentives and penalties, the promotion of technological development, and the coordination of the interests of all parties are all key to promoting BC emissions reduction in Arctic shipping. Additionally, unlike traditional evolutionary game studies on shipping emissions reduction,

previous studies often assume in scenarios that the government promotes the construction of green ports (such as building shore power, etc.) and green emissions reduction by shipping companies (transforming ships, installing emission reduction equipment, etc.) through incentive and penalty mechanisms. In such behaviors, ports and shipping companies are often interdependent and competitive (Meng et al. 2022). We find that under the port fee differentiation policy, coastal governments and ports can effectively guide shipping companies' emission reduction behaviors through coordinated policy planning, thereby improving the sustainability and long-term effectiveness of the policy. Therefore, collective action is crucial, and the international community must prioritize the long-term health of Arctic ecosystems over short-term economic benefits to ensure a sustainable future for this vital and fragile region.

Specifically, the active participation of Arctic coastal governments is a key factor in promoting BC emission reductions, otherwise all stakeholders will operate in a natural game state without effective constraints. In particular, shipping companies tend to exhibit a “U” curve in the early stages of action and may display evasive behavior in a weak regulatory environment. Furthermore, the regulatory intensity of Arctic coastal governments has a significant impact on institutional evolution. Among them, adjustments to the subsidy intensity are likely to lead to negative emission reduction behaviors by shipping companies, while adjustments to the penalty intensity only affect the rate of evolution of ports and shipping companies, without influencing their emission reduction decisions. In reality, shipping subsidies can take precedence over port subsidies.

Secondly, a single port fee difference policy is only effective under the conditions of excess discount or excess penalty, but ports need to face the reality of policy implementation costs and reduced port attractiveness. Among them, a combination of preferential and additional port fee differential policies will be more suitable for Arctic shipping BC emission reduction. At the same time, to ensure the effective implementation of the port fee differential policy, a regional cooperation mechanism needs to be established between ports and with regional stakeholders, which is also shown by our results. At the same time, this is consistent with the views of Becqué et al. (2017) and the International Transport Forum, (2018) on the lessons learned from the current port fee differential policy.

Finally, the cost of BC emission reduction technology is the key to promoting the green transformation of the Arctic shipping industry. When the cost of emission reduction technology is high, it will cause the system to evolve towards $E_3(0, 1, 0)$. To meet this challenge, on the one hand, reasonable subsidies and penalties can be set up to encourage shipping companies to gradually adapt to and invest in emission reduction technologies. On the other hand, in 2022, the proportion of the flag states of ships on the Arctic route was 81.21% (PAME, 2023). In the future, Arctic countries should increase their investment in the research and development of BC emission reduction technology to accelerate the maturity and commercialization of technology. At the same time, due to the challenges of the Arctic region's natural environment, the region's ship emission reduction equipment has different demands for antifreeze and other aspects than other regions. The shipping industry can cooperate with Arctic countries to research and develop BC emission reduction technologies to integrate resources and knowledge, improve the efficiency of technology research and development, and reduce development costs, including establishing joint funds.

Limitations. This study has several limitations. First, the study is based on relatively ideal assumptions, assuming that the

government, ports, and shipping companies can make independent decisions with complete information. However, in reality, participants may make decisions with incomplete information, and there may be vertical cooperation. Second, this study does not consider the regional diffusion effect and potential free-rider behavior after BC emissions, which may affect the actual effect of emission reduction measures. In addition, the evolutionary game model in this study mainly focuses on the three core participants in Arctic shipping and does not involve other stakeholders, such as the green choice preferences of carriers or emission reduction technology providers. Therefore, future research should expand the game model to cover more stakeholders and add more information variables. Finally, there are differences in the current port fee differentiation policies among ports, and the model can be further refined in the future to analyze the impact of the simultaneous existence of different policies on the behavior of shipping companies.

Data availability

No datasets were generated or analysed during the current study.

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Author contributions

XL contributed to the conception of the study and wrote the manuscript. ZF contributed to the study conception and design. YR, QQ and CR helped perform the analysis, with constructive discussion, and assisted with manuscript preparation and revision. All authors substantially contributed to the article and approved the submitted version.

Competing interests

The authors declare no competing interests.

Informed consent

This study does not contain any studies with human participants performed by any of the authors. Informed consent was not relevant.

Ethical approval

This study does not contain any studies with human participants performed by any of the authors.

Additional information

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