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Impacts of Carbon Border Adjustment Mechanism on the Development of Chinese Steel Enterprises and Government Management Decisions: A Tripartite Evolutionary Game Analysis

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Abstract: Upon the implementation of the European Union Carbon Border Adjustment Mechanism (CBAM), substantial challenges are anticipated to impact the international trade of Chinese steel products. To safeguard the competitiveness of Chinese steel products on the global stage, this paper establishes a tripartite evolutionary game model, involving large steel enterprises, small and medium-sized steel enterprises, and the government. The model integrates collaborative emission reduction and free-riding benefits among enterprises, along with the government's dynamic subsidies and penalties. The paper analyzes the evolutionary trends and stable states of the three parties during different stages of CBAM, including a sensitivity analysis of key parameters. The findings indicate that large enterprises demonstrate a heightened sensitivity to CBAM, while small and medium-sized enterprises are more significantly influenced by free-riding benefits. Government intervention should be strategically timed and incline towards passive management during the strengthening phase of CBAM. Additionally, the refinement of the Chinese carbon market emerges as an effective means to counter CBAM. This paper provides theoretical support for how steel enterprises and the government can respond to CBAM, aiding stakeholders in selecting optimal strategies during different implementation stages and mitigating the impacts of CBAM to the maximum extent possible.

Keywords: carbon border adjustment mechanism; evolutionary game; steel enterprises; government; strategic decision-making

1. Introduction

Addressing carbon leakage resulting from differences in climate policies has become an urgent global challenge in carbon emissions reduction [1]. In order to tackle global carbon leakage and assist in global decarbonization, the European Commission introduced the Carbon Border Adjustment Mechanism (CBAM) in July 2021, with the commitment to achieve a net reduction of at least 55% in greenhouse gas emissions by 2030. The legislation was officially passed in October 2023. Grounded in the implicit carbon emissions of imported goods, the CBAM imposes additional carbon tariffs on goods imported into the European Union [2]. Presently, the primary targets for the CBAM are focused on carbon-intensive industries such as the steel sector [3]. China, being a major exporter of steel, recorded a steel export volume of 669 million tons in 2021 [4], with approximately 4 million tons annually exported to the European Union. Consequently, it is evident that the implementation of the CBAM legislation will significantly impact Chinese steel enterprises engaged in export activities. The levying of carbon tariffs will augment enterprise costs through a cascading mechanism [5,6]. Additionally, the enforcement of carbon tariff policies will lead to a reduction in the overall competitiveness of Chinese steel products in the international market [7], thereby altering the existing international market structure to a certain extent. Mitigating the impacts brought about by CBAM,

safeguarding the international competitiveness of steel products, is poised to become a pressing challenge for both steel enterprises and governments in the future.

Therefore, the primary research objective of this paper is to construct an evolutionary game model for the interactions between different types of steel enterprises and the Chinese government under the backdrop of CBAM. The study aims to investigate the changes in the behaviors of the three entities at various stages of CBAM implementation and explore optimal decision-making strategies that alleviate the impact of CBAM while maximizing self-interest. This paper will focus on the following questions: (1) What coping strategies will be adopted by steel enterprises of different scales and the Chinese government at different stages of CBAM implementation? (2) Does the tripartite evolutionary model have points of evolutionary stability? (3) How do relevant parameters impact stakeholders?

To address the aforementioned questions, this paper constructs a more comprehensive and specific dynamic tripartite evolutionary game model. It analyzes the impact of CBAM from the perspective of stakeholders' behavioral decision-making and determines the evolutionary stable strategies of the model. Based on real cases and interviews with relevant personnel, the study identifies the key factors influencing the strategic choices of the main actors and conducts simulation experiments on variations in typical parameters. The contributions of this research are as follows: (1) It broadens the scope of China's research on CBAM. (2) By employing an evolutionary game approach, it dynamically simulates the strategic behaviors and decision choices of the government and enterprises in response to CBAM. (3) Through the analysis of the evolutionary outcomes of government and enterprise strategies at different stages of CBAM, it provides a scientific basis for formulating new environmental strategies to cope with CBAM in the future.

2. Literature review

2.1. The Current State of Research on the Impact of CBAM on China

Regarding the impact of CBAM on China, Guo et al., using the GTAP model, verified that CBAM has negative effects on China's economic development, trade levels, and resident welfare [8]. Lin and Zhao[9]., through an assessment of the Chinese futures market, demonstrated significant adverse impacts of CBAM on China's energy-intensive export-oriented enterprises. Qi et al. [10] by constructing a price-variable resource allocation model, confirmed the negative effects of CBAM on China's commodity exports. They further emphasized that stabilizing a higher carbon price could reduce the impact of CBAM. Yang and Yan [11] comparing the effects of carbon tariffs in the United States and the European Union on the steel industry, concluded that carbon tariffs would negatively affect the value-added of steel producers, accompanied by welfare losses. Combining the above literature illustrates that, in the future trade of the steel market, the impact of CBAM will be one of the most critical factors. Most existing literature focuses on the welfare losses caused by CBAM, environmental carbon leakage, and debates on trade measures. However, there is relatively less research analyzing the decision-making impact on stakeholders involved in CBAM. Therefore, this paper aims to analyze and evaluate the strategies of governments and different types of enterprises in response to CBAM.

2.2. The Current State of Research on Carbon Tax Policies

Currently, research on carbon tax policies and their impact on industries or businesses often employs input-output models, the "tragedy of the commons" model, profit maximization models, and general equilibrium models. For example, Yu et al. [12] using an input-output model, explored the impact of carbon taxes on different age and income groups, revealing the burden of carbon taxes on different demographics. They demonstrated that carbon taxes pose energy challenges for low-income elderly individuals and require support mechanisms to mitigate the impact of carbon taxes. Naef et al. [13] constructed the "tragedy of the commons" dilemma involving carbon taxes, fossil fuel revenue, and climate change. They analyzed the support rate of oil companies for carbon tax policies, validating that oil and gas companies can use carbon taxes to escape competition from coal. However,

this study did not address the issue of profit maximization for businesses; it solely analyzed the behavioral choices of relevant enterprises. Wang et al. [14] and others used a static profit maximization model to verify the impact of carbon taxes and low-carbon credits on manufacturing activities. They demonstrated that while carbon tax policies can control carbon emissions, capital still needs to consider low-carbon costs and low-carbon financing. Lamb et al. [15] and colleagues used a CGE model to simulate and evaluate the contributions and impacts of carbon taxes, the phasing out of coal-fired power plants, and subsidies for unconventional renewable energy sources on emission reduction. They indicated that all three policies can reduce greenhouse gas emissions. Additionally, the phasing out of coal-fired power plants has a significant impact on GDP, while subsidies for unconventional renewable energy sources affect household income and expenses.

In summary, in studying the impact of carbon taxes on industries or businesses, there is a lack of research on the decision-making of enterprises in response to carbon tax policies. Moreover, in terms of model application, there is a lack of a dynamic, evolving game-theoretic form that adjusts to meet the goal of profit maximization for businesses.

2.3. The Application of Evolutionary Game Theory in the Steel Industry

Evolutionary game theory has become a crucial theoretical approach for addressing environmental issues, combining game theory with dynamic evolutionary processes to explain the phenomena of mutual learning and competition during the evolution of agents. Methodologically, compared to traditional game theory, evolutionary game theory places more emphasis on dynamic equilibrium among agents, highlighting the limited rationality of stakeholders' behavior in an environment of incomplete information [16].

This Aligns with the Competitive and Cooperative Relationship Between Enterprises and Governments. Zhou et al. [17] studied the relationship between government intervention and low-carbon innovation technology by constructing a three-way evolutionary model. Meng et al. [18] built a three-way evolutionary model between the government and the shipping industry, analyzing the impact of government regulation on energy-saving and emission reduction strategies in the shipping industry. Yuan et al. [19] analyzed the relationship between the government and prefabricated housing construction by constructing a three-way evolutionary model, proposing a mechanism for promoting prefabricated housing construction . In recent years, evolutionary game theory has also been widely applied to the steel industry. Zhang et al. [20] constructed an evolutionary model of pollution coordination governance among steel enterprises under the carbon quota trading mechanism. Liu et al. [21] analyzed the game relationship between steel enterprises, scrap steel enterprises, and the government from the perspective of evolutionary game theory, deriving corresponding behavioral strategies. Zhang et al.[22] simulated the relationship between Chinese iron and steel enterprises and international iron ore enterprises to provide the basis for strategic choices in iron ore negotiations. Lin et al. [23] used the method of evolutionary game theory to analyze the interactive relationship between steel enterprises and the government in the post-pandemic era, offering policy recommendations for the sustainable development of steel enterprises.

2.4. Summary

In summary, previous research on the steel industry has mostly focused on the impact of domestic policies in China and the promotion of relevant technologies. However, there is limited research on the relationship and response strategies between steel enterprises and the government after the implementation of CBAM. This paper, using the method of evolutionary game theory, can simulate the interactions between carbon tax collection, stakeholder benefits, and various influencing factors over a certain period, reflecting the optimal choices for government and corporate strategies under carbon border tax imposition.

3. Construction of a tripartite evolutionary model

3.1. Description of the problem

Under the implementation of CBAM, there exists a competitive game relationship between large-scale steel enterprises and small and medium-sized steel enterprises, with the government serving as a market guide and providing relevant policy and financial support as a crucial external force. Therefore, the model includes three participants: large-scale steel enterprises, small and medium-sized steel enterprises, and the government. They all make independent decisions under bounded rationality to maximize their own interests. Large-scale and small and medium-sized steel enterprises face CBAM and government management by deciding whether to undergo low-carbon upgrades. The government, as a key external force, can choose whether to proactively address CBAM and formulate its own decisions. Since all three parties need to satisfy their own profits, their strategic choices will also be dynamic. Using an evolutionary game model to identify the evolutionary stable points among the three parties is crucial in understanding how to better respond to CBAM. The logical relationship among the three entities is illustrated in Figure 1.
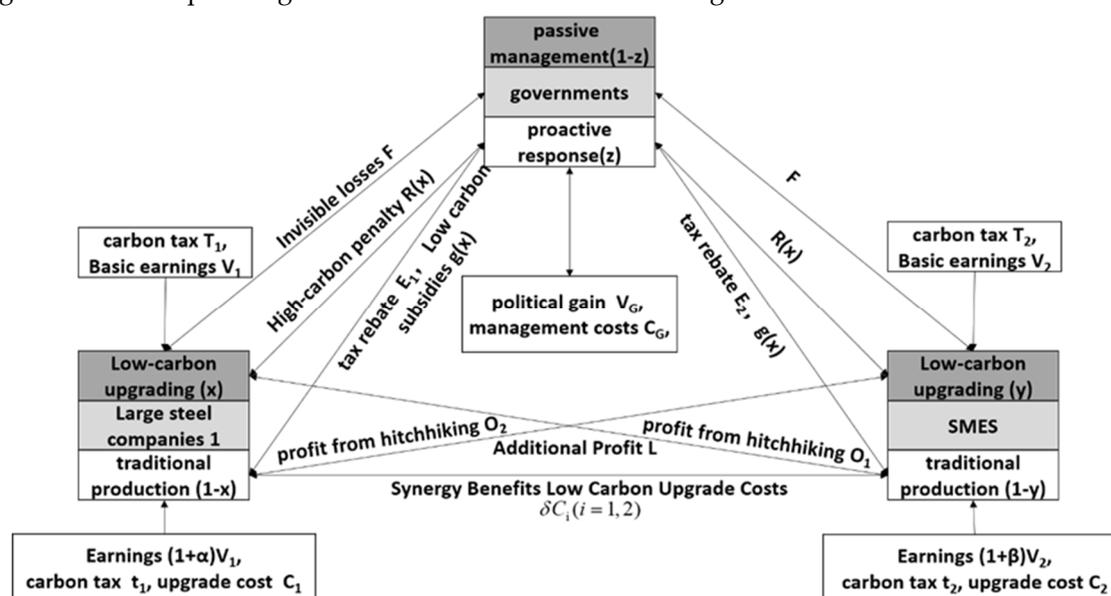

Figure 1. Logical relationships between stakeholders.

3.2. Model assumptions

U Grounded in the model participation of the behavioral logic relationships among the three entities, the following hypotheses can be postulated.

Assumption 1: The decision dynamics of steel enterprises will be influenced by environmental policies, government attitudes, and the interactions of other steel enterprises. This will lead to the formation of a competitive-cooperative equilibrium state between the government and enterprises [24]. Considering the entire steel industry as a comprehensive system, the assumption involves the existence of a large-scale steel enterprise (Enterprise 1), a medium-sized steel enterprise (Enterprise 2), and the government playing a guiding and managerial role. All three entities will make decisions based on the principle of maximizing their individual profits and possess the ability to learn, compete, and cooperate with each other. The decision set for Enterprise 1 includes (1: undergo low-carbon upgrade, 0: maintain the existing production mode). The probability of choosing the decision 1 is denoted as x ($0 \leq x \leq 1$), and the probability of choosing 0 is denoted as 1-x. The decision set for Enterprise 2 includes (1: undergo low-carbon upgrade, 0: maintain the existing production mode). The probability of choosing the decision 1 is denoted as y ($0 \leq y \leq 1$), and the probability of choosing 0 is denoted as 1-y. The decision set for the government includes (1: proactively address CBAM, 0:

passively manage). The probability of choosing the decision 1 is denoted as z ($0 \leq y \leq 1$), and the probability of choosing 0 is denoted as 1-z. Here, x y, and z are all functions of time t.

    Assumption 2: When both Enterprise 1 and Enterprise 2 choose the traditional production mode, both parties receive basic benefits $V_i(i=1,2)$. Enterprises opting for low-carbon upgrade mode can gain returns from low-carbon investments. This brings additional benefits to Enterprise 1, denoted as αV, where α represents the input-output ratio of low-carbon production for Enterprise 1, and additional benefits to Enterprise 2, denoted as βV, where β represents the input-output ratio of low-carbon production for Enterprise 2. When one enterprise chooses the low-carbon upgrade production strategy while the other adheres to the traditional production mode, the enterprise implementing low-carbon production incurs corresponding costs C_i. When both enterprises choose low-carbon upgrade, collaborative emission reduction utility is generated [25], and the emission reduction cost is reduced to $\delta C_i (i=1,2)$, where δ is the synergy coefficient $(0 < \delta < 1)$.

    Assumption 3: Currently, there is a stronger market demand for products produced through low-carbon processes in the global steel market. Consumers are willing to pay higher prices for environmentally friendly low-carbon products compared to regular products [26]. If one enterprise chooses the low-carbon production mode while the other adheres to traditional production, the enterprise implementing low-carbon production gains additional income denoted as L. When both enterprises choose low-carbon production, the two enterprises compete at the same level, and hence, neither receives additional income. Additionally, government subsidies for dynamic low-carbon initiatives to enterprises are directly proportional to the share of low-carbon enterprises [27]. The subsidy amount for enterprises is represented by $g(x) = g \times e$, where g is the maximum subsidy amount, and e is the proportion of low-carbon enterprises. Similarly, under increased government intervention, there will be dynamic penalties for high-carbon enterprises, i.e., those enterprises still using traditional production methods. The government's penalty intensity for high-carbon enterprises is also related to the proportion of enterprises using traditional production methods, represented by the penalty function $R(x) = r \times (1-e)$, where r is the maximum penalty amount.

    Assumption 4: Considering the management of air pollution in the steel industry as a collective interest, Enterprise 1 and Enterprise 2 are two actors within this collective. The benefits of air pollution control are shared by the actors [28]. The cost of low-carbon governance is borne individually by each actor. Therefore, when one enterprise chooses a low-carbon upgrade strategy, the willingness of the other actor to choose a low-carbon upgrade will be suppressed, leading to free-riding behavior [29]. When Enterprise 1 chooses a low-carbon upgrade, Enterprise 2 gains benefits denoted as O_2 due to free-riding. Similarly, when Enterprise 2 chooses a low-carbon upgrade, Enterprise 1 gains benefits denoted as O_1 due to free-riding.

    Assumption 5: If an enterprise maintains its traditional production mode, the carbon emission intensity per ton of steel is denoted as N_i. When the enterprise adopts a low-carbon upgrade strategy, the carbon emission intensity per ton of steel becomes M_i, at this time $N_i > M_i (i=1,2)$. Influenced by the EU CBAM, additional carbon taxes are imposed on steel product exports. The export quantity of steel products for the enterprise is represented by l. For analytical convenience, it is assumed that after the low-carbon upgrade, the carbon emission intensity per ton of steel is equivalent to that of a European steel enterprise with a similar scale and product profile. The carbon emission intensity per ton of steel for a comparable European enterprise under the EU Emissions Trading System (EU-EST) is denoted as ES. This European enterprise receives free carbon allowances with a ratio denoted as b and the carbon trading prices in the EU and China are denoted as EP and CP, at this time $0 \leq b < 1$, $EP < CP$. In this scenario, the CBAM tax (t) for the enterprise after implementing the low-carbon upgrade is calculated as follows:

$$t = (M_i - M_i \times b) \times (EP - CP) \times l \tag{1}$$

    When the enterprise adopts the traditional production mode, the CBAM tax expense (T) is calculated as follows:

$$T = (N_i - ES \times b) \times (EP - CP) \times l \tag{2}$$

6

Assumption 6: When the government proactively responds to CBAM regulations, it will gain corresponding environmental reputation and image internationally [30]. Additionally, it will enhance the international market access for domestic goods [31]. Proactive compliance with international regulations also demonstrates the government's commitment to compliance in international affairs [32], increases international trust in China, and results in corresponding political benefits VG. To protect the competitiveness of domestic products in the international market [33,34], the government encourages enterprises to undergo low-carbon transformation by providing a certain amount of tax rebate E_i for products from low-carbon enterprises and dynamic subsidies. Under the choice of actively facing CBAM, the government incurs additional regulatory and operational costs C_g. Regardless of the measures taken by the government when some enterprises maintain traditional high-carbon production modes, it will result in external implicit losses such as ecological management fees, public and social health costs [35], climate adjustment measures, and other external implicit losses F [35,36].

According to the above model assumptions, a tripartite game tree for the government, large enterprise 1, and small-to-medium-sized enterprise 2 is constructed, as shown in Figure 2. The payoff matrix for the model is presented in Table 1.
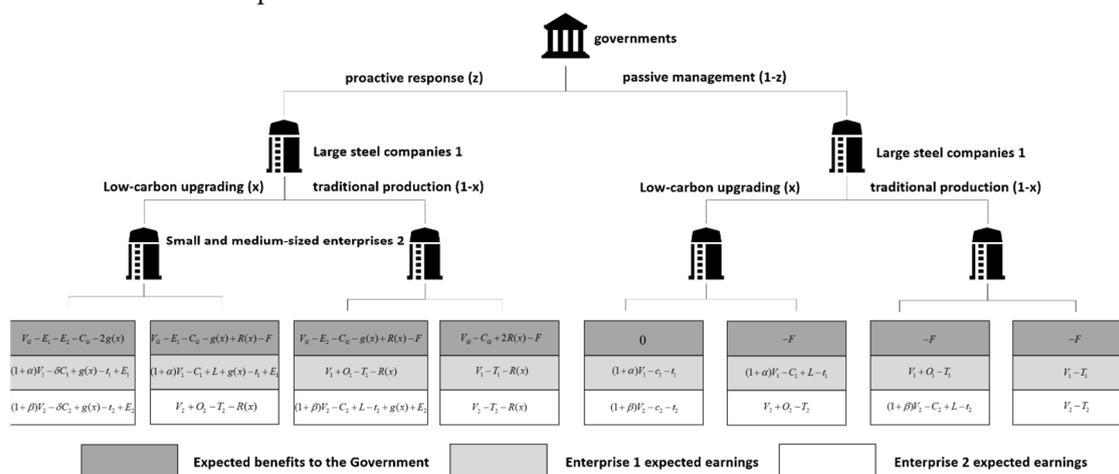

Figure 2. A tripartite pure strategy game tree.

Table 1. CBAM-Oriented Government-Business Tripartite Game Benefits Matrix.

Game Participants		Governments			
		Proactive response (z)		Passive management (1-z)	
		Small and medium-sized enterprises 2			
		Low-carbon upgrading (y)	traditional production (1-y)	Low-carbon upgrading (y)	traditional production (1-y)
Large steel companies 1	Low-carbon upgrading (x)	$V_G - E_1 - E_2 - C_G - 2g(x)$ $(1+\alpha)V_1 - \delta C_1 + g(x) - t_1 + E_1$ $(1+\beta)V_2 - \delta C_2 + g(x) - t_2 + E_2$	$V_G - E_1 - C_G - g(x) + R(x) - F$ $(1+\alpha)V_1 - C_1 + L + g(x) - t_1 + E_1$ $V_2 + O_2 - T_2 - R(x)$	0 $(1+\alpha)V_1 - c_1 - t_1$ $(1+\beta)V_2 - c_2 - t_2$	$-F$ $(1+\alpha)V_1 - C_1 + L - t_1$ $V_2 + O_2 - T_2$
	traditional production (1-x)	$V_G - E_2 - C_G - g(x) + R(x) - F$ $V_1 + O_1 - T_1 - R(x)$ $(1+\beta)V_2 - C_2 + L - t_2 + g(x) + E_2$	$V_G - C_G + 2R(x) - F$ $V_1 - T_1 - R(x)$ $V_2 - T_2 - R(x)$	$-F$ $V_1 + O_1 - T_1$ $(1+\beta)V_2 - C_2 + L - t_2$	$-F$ $V_1 - T_1$ $V_2 - T_2$

4. Model analysis

4.1. Analysis of replication dynamics

1. Large Steel Enterprise 1

The expected payoff u_{11} for Enterprise 1 choosing the low-carbon upgrade strategy is:

$$
\begin{aligned}
u_{11} &= yz[(1+\alpha)V_1 - \delta C_1 + g(x) - t_1 + E_1] + y(1-z)[(1+\partial)V_1 - \delta C_1 - t_1] + \\
&\quad z(1-y)[(1+\alpha)V_1 - C_1 + L + g(x) - t_1 + E_1] + (1-y)(1-z)[(1+\partial)V_1 - C_1 + L - t_1] \\
&= (1+\alpha)V_1 - C_1 + L - t_1 + y(C_1 - \delta C_1 - L) + z(g(x) + E_1)
\end{aligned}
\tag{3}
$$

The expected payoff u_{12} for choosing to maintain the traditional production mode is:

$$
\begin{aligned}
u_{12} &= yz(V_1 + O_1 - T_1 - R(x)) + y(1-z)(V_1 + O_1 - T_1) + z \\
&\quad (1-y)(V_1 - T_1 - R(x)) + (1-y)(1-z)(V_1 - T_1) \\
&= V_1 - T_1 + O_1 y - R(x)z
\end{aligned}
\tag{4}
$$

The replicator dynamic equation for the production strategy choice of steel enterprise 1, derived from equations (3) and (4), is:

$$
\begin{aligned}
F(x) &= \frac{dx}{dt} = x(u_{11} - \bar{u}_1) = x(1-x)(u_{11} - u_{12}) \\
&= x(1-x)[(1+\alpha)V_1 - C_1 + L - t_1 + y(C_1 - c_1 - L) + z(g(x) + E_1) - V_1 + T_1 - O_1 y + R(x)z] \\
&= x(1-x)[\alpha V_1 - C_1 + L - t_1 + T_1 + y(C_1 - \delta C_1 - L - O_1) + z(g(x) + R(x) + E_1)]
\end{aligned}
\tag{5}
$$

2.Small and medium-sized steel companies 2

The expected payoff u_{21} for Enterprise 2 choosing the low-carbon upgrading strategy is:

$$
\begin{aligned}
u_{21} &= xz[(1+\beta)V_2 - \delta C_2 + g(x) - t_2 + E_2] + x(1-z)[(1+\beta)V_2 - \delta C_2 - t_2] + \\
&\quad z(1-x)[(1+\beta)V_2 - C_2 + L + g(x) - t_2 + E_2] + (1-x)(1-z)[(1+\beta)V_2 - C_2 + L - t_2] \\
&= (1+\beta)V_2 - C_2 + L - t_2 + x(C_2 - \delta C_2 - L) + z(g(x) + E_2)
\end{aligned}
\tag{6}
$$

The expected payoff u_{22} for Enterprise 2 maintaining the traditional production mode is:

$$
\begin{aligned}
u_{22} &= xz(V_2 + O_2 - T_2 - R(x)) + x(1-z)(V_2 + O_2 - T_2) + z \\
&\quad (1-x)(V_2 - T_2 - R(x)) + (1-x)(1-z)(V_2 - T_2) \\
&= V_2 - T_2 + O_2 x - R(x)z
\end{aligned}
\tag{7}
$$

Based on equations (6) and (7), the replicator dynamic equation for steel enterprise 2's production strategy choice is given by:

$$
\begin{aligned}
F(y) &= \frac{dy}{dt} = y(u_{21} - \bar{u}_2) = y(1-y)(u_{21} - u_{22}) \\
&= y(1-y)[(1+\beta)V_2 - C_2 + L - t_2 + x(C_2 - \delta C_2 - L) + z(g(x) + E_2) - V_2 + T_2 - O_2 x + R(x)z] \\
&= y(1-y)[\beta V_2 - C_2 + L - t_2 + T_2 + x(C_2 - \delta C_2 - L - O_2) + z(g(x) + R(x) + E_2)]
\end{aligned}
\tag{8}
$$

3.government

The expected return u_{31} to the government's choice of a proactive CBAM response strategy is:

$$
\begin{aligned}
u_{31} &= xy(V_G - E_1 - E_2 - C_G - 2g(x)) + x(1-y)(V_G - E_1 - C_G - g(x) + R(x) - F) + \\
&\quad y(1-x)(V_G - E_2 - C_G - g(x) + R(x) - F) + (1-x)(1-y)(V_G - C_G + 2R(x) - F) \\
&= Fxy - x(E_1 + g(x) + R(x)) - y(E_2 + g(x) + R(x))
\end{aligned}
\tag{9}
$$

The expected return u_{32} from passive management is:

$$
\begin{aligned}
u_{32} &= -F(1-y)x - F(1-x)y - F(1-x)(1-y) \\
&= -F + Fxy
\end{aligned}
\tag{10}
$$

The replication dynamic equation for management strategy choice on the government side is:

$$
\begin{aligned}
F(z) &= \frac{dz}{dt} = z(u_{31} - \bar{u}_3) = z(1-z)(u_{31} - u_{32}) \\
&= z(1-z)[Fxy - x(E_1 + g(x) + R(x)) - y(E_2 + g(x) + R(x)) + F - Fxy] \\
&= z(1-z)[F - x(E_1 + g(x) + R(x)) - y(E_2 + g(x) + R(x))]
\end{aligned}
\tag{11}
$$

4.2. Stable equilibrium analysis

By associating (5), (8) and (11), the model power system is formed as shown in the following equation:

$$\begin{cases} F(x) = x(1-x)[\alpha V_1 - C_1 + L - t_1 + T_1 + y(C_1 - \delta C_1 - L - O_1) + z(g(x) + R(x) + E_1)] \\ F(y) = y(1-y)[\beta V_2 - C_2 + L - t_2 + T_2 + \mathrm{x}(C_2 - \delta C_2 - L - O_2) + z(g(x) + R(x) + E_2)] \\ \quad\quad F(z) = z(1-z)[F - x(E_1 + g(x) + R(x)) - y(E_2 + g(x) + R(x))] \end{cases}$$

(12)

When the decision change rates of the three entities are zero, the equilibrium points of this tripartite evolutionary system can be obtained. That is, when $F(x) = 0, F(y) = 0, F(z) = 0$, There exist 8 pure strategy stable points: $P_1(0,0,0)$, $P_2(1,0,0)$, $P_3(0,0,1)$, $P_4(1,0,1)$, $P_5(0,1,0)$, $P_6(1,1,0)$, $P_7(0,1,1)$, $P_8(1,1,1)$ and One mixed strategy equilibrium point $P_9(x^*, y^*, z^*)$.

$$\begin{cases} x^* = \dfrac{F - y(E_2 + g(x) + R(x))}{E_1 + g(x) + R(x)} \\ y^* = \dfrac{\alpha V_1 - C_1 + L - t_1 + T_1 + z[g(x) + R(x) + E_1]}{\delta C_1 + L + O_1 - C_1} \\ z^* = \dfrac{\beta V_2 - C_2 + L - t_2 + T_2 + \mathrm{x}(C_2 - \delta C_2 - L - O_2)}{-[g(x) + R(x) + E_2]} \end{cases}$$

(13)

According to the arguments presented in the papers by Wainwright[37] and Lyapunov[38], to determine whether a stable point is an asymptotically stable point in the dynamic evolutionary system, it must exhibit a pure Nash equilibrium strategy balance. Therefore, temporarily ignoring the mixed strategy point $P_9(x^*, y^*, z^*)$, the analysis will focus on the remaining 8 equilibrium points. Secondly, based on Lyapunov's method for system stability determination [39], when all eigenvalues of the Jacobian matrix of the evolution model are negative, the point is an asymptotically stable point. When at least one eigenvalue is positive, the equilibrium point is unstable. If there are eigenvalues equal to 0 with the rest being negative, the stability of the point cannot be determined, indicating a saddle point. Using the above methods and the system's dynamic system, the Jacobian matrix can be obtained:

$$J = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial F(x)}{\partial x} & \dfrac{\partial F(x)}{\partial y} & \dfrac{\partial F(x)}{\partial z} \\ \dfrac{\partial F(y)}{\partial x} & \dfrac{\partial F(y)}{\partial y} & \dfrac{\partial F(y)}{\partial z} \\ \dfrac{\partial F(z)}{\partial x} & \dfrac{\partial F(z)}{\partial y} & \dfrac{\partial F(z)}{\partial z} \end{bmatrix}$$

(14)

The arithmetic is available:

$$\begin{cases} J_{11} = (1-2x)[\alpha V_1 - C_1 + L - t_1 + T_1 + y(C_1 - \delta C_1 - L - O_1) + z(g(x) + R(x) + E_1)] \\ J_{12} = x(1-x)(C_1 - \delta C_1 - L - O_1) \\ J_{13} = x(1-x)(g(x) + R(x) + E_1) \\ J_{21} = y(1-y)(C_2 - \delta C_2 - L - O_2) \\ J_{22} = (1-2y)[\beta V_2 - C_2 + L - t_2 + T_2 + \mathrm{x}(C_2 - \delta C_2 - L - O_2) + z(g(x) + R(x) + E_2)] \\ J_{23} = y(1-y)(g(x) + R(x) + E_2) \\ J_{31} = z(1-z)(E_1 + g(x) + R(x)) \\ J_{32} = z(1-z)(E_2 + g(x) + R(x)) \\ J_{33} = (1-2z)[F - x(E_1 + g(x) + R(x)) - y(E_2 + g(x) + R(x))] \end{cases}$$

Based on the above results the eigenvalues of the 8 equilibrium points can be calculated, As shown in Table 2.

Table 2. Jacobian matrix eigenvalues.

Equilibrium point	Eigenvalue $\lambda 1$	Eigenvalue $\lambda 2$	Eigenvalue $\lambda 3$
$P_1(0,0,0)$	$\alpha V_1 - C_1 + L - t_1 + T_1$	$\beta V_2 - C_2 + L - t_2 + T_2$	F
$P_2(1,0,0)$	$-(\alpha V_1 - C_1 + L - t_1 + T_1)$	$\beta V_2 - t_2 + T_2 - \delta C_2 - O_2$	$F - (E_1 + g(x) + R(x))$
$P_3(0,0,1)$	$\alpha V_1 - C_1 + L - t_1 + T_1$ $+ E_1 + g(x) + R(x)$	$\beta V_2 - C_2 + L - t_2 + T_2 +$ $E_2 + g(x) + R(x)$	$-F$
$P_4(1,0,1)$	$-(\alpha V_1 - C_1 + L - t_1 + T_1$ $+ g(x) + R(x) + E_1)$	$\beta V_2 - \delta C_2 - t_2 + T_2 - O_2$ $+ g(x) + R(x) + E_2$	$-[F - (E_1 + g(x) + R(x))]$
$P_5(0,1,0)$	$\alpha V_1 - \delta C_1 - t_1 + T_1 - O_1$	$-(\beta V_2 - C_2 + L - t_2 + T_2)$	$F - (E_2 + g(x) + R(x))$
$P_6(1,1,0)$	$-(\alpha V_1 - \delta C_1 - t_1 + T_1 - O_1)$	$-(\beta V_2 - \delta C_2 - t_2 + T_2 - O_2)$	$F - (E_1 + g(x) + R(x))$ $-(E_2 + g(x) + R(x))$
$P_7(0,1,1)$	$\alpha V_1 - \delta C_1 + T_1 - t_1 - O_1$ $+ E_1 + R(x) + g(x)$	$-(\beta V_2 - C_2 + L - t_2 + T_2$ $+ g(x) + R(x) + E_2)$	$-[F - (E_2 + g(x) + R(x))]$
$P_8(1,1,1)$	$-(\alpha V_1 - t_1 + T_1 - \delta C_1 - O_1$ $+ g(x) + R(x) + E_1)$	$-(\beta V_2 - t_2 + T_2 - \delta C_2 - O_2$ $+ g(x) + R(x) + E_2)$	$-[F - (E_1 + g(x) + R(x))$ $-(E_2 + g(x) + R(x))]$

By taking the eigenvalues in the above table, the ESS of the system for different conditions can be derived, as can be seen through Table 3:

Table 3. Equilibrium point stabilization conditions.

Equilibrium point	stability	Stability conditions
$P_1(0,0,0)$	saddle point	-
$P_2(1,0,0)$	ESS	$\beta V_2 - t_2 + T_2 - \delta C_2 - O_2 < 0$ $\alpha V_1 - C_1 + L - t_1 + T_1 > 0$ $F < E_1 + g(x) + R(x)$
$P_3(0,0,1)$	ESS	$\alpha V_i - C_i + L - t_i + T_i + E_i + g(x) + R(x) < 0$ $\beta V_2 - C_2 + L - t_2 + T_2 + E_2 + g(x) + R(x) < 0$
$P_4(1,0,1)$	ESS	$\alpha V_1 - C_1 + L - t_1 + T_1 + g(x) + R(x) + E_1 > 0$ $\beta V_2 - \delta C_2 - t_2 + T_2 - O_2 + g(x) + R(x) + E_2 < 0$ $F > E_1 + g(x) + R(x)$
$P_5(0,1,0)$	ESS	$\alpha V_1 - \delta C_1 - t_1 + T_1 - O_1 < 0$ $\beta V_2 - C_2 + L - t_2 + T_2 > 0$ $F < (E_2 + g(x) + R(x))$
$P_6(1,1,0)$	ESS	$\alpha V_1 - \delta C_1 - t_1 + T_1 - O_1 > 0$ $\beta V_2 - \delta C_2 - t_2 + T_2 - O_2 > 0$ $F < (E_1 + g(x) + R(x)) + (E_2 + g(x) + R(x))$
$P_7(0,1,1)$	ESS	$\alpha V_1 - \delta C_1 + T_1 - t_1 - O_1 + E_1 + R(x) + g(x) < 0$ $\beta V_2 - C_2 + L - t_2 + T_2 + g(x) + R(x) + E_2 > 0$ $F > E_2 + g(x) + R(x)$
$P_8(1,1,1)$	ESS	$\alpha V_1 - t_1 + T_1 - \delta C_1 - O_1 + g(x) + R(x) + E_1 > 0$ $\beta V_1 - t_1 + T_1 - \delta C_1 - O_1 + g(x) + R(x) + E_1 > 0$ $F - (E_1 + g(x) + R(x)) - (E_2 + g(x) + R(x)) > 0$

As indicated in the above table, due to the non-negativity of the hidden loss F caused by high emissions from enterprises, point $P_1(0,0,0)$ cannot be a stable point in the evolutionary system. It can

only be a saddle point or an unstable point. Only points $P_2(1,0,0)$, $P_3(0,0,1)$, $P_4(1,0,1)$, $P_5(0,1,0)$, $P_6(1,1,0)$, $P_7(0,1,1)$ and $P_8(1,1,1)$ have the potential to become ES) under certain conditions. Due to space limitations and for the sake of simplification, it is unnecessary to analyze all potential ESS. With the initiation of the CBAM legislation in October 2023, the period from October 2023 to the end of December 2025 is considered a transition period. CBAM is formally implemented from 2026, and its enforcement strengthens each year from 2026 to 2034. According to the progression of the CBAM legislation, the implementation of CBAM is divided into four phases: the Window Phase, Transition Phase, Implementation Phase, and Strengthening Phase.

First Stage: Window Phase, which occurs before the initiation of CBAM. In this phase, large steel enterprises, due to their significant overseas market share, are the first to be impacted by CBAM. They begin to realize that they must mitigate the losses caused by CBAM by upgrading their low-carbon industries. Specifically, when the benefits of low-carbon production outweigh the costs, i.e., $\alpha V_1 + L > C_1 + t_1 - T_1$, large enterprises will take measures to upgrade to low-carbon production; small and medium-sized enterprises, influenced by free-rider benefits and upgrade costs, will choose to maintain their existing production mode($\beta V_2 - t_2 + T_2 - \delta C_2 - O_2 < 0$).At the same time, as the CBAM regulations have not officially started, the government is more inclined to adopt a passive and wait-and-see attitude. Therefore, $P_2(1,0,0)$ is the optimal stable strategy point for dealing with this stage.

Second Stage: Transition Phase. With the formal launch of the CBAM regulations in October 2023, on the foundation of the window period, the government begins actively intervening by implementing measures such as carbon emission incentives and penalties, fiscal subsidies, etc., to assist businesses in coping with the impact of CBAM implementation. Simultaneously, constrained by societal environmental demands, the government faces an increased implicit cost for high-carbon enterprises($F > E_1 + g(x) + R(x)$).The government is inclined to proactively respond to CBAM decisions. During this stage, small and medium-sized enterprises are less affected by CBAM due to their lower export volumes. Consequently, they continue to opt for maintaining traditional production methods, countering the costs of upgrading and high-carbon penalties through the benefits derived from free-riding. At this stage, $P_4(1,0,1)$ is the corresponding optimal equilibrium point.

Third stage: Implementation stage. This stage corresponds to the substantial implementation of CBAM starting from January 2026. Importers of goods covered by CBAM need to purchase CBAM certificates for the implied carbon emissions. At this stage, as CBAM is partially implemented, the CBAM regulations are becoming more mature. Steel enterprises, whether large or small, are increasingly affected by CBAM. Under the influence of CBAM and the government's financial subsidies and emission reward-penalty mechanisms, the benefits of low-carbon upgrades far exceed those of maintaining traditional production. $\alpha V_1 - t_1 + T_1 - \delta C_1 - O_1 + g(x) + R(x) + E_1 > 0,$ $\beta V_2 - t_2 + T_2 - \delta C_2 - O_2 + g(x) + R(x) + E_2 > 0$. Simultaneously, the government incentivizes all enterprises, and the cost is lower than dealing with the external implicit losses generated by high carbon emissions, such as ecological management fees, public social health costs, climate adjustment measures, $F > (E_1 + g(x) + R(x)) - (E_2 + g(x) + R(x))$, Therefore, during this stage, the point $P_8(1,1,1)$ is considered as the optimal equilibrium point.

Fourth phase: Strengthening Phase. In this stage, CBAM will be fully implemented, and free quotas will be completely eliminated. At this stage, the development strategies of both enterprises no longer rely on government financial subsidies and incentive measures. The benefits of low-carbon upgrade strategies are entirely greater than those of traditional production, $\alpha V_1 - \delta C_1 - t_1 + T_1 - O_1 > 0, \beta V_2 - \delta C_2 - t_2 + T_2 - O_2 > 0$ .Government-side implicit losses and political gains will be lower than fiscal expenditures, leading to the cessation of incentive measures and punitive interventions in the market. This inequality is satisfied

$$F < (E_1 + g(x) + R(x)) - (E_2 + g(x) + R(x))$$,the government is more inclined towards a passive management strategy. During this stage, point $P_6(1,1,0)$ becomes the optimal equilibrium point.

5. Evolutionary numerical modeling simulation

To visualize the dynamic evolution of various stakeholders' behaviors in the context of CBAM, determining how the system stabilizes under different conditions, this section employs MATLAB for numerical analysis. MATLAB can represent graphics as different vectors and matrices, facilitating the 2D and 3D visualization of expression graphics. Therefore, through data simulation, a more intuitive quantitative analysis of the iteration and interaction of the gaming stakeholders can be conducted, displaying the tripartite evolutionary gaming process and the ultimate stable state of the entire system. This section will describe the parameter settings involved in numerical simulation in Section 5.1. In Section 5.2, the simulation of the evolutionary paths of stakeholders during the window phase, transition phase, implementation phase, and reinforcement phase of CBAM will be presented. In Section 5.3, the sensitivity of different parameter variations during the implementation phase will be examined.

5.1. Parameter Sources and Settings

This study is based on two steel plants in southern China and eastern China as examples. The southern steel plant utilizes amine-based technology to capture carbon emissions from the blast furnace. Amine-based technology is one of the most popular carbon capture technologies worldwide and is a cost-effective method. The annual emissions from this plant are approximately 15.5 million tons. The application of this technology allows the steel plant to capture about 500,000 tons of carbon dioxide per year, incurring additional fixed operating costs of 12 million RMB per year. The eastern steel plant, during its low-carbon upgrades, actively adopts various low-carbon technologies such as sintering waste heat recovery and power generation, converter flue gas waste heat recovery, blast furnace TRT power generation equipment, and the application of renewable energy for multi-energy complementation. The annual emissions from this plant are around 13 million tons. The annual investment cost for individual low-carbon technologies ranges from 10 to 18 million RMB. The application of the multi-energy complementation technology using renewable energy alone can reduce carbon dioxide emissions by approximately 20,000 tons per year.

According to the actual project data and references from additional literature, the initial parameters for setting up the game model are determined to simultaneously satisfy the two principles of realism, as proposed by Chen[40] and Jiang[41]. In the case of Lingang Corporation obtaining government financial subsidies, the government's maximum subsidy g is based on actual cases and does not exceed 50% of the investment cost. The government's penalties for emissions from high-carbon enterprises are referenced from the research data of Zhou et al. [17] and Lin et al. [42]. The coefficients of low-carbon input and output for both enterprise entities, denoted as α and β, are referenced from the initial values in the study by Chu et al. [43]. The basic profits Vi(i=1,2) and low-carbon investment costs Ci(i=1,2) associated with maintaining the original production mode for both enterprises are set based on the research by Mörsdorf et al. [44]. The free quota ratio for the European Union, denoted as b, is referenced from the relevant rules of the European Parliament's Carbon Border Adjustment Mechanism for the sake of simulation analysis, and it is proportionally reduced. Considering real-time data from the European Union Emissions Trading System (ETS) and future predictions of EU carbon prices, where the EU carbon trading price has exceeded 99 euros per ton and is expected to continue rising, the initial value of the EU carbon price (EP) is set to 1. Research on trading price information in the Chinese carbon market indicates that the recent trading prices range from 65-74 yuan/ton. To simplify the analysis and incorporate currency unit exchange rates, the initial value of the Chinese carbon price (CP) is set to 0.083. The values for the government's proactive response to the CBAM political gains (Vg) and high-carbon implicit losses (F) are abstract and determined through consultation with government experts and literature research [18,45]. The government's tax refund subsidies for enterprises Ei (i=1,2) are set based on the research data from

Wang [46] and Chang et al.[47]. Combining the actual situation and relevant literature research, four sets of parameter values for different stages are summarized, with specific parameters shown in Table 4:

Table 4. Parameter assignment table.

parameter value	window stage	Transition phase	Implementation phase	intensive phase
V1	15	15	15	15
V2	10	10	10	12
α	0.35	0.35	0.35	0.35
β	0.25	0.25	0.25	0.25
C1	12	12	12	12
C2	10	10	10	10
δ	0.75	0.75	0.75	0.75
e	0.4	0.4	0.5	0.5
g	2	2	3	3
r	3	3	4	4
Oi	3	5	3	2
L	5	5	4	4
N1	15	15	14	14
N2	12	10	10	10
M1	8	8	8	8
M2	6	6	6	6
ES	6	6	6	6
b	1	0.9	0.5	0
EP	1	1	1	1
CP	0.083	0.083	0.083	0.083
l	1	1	1	2
Vg	10	10	10	10
Cg	6	6	6	6
F	5	8	15	8
E1	4	4	4	4
E2	3	3	3	3

5.2. Results of evolutionary paths at different stages

(1) The evolutionary paths of stakeholders during the CBAM window stage are as follows:

Based on the simulated parameters during the window stage, Figure 3a shows the evolutionary trajectories of the three players over 80 iterations, while Figure 3b presents the evolution trends of the relevant stakeholders with different colored lines. From the graph, it can be observed that different initial strategies eventually converge to the point , indicating the ESS for the large steel enterprise, small and medium-sized steel enterprise, and government as (adopting low-carbon upgrade, maintaining traditional production, passive management). This effectively validates the theoretical analysis in Section 3.6. This indicates that during the window period before CBAM is launched, factors such as export volume, free-riding benefits, and the cost of low-carbon upgrades inhibit the choice of a low-carbon upgrade strategy by small and medium-sized enterprises. The lack of clarity in government policies and insufficient awareness of the implicit losses caused by high-carbon enterprises lead to an inclination among enterprises to adopt a passive wait-and-see approach. Large enterprises, being the first to be impacted by CBAM due to their export business, tend to choose low-carbon upgrades.
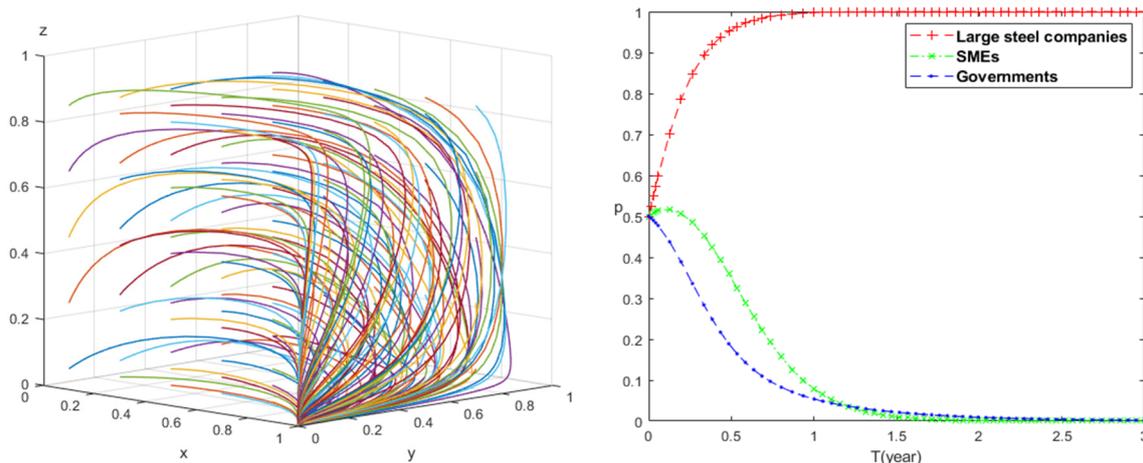
a. Window stage evolution path   b. Trends in window stage evolution

Figure 3. Evolutionary Process During the Window Stage.

(2) Evolutionary Paths of Stakeholders in the CBAM Transition Stage

In the transition phase, through simulation and gaming, the trajectory chart after 80 iterations is shown in Figure 4a, and the evolutionary trend is depicted in Figure 4b. In this phase, based on the window stage, government policies ultimately converge to 1, stabilizing the evolutionary system with the strategy $P_4(1,0,1)$. During the transition phase, the government initiates active responses to CBAM, exerting its guiding role by promoting low-carbon development through fiscal subsidies and a dynamic emission reward and penalty mechanism. This proactive environmental strategy enhances the government's international image, leading to certain political gains.
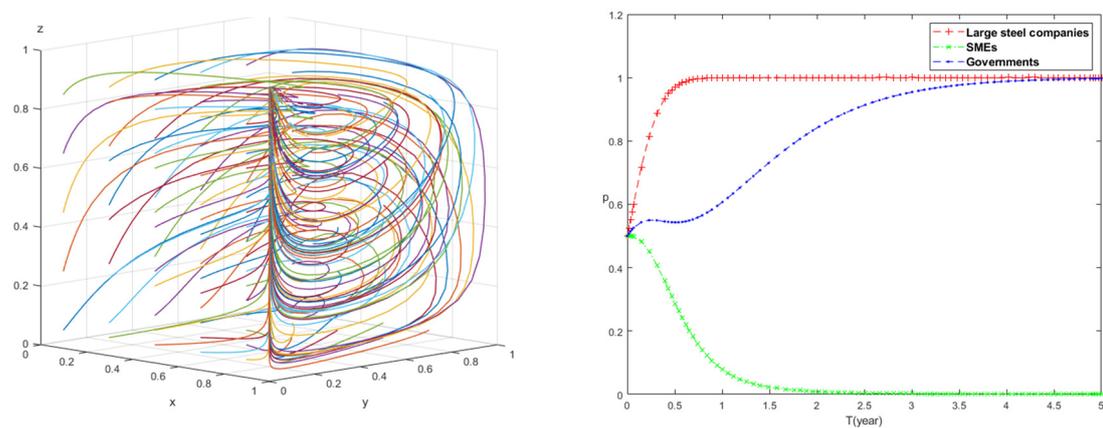
a. Transition phase evolutionary path   b. Evolutionary trends in the transition phase

Figure 4. Transition Phase Evolutionary Process.

(3) Stakeholder Evolutionary Paths in the CBAM Implementation Phase

According to the implementation phase as shown in Table 4, each parameter corresponds to instances and stable conditions, including $\alpha V_1 - t_1 + T_1 - \delta C_1 - O_1 + g(x) + R(x) + E_1 > 0$, $\beta V_1 - t_1 + T_1 - \delta C_1 - O_1 + g(x) + R(x) + E_1 > 0$ and $F - (E_1 + g(x) + R(x)) - (E_2 + g(x) + R(x)) > 0$. By

generating evolution paths over time for different initial strategies using MATLAB, as shown in Figure 5a, it can be observed that after multiple iterations, the path ultimately converges to (1,1,1), indicating an ESS for the implementation phase is $P_8(1,1,1)$. This phase signifies that, with the formal implementation of CBAM, businesses, influenced by carbon taxes and government regulations, opt for low-carbon upgrading strategies. Simultaneously, the government plays a regulatory and incentivizing role in the implementation phase, mitigating the impact of CBAM and benefiting from it, hence choosing an active response strategy.

a. Implementation phase evolution path

b. Trends in evolution of implementation phases
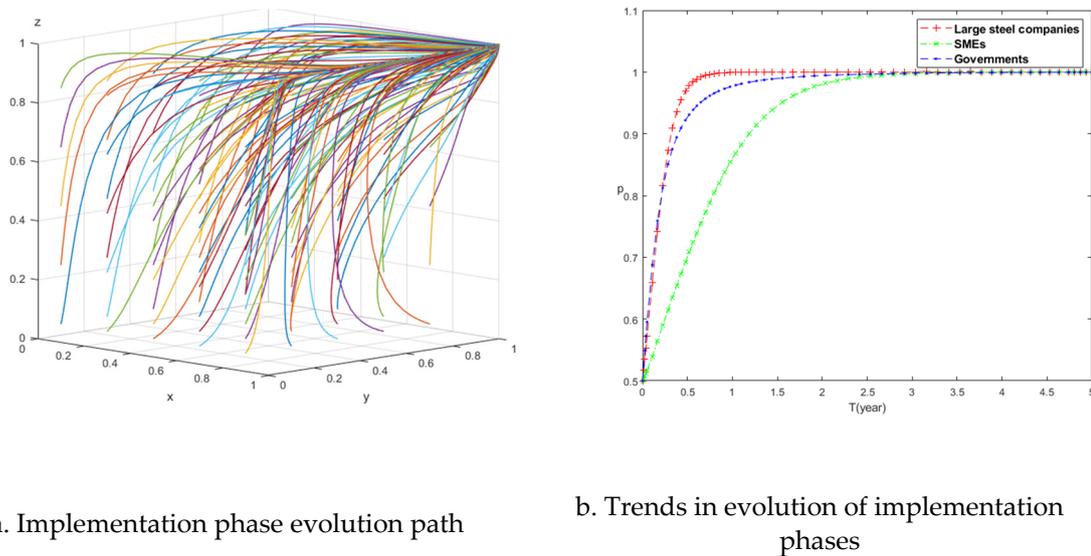
Figure 5. Evolution of the implementation phase.

(4) Stakeholder Evolutionary Paths in the CBAM Enhancement Phase

In the CBAM strengthening stage, the numerical simulation reveals that the system converges to $P_6(1,1,0)$, indicating the presence of a unique Evolutionarily Stable Strategy (ESS). The evolution path and trajectory of the system are depicted in Figures 6a and 6b. During this stage, as the CBAM implementation progressively intensifies, the enterprises experience an increasing impact from CBAM. The incentives associated with maintaining traditional production and benefiting from free-riding gradually become inadequate in comparison to the substantial carbon taxes. Consequently, steel enterprises universally opt for low-carbon upgrades. With the escalating prioritization of low-carbon strategies by enterprises and the refinement of CBAM regulations, the government gradually disengages from proactive management, diminishes its intervention in the market, and fosters an environment conducive to independent development by enterprises, thus converging towards a passive management strategy.
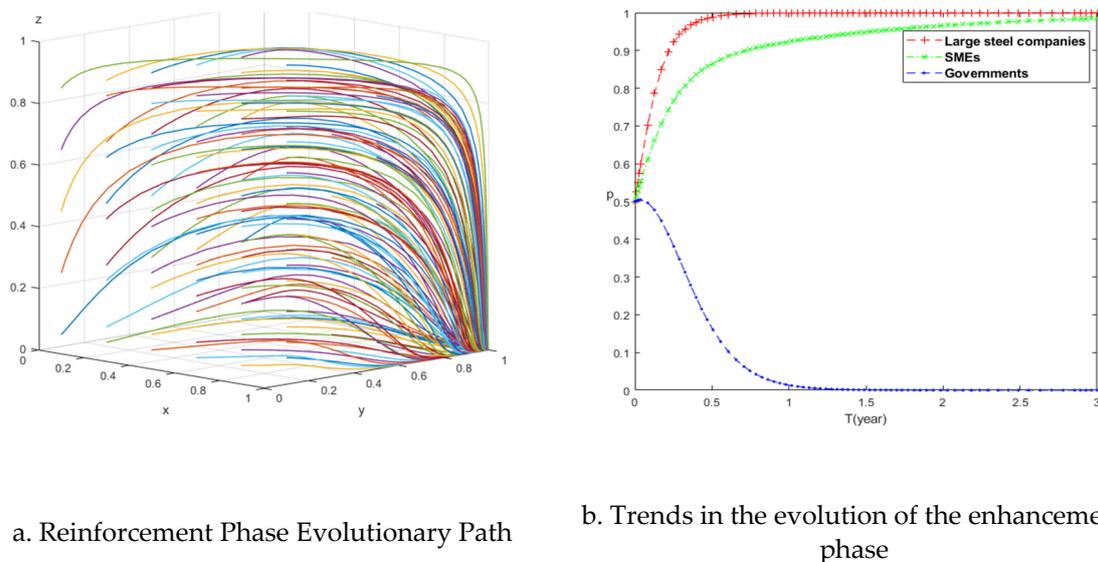
a. Reinforcement Phase Evolutionary Path

b. Trends in the evolution of the enhancement phase

Figure 6. Enhanced Stage Evolutionary Process.

5.3. Sensitivity analysis of key variables to tripartite evolutionary systems

This section evaluates the impact of key parameters on the evolutionary outcomes and trajectories of the tripartite game after the formal implementation of CBAM. This provides theoretical support and policy recommendations for future strategic choices by businesses and governments. Using the parameters from the CBAM implementation stage as a foundation, the initial intentions of x, y, and z are set to 0.2 to ensure uniform control.

(1) Impact of Changes in Free-Riding Effect

Maintaining the baseline parameters unchanged, the free-riding benefits (O) were set to 2, 2.35, 5, and 6. From Figure 8, it can be observed that O primarily influences the strategy choices of small and medium-sized enterprises (SMEs). When O exceeds 5, SMEs tend to choose strategy 0, meaning they maintain traditional production. The increase in O has limited effects on large steel enterprises and the government, only influencing the time required for evolution to reach a stable state, with the ultimate evolutionary outcome still tending towards 1. Additionally, as the free-riding benefits decrease, the system evolves more rapidly towards the ideal state (1,1,1), as shown in Figure 11. The above results indicate that free-rider benefits are a crucial factor hindering the low-carbon upgrade of steel enterprises. Only by reducing the free-rider benefits among enterprises can the three parties evolve towards the ideal state of (1,1,1).
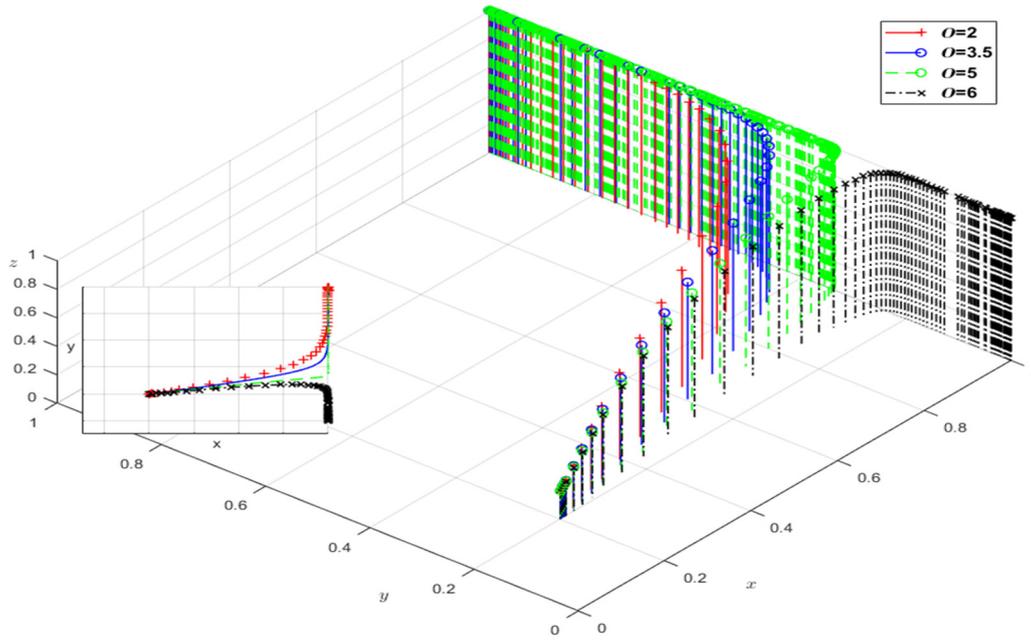
Figure 7. Simulation of System Evolution Trajectories under Different O.

a. Evolutionary Outcomes of Different O on x

b. Evolutionary Outcomes of Different O on y

c. Evolutionary Outcomes of Different O on z

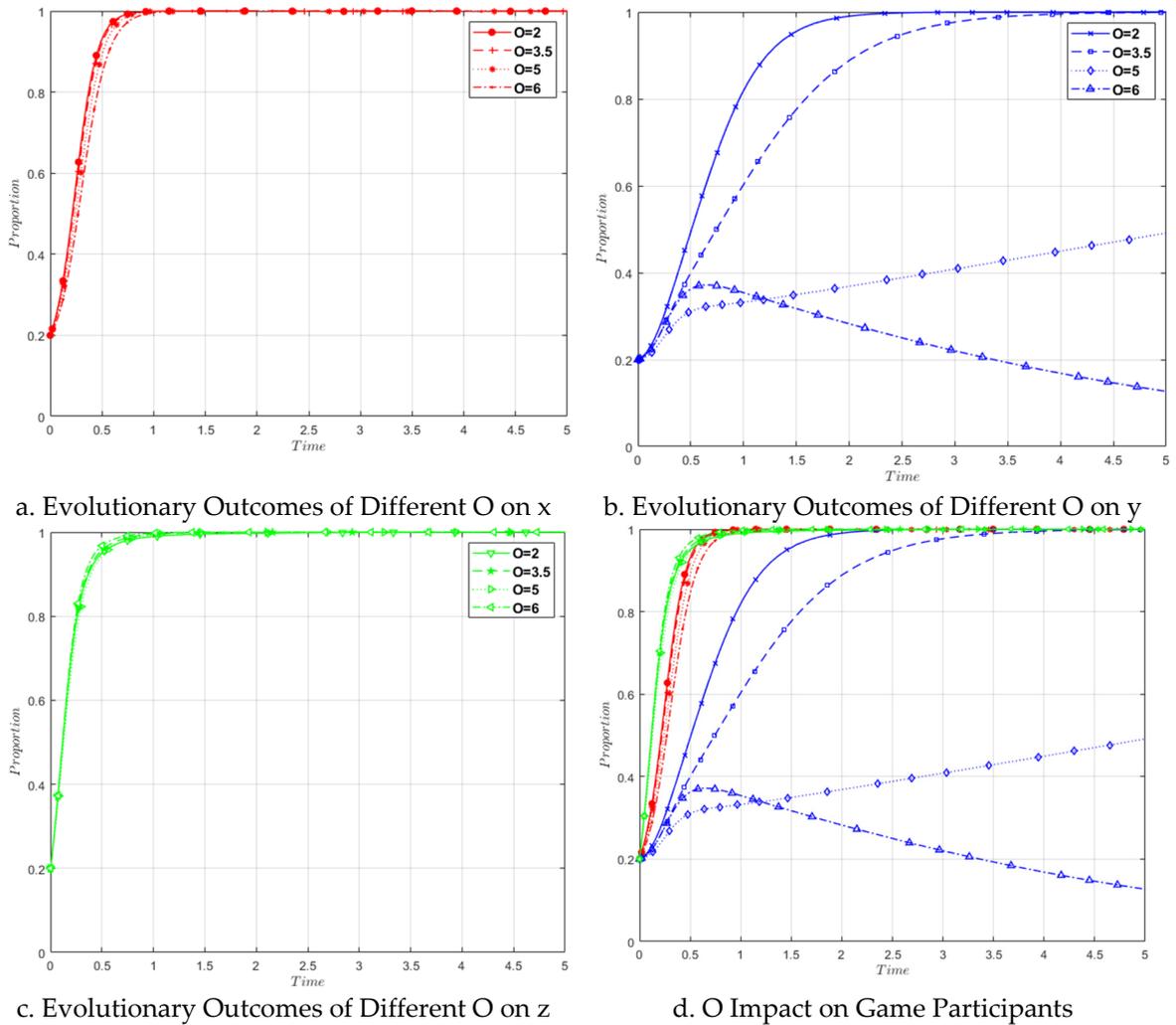d. O Impact on Game Participants

Figure 8. illustrates the evolution of the behaviors of the three parties under different levels of free riding benefits.

(2) Impact of changes in export volumes

When the export volumes are set to 0.3, 1, 1.7, and 3, numerical simulations of the trilateral game model were conducted, and the evolutionary trajectory is shown in Figure 9. As the export volume decreases from 3 to 0.3, the evolutionary outcome for large enterprises remains oriented towards 1, but the stability time of evolution increases. Small and medium-sized enterprises evolve towards 0 when the export volume is low. This indicates that the export volume determines the magnitude of CBAM costs, with smaller export volumes resulting in relatively less impact on enterprises. As the export volume increases, the attention and response of enterprises to CBAM need to correspondingly increase. The government's evolutionary rate is inversely proportional to the increase in export volume. This implies that as the export volume increases, the government, in order to regulate the market and ensure the competitiveness of Chinese steel products in international trade, needs to mitigate the impact of CBAM through fiscal subsidies and tax refunds. This, to some extent, increases the government's fiscal expenditure, resulting in a certain economic burden and reducing the government's proactive response to CBAM.
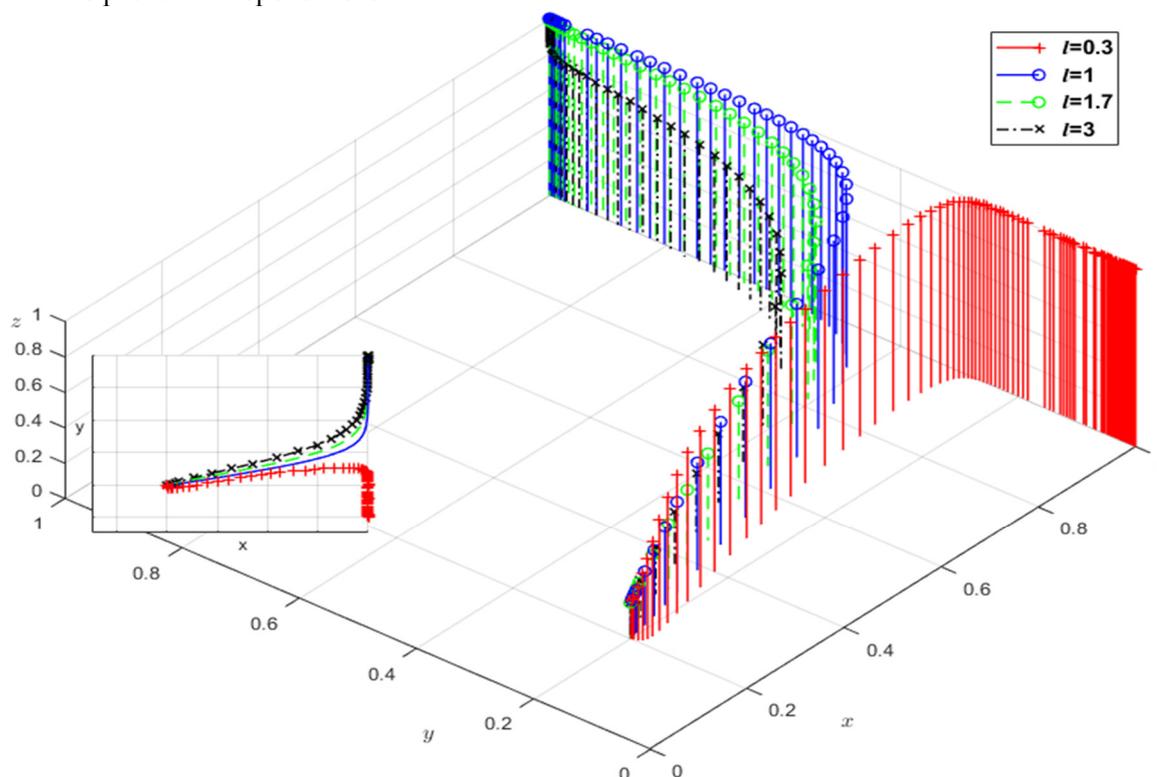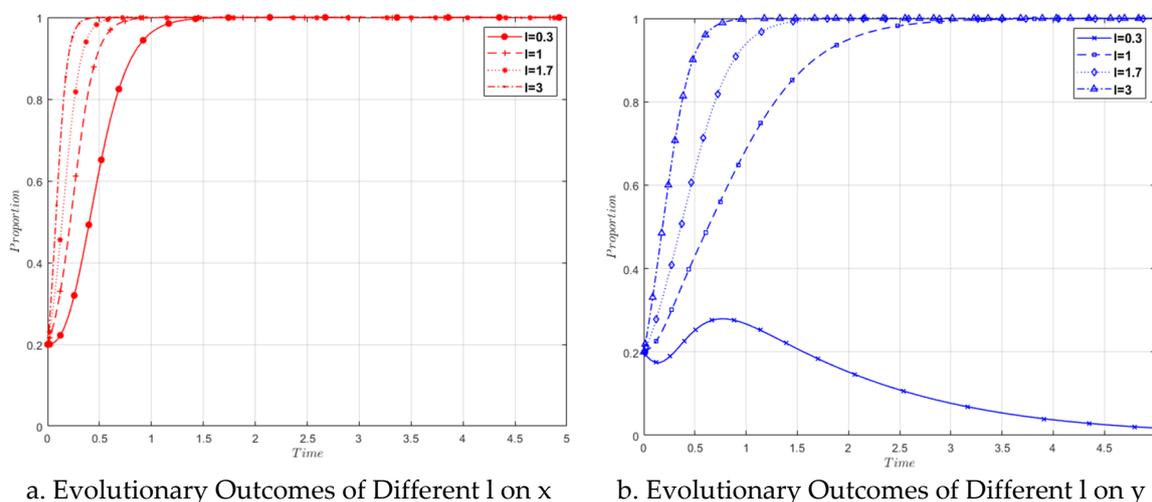

Figure 9. Simulation trajectories of the system under different l.

a. Evolutionary Outcomes of Different l on x
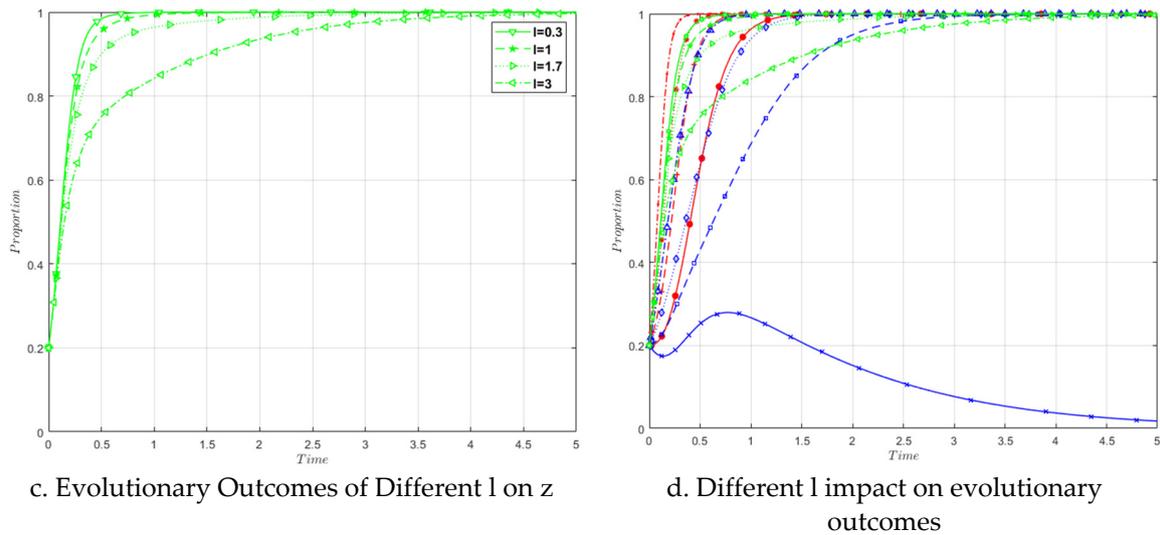
b. Evolutionary Outcomes of Different l on y

c. Evolutionary Outcomes of Different l on z

d. Different l impact on evolutionary outcomes

Figure 10. The Evolution of Tripartite Behavior under Different Export Volumes.

(3) The Impact of Changes in the Chinese Carbon Market Prices

To explore whether changes in the carbon market prices in China can mitigate the impact of CBAM, the Chinese carbon price (CP) was set at 0.083, 0.3, 0.6, and 0.8. As shown in Figure 12, when CP increases to 0.6 and 0.8, y tends to be 0, but the impact on x and z is limited, only changing the evolution rate. During the CBAM implementation phase, with the increase in the Chinese carbon market price, small and medium-sized enterprises are more willing to maintain their existing production mode, and the evolution rates of large steel enterprises and the government are also reduced. The above results indicate that enhancing the Chinese carbon market is an effective means to alleviate the impact of CBAM implementation. This research outcome aligns with the findings of Qi et al. [10].
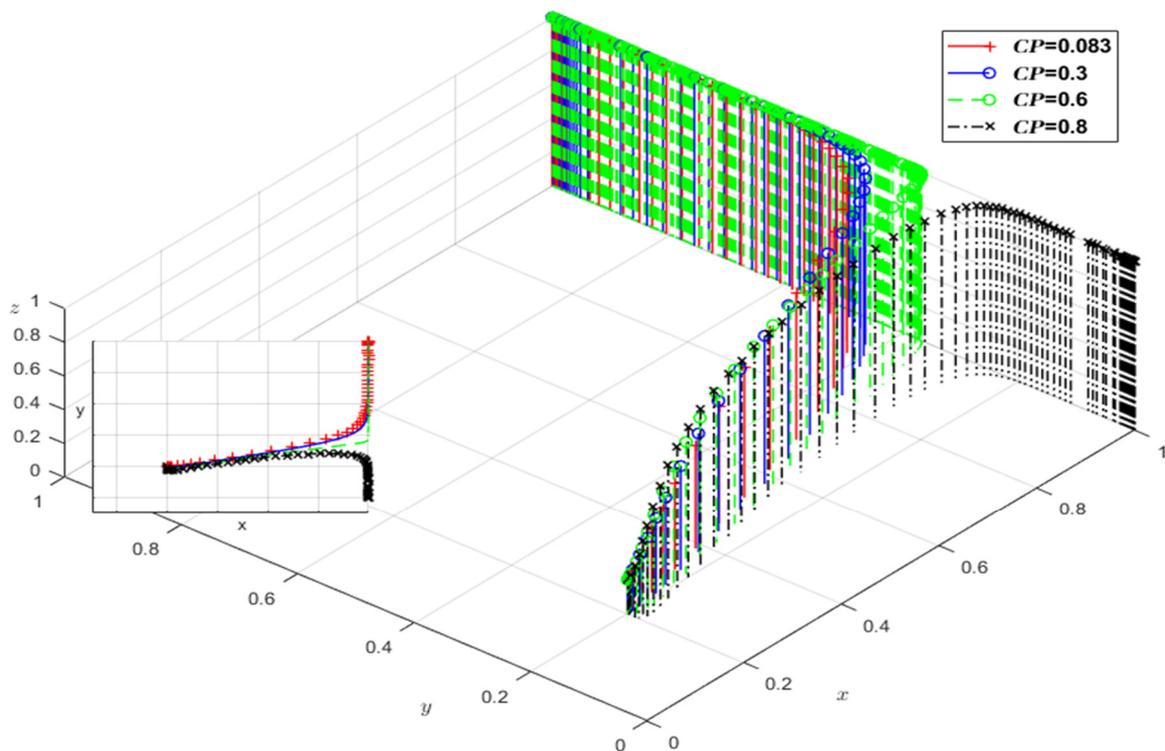

Figure 11. Simulation of System Evolution Trajectories under Different CP.

a. Impact of CP on x evolution

a. Impact of CP on y evolution

a. Impact of CP on z evolution

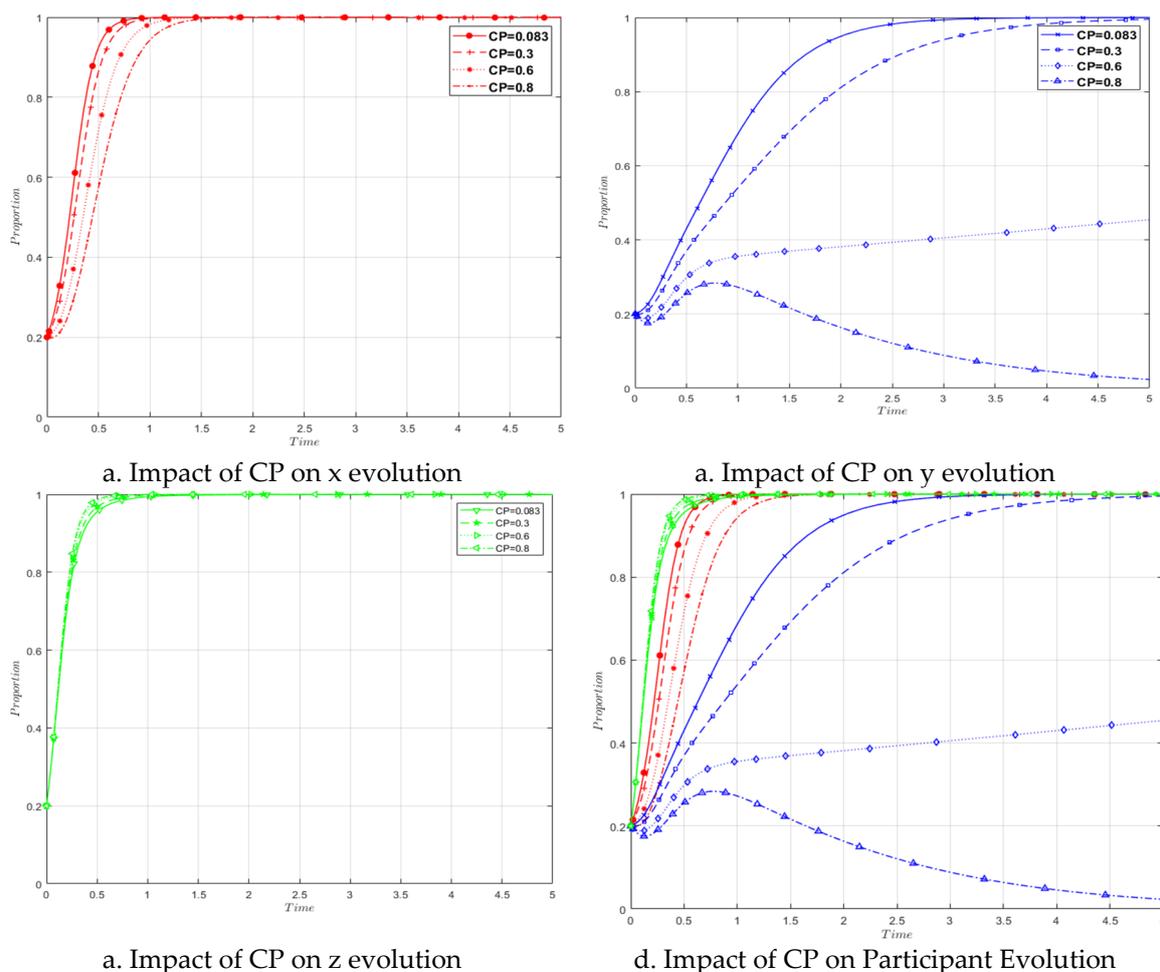d. Impact of CP on Participant Evolution

Figure 12. Evolution of Trilateral Behavior under Different Carbon Prices in China.

(4) The Impact of Changes in the European Union's Free Carbon Allowances

The evolution of different stages of free carbon emission quotas proposed by CBAM was simulated by setting the free quota parameter b to 1, 0.69, 0.35, and 0, corresponding to the window phase, transition phase, implementation phase, and strengthening phase of CBAM, respectively. The evolution trajectories and behaviors of the tripartite system under different free quota levels are shown in Figures 13 and 14. From the figures, it can be observed that the variation in free quotas does not have a decisive impact on the stakeholders within the model. In scenarios with high free quotas, the rates at which x, y, and z evolve to the stable strategy point 1 are slower, requiring a longer time compared to the 0-free carbon quota stage. When b=1, the government's decision evolution does not reach 1, indicating that in the high free quota stage, the government, while more inclined to choose an active response strategy, cannot ignore the possibility of choosing a passive management strategy.
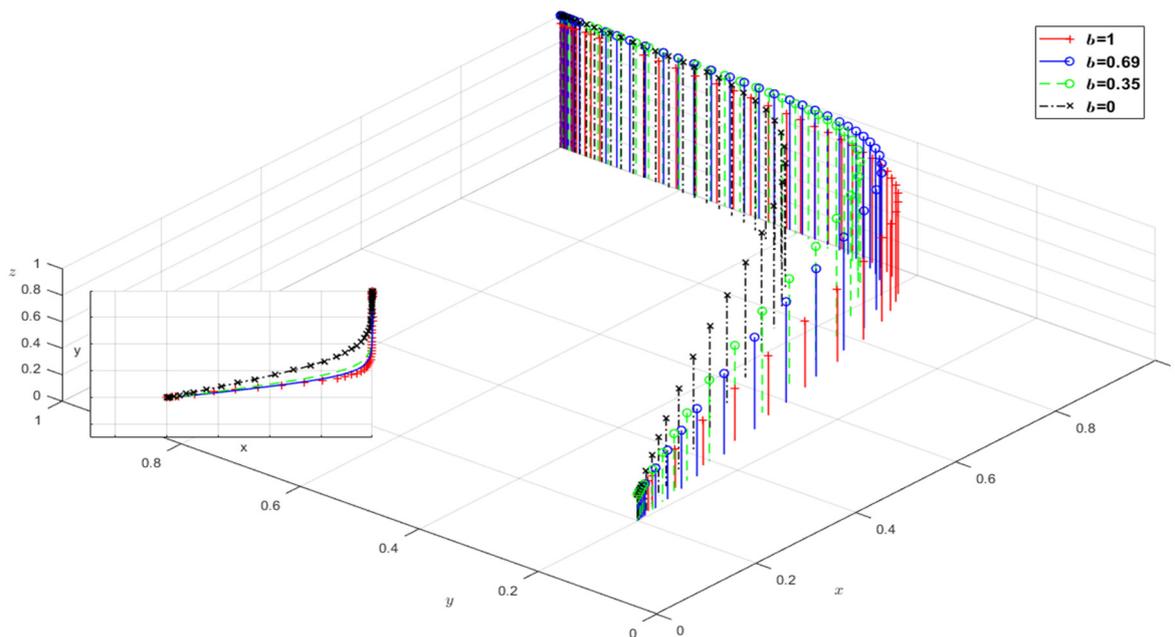
Figure 13. Simulation Trajectories of the System under Different b.

a. Different b Effects on the Evolution of x

b. Different b Effects on the Evolution of y

c Different b Effects on the Evolution of z

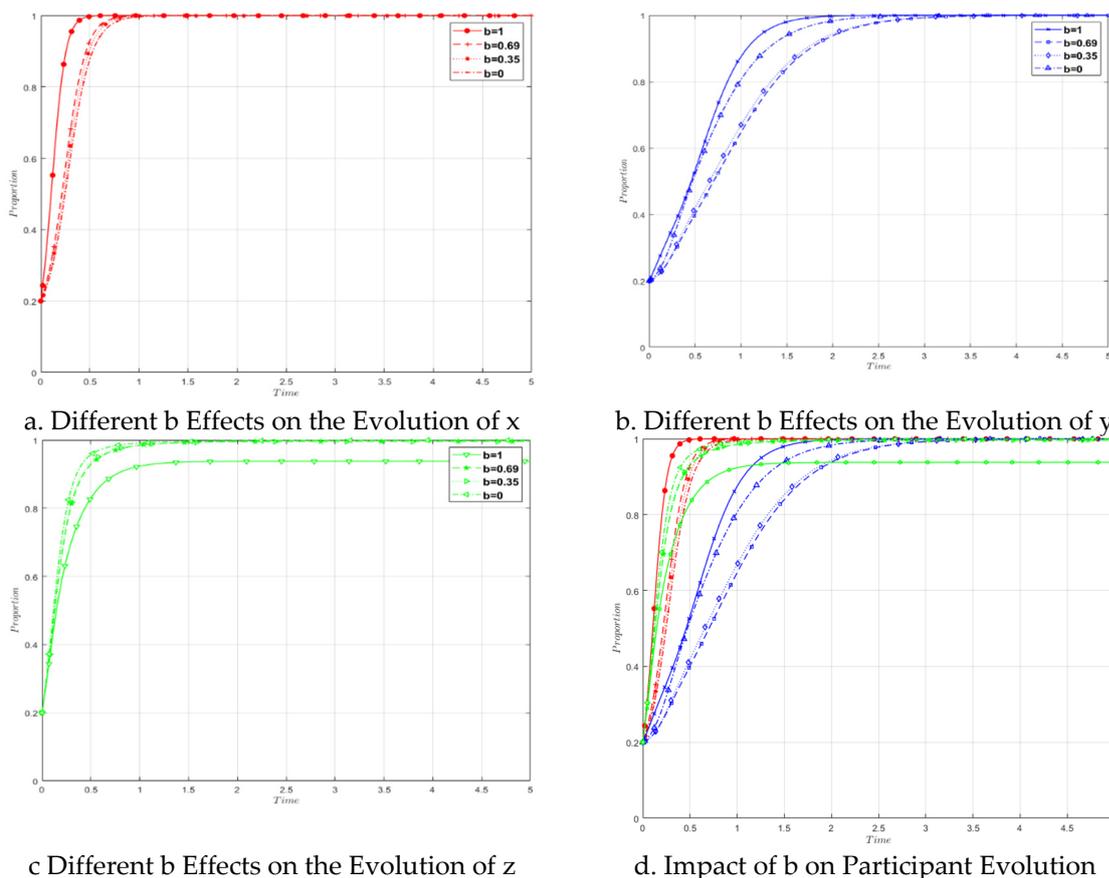d. Impact of b on Participant Evolution

Figure 14. Evolution of Trilateral Behavior Under Different EU Free Carbon Allowance Scenarios.

(4) The Impact of Dynamic Subsidy Intensity Changes by the Government

The analysis of dynamic subsidies and penalties for enterprises is similar, and this section will focus on dynamic subsidies. Based on the assumptions mentioned earlier, the government's subsidy intensity to iron and steel enterprises for low-carbon initiatives will vary based on the proportion of low-carbon enterprises. When the proportion of low-carbon enterprises is low, the government will expand the subsidy intensity to encourage iron and steel enterprises to undergo low-carbon upgrades.

Setting the low-carbon proportion and subsidy amount to 0.3 and 8, 0.4 and 6, 0.5 and 4, 0.6 and 2, the corresponding evolutionary trajectories and results are shown in Figures 15 and 16. According to the evolution results, when the proportion (e) is 0.3 and 0.4, the evolution trajectory shows fluctuating development, and there is no stable evolution point. This indicates that the government, constrained by excessive fiscal expenditures, will continuously adjust its management decisions. The evolution curve of small and medium-sized enterprises follows the trend of government decisions, indicating that small and medium-sized enterprises will adjust their production strategies in response to changes in government decisions, making it difficult to reach a stable evolution point. As the proportion increases, the government subsidy amount decreases to a level within acceptable expenditure limits. The model reaches a stable evolution point (1,1,1). Simulation results show that, for the government, excessively high fiscal subsidies impose a significant burden on itself during policy implementation, leading to fluctuations in the strategies of small and medium-sized enterprises following changes in government attitudes. Moderate levels of fiscal subsidies help guide enterprises toward low-carbon upgrades, but excessively low low-carbon subsidies will prolong the time required to evolve to a stable state.
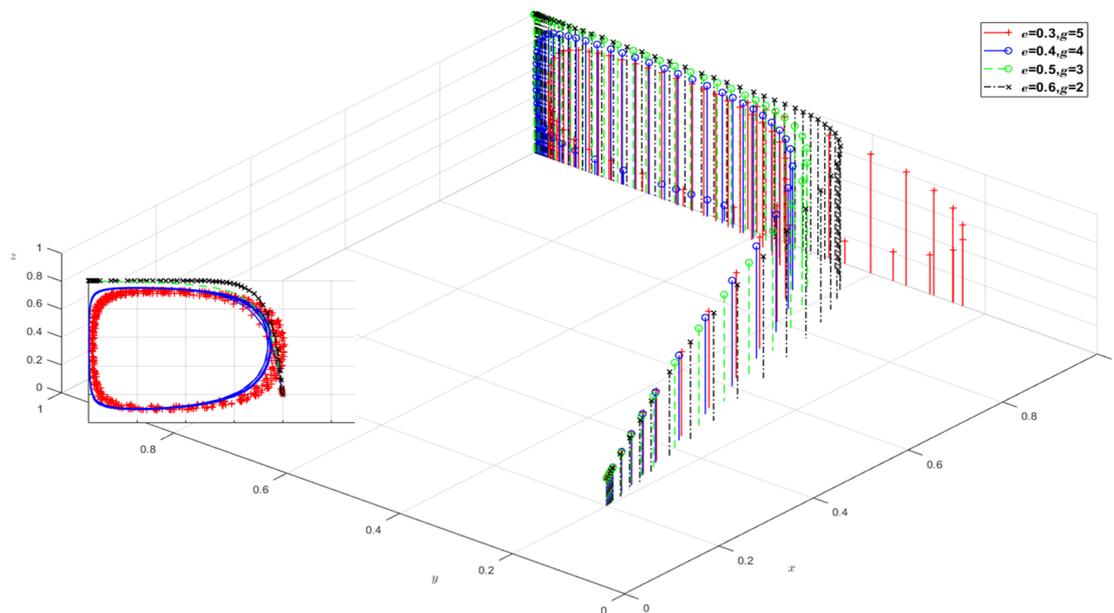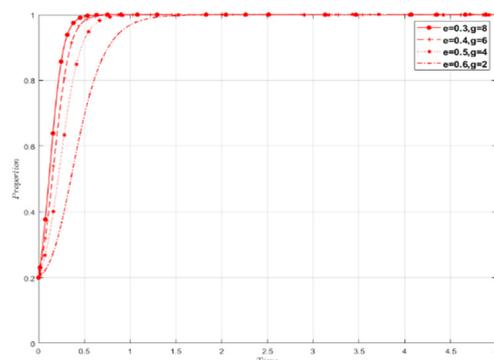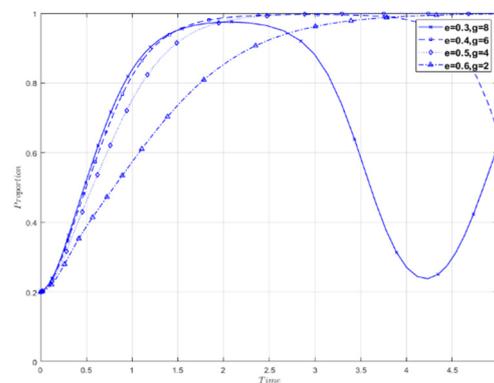

Figure 15. Simulation of System Evolution Trajectories under Dynamic Subsidies.

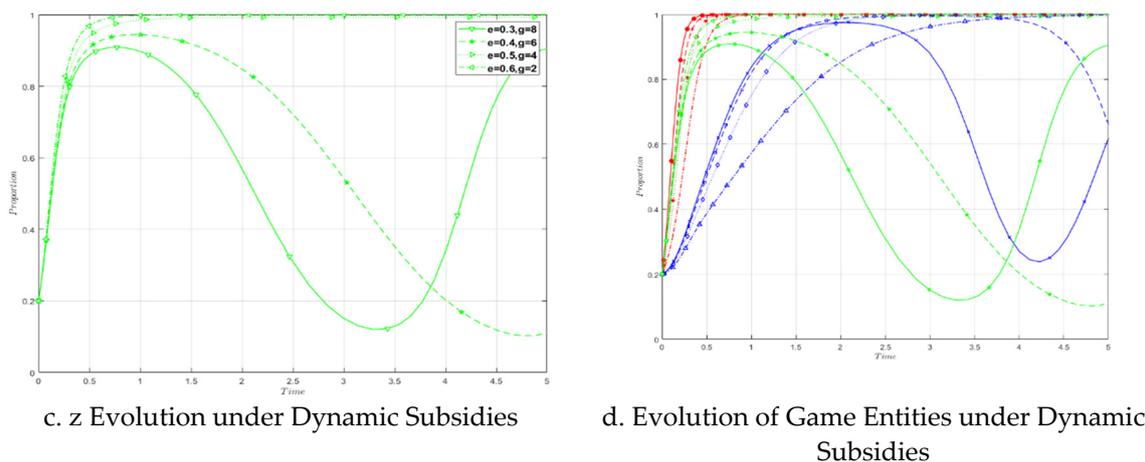a. x Evolution under Dynamic Subsidies

b. y Evolution under Dynamic Subsidies

c. z Evolution under Dynamic Subsidies   d. Evolution of Game Entities under Dynamic Subsidies

Figure 16. Evolution of the Behavior of the Three Parties under Dynamic Subsidies.

6. Conclusions and policy recommendations

Since October 1, 2023, the CBAM (Carbon Border Adjustment Mechanism) Act has entered a transitional phase, and the impact on China's steel trade has been increasing with the improvement and implementation of regulations. This study focuses on different types of steel enterprises and the strategies adopted by the Chinese government. Utilizing evolutionary game theory, the research investigates the game relationships and decision-making choices among stakeholders during different stages of CBAM implementation. It explores the strategic interactions and dynamic evolution pathways between the government and enterprises, analyzing the influence of key parameters on the strategies of all parties during the formal implementation stage of CBAM. The research yields the following conclusions:

(1) Large-scale steel enterprises exhibit greater sensitivity to CBAM, leading them to prioritize low-carbon upgrade strategies. The government's attitude towards CBAM management will shift gradually from passive to proactive as CBAM is implemented, and with the improvement of regulations and changes in corporate behavior, it will ultimately return to a passive state. Small and medium-sized enterprises are less affected by CBAM, and the probability of choosing low-carbon upgrade strategies depends on proactive government management.

(2) Free-rider benefits are a major hindrance to enterprises' low-carbon upgrades, with substantial free-rider benefits significantly suppressing the enthusiasm of small and medium-sized enterprises for low-carbon upgrades.

(3) The export volume of steel products plays a decisive role in enterprises' decisions to choose low-carbon upgrades. With an increase in export volume, steel enterprises of different scales evolve towards the decision of "implementing low-carbon upgrades" in a shorter time and at a faster rate. Government constraints, such as limitations on fiscal expenditures like tax refunds, will slow down the speed of evolution towards a stable state.

(4) With the implementation of CBAM, the reduction of free carbon quotas in the EU will not have a decisive impact on the decisions of the three parties involved but will only affect the rate at which the entities evolve towards stable points.

(5) The improvement of the Chinese carbon market serves as an effective means to address CBAM. When the gap between domestic carbon prices in China and EU carbon prices narrows, it will alter the evolutionary trend of enterprises, shifting from upgrades to maintaining their existing structures. This highlights that a robust carbon pricing mechanism can effectively alleviate the trade impact brought about by CBAM.

(6) Government dynamic subsidies and penalties for enterprises should be within an optimal range to generate the most effective incentives and punitive effects with minimal fiscal expenditure. Excessive penalties or subsidies are not conducive to enterprises choosing low-carbon production models and can increase the financial burden on companies. Small and medium-sized steel enterprises exhibit greater sensitivity to government policies, leading to evolutionary changes in response to fluctuations in government strategies.

Promoting the low-carbon transformation of Chinese steel enterprises and reducing the carbon emission intensity per ton of steel products form the foundation for addressing the implementation of CBAM. In order to facilitate the industrial upgrading of steel enterprises, mitigate the impact of CBAM on Chinese steel enterprises, and safeguard the competitiveness of Chinese steel products in the international market, this study proposes the following policy recommendations:

(1) To prevent free-rider phenomena and expedite the low-carbon upgrading transformation of steel enterprises, the government should formulate effective environmental policies and regulations. Establishing a low-carbon standard system, increasing the free-riding costs for small and medium-sized enterprises as well as large enterprises, and minimizing the benefits derived by enterprises from free-riding behaviors are essential measures. This approach aims to reduce free-rider occurrences, thereby promoting the low-carbon upgrading of enterprises.

(2) Enhance the mechanism of the Chinese carbon trading market and reduce the gap between Chinese carbon prices and international carbon prices. Establish a robust carbon pricing mechanism and progressively facilitate the entry of the steel industry into the Chinese carbon market. This will alleviate the carbon tax pressure resulting from the implementation of CBAM, ensuring the high competitiveness of steel products in the international market.

(3) The government should implement appropriate penalties and fiscal support to facilitate the evolution of enterprises towards the "implementing low-carbon upgrades" strategy. When providing subsidies and penalties, a graded approach based on different enterprise scales should be adopted to determine the penalty and low-carbon subsidy amounts. This approach prevents individual enterprises from exploiting low-carbon subsidies, while also avoiding additional fiscal pressure on the government due to excessive financial expenditures. Through judicious penalties and incentives, the entire steel industry can be encouraged to undergo low-carbon upgrades, harnessing the regulatory guidance role of the government.

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