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Climate policy synergy: a tripartite evolutionary game analysis of ESG compliance and tax incentives on corporate carbon governance

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The effective combination of reasonable tax incentives and environmental, social, and governance (ESG) legal compliance management can significantly promote corporate carbon emission reduction and realize the goal of sustainable development. This thesis explores the impact of tax incentives on corporate carbon emission reduction in the context of ESG compliance management. By constructing a tripartite evolutionary game model and conducting simulation analysis, the results of the study show that through integrating ISO 37301 compliance frameworks and OECD carbon pricing benchmarks, a tax incentive gradient coupled with ESG digital compliance tools (e.g., blockchain) can accelerate strategic convergence among stakeholders. Strategic synergies among stakeholders are achieved by appropriately adjusting the income distribution coefficients and cost-sharing coefficients to optimize the allocation of resources and environmental benefits. In addition, the modeling is based on the key assumptions that each participant has limited rationality, and the constraints, such as regulatory restrictions and economic trade-offs in reality, have been considered in the model.

KEYWORDS
corporate carbon governance, corporate responsibility, environmental, social, and governance, ESG legal compliance, resource optimization

1 Introduction

The escalating severity of global climate change has intensified multifaceted pressures on corporate carbon emissions—a major source of greenhouse gases—from governments, investors, and the public. In response, countries worldwide have introduced low-carbon development policies, leveraging economic instruments such as tax incentives to spur corporate transformation and sustainable upgrading (Castellano et al., 2024). The trajectory of global corporate carbon emissions has been shaped by a complex interplay of economic development, shifts in energy structure, and policy interventions. The period from 2000 to 2010 was characterized by relatively high growth, largely driven by rapid industrialization in developing countries (Ren and Lin, 2024). Subsequently, a noticeable decline ensued from 2010 to 2020, attributable to the widespread implementation of low-carbon policies, technological advancements, and the expansion of renewable energy. Since 2020, growth rates have fluctuated under the compounded impacts of the COVID-19 pandemic, global energy crises, and ongoing policy adjustments (Zhu et al., 2020). This evolving context underscores the persistent urgency of mitigating climate change. Consequently, tax policy has emerged as a critical economic tool for guiding corporate behavior and incentivizing green investment, playing a pivotal role in national strategies to promote sustainable development and reduce corporate carbon emissions (Ao et al., 2023).

The purpose of this article is to explore the legal impact of tax policies on corporate carbon emission reduction under the framework of environmental, social, and governance (ESG) objectives and to propose corresponding optimization suggestions (Karwowski and Raulinajtys-Grzybek, 2021). This article explores how tax incentive measures influence decisions to reduce corporate carbon emissions within the framework of ESG legal compliance, with a particular focus on the iron and steel industry. Specifically, the study raises the following research questions: What tax loopholes and enforcement issues exist in the management of tax incentive policies under ESG legal compliance? How do these issues affect corporate carbon reduction decisions, especially in the context of the iron and steel industry? How can corporate low-carbon transformation be further promoted by optimizing tax incentive measures and improving legal supervision? To address the above questions, this article constructs a theoretical framework based on a tripartite evolutionary game model and systematically explores the effects of tax incentives, legislative gaps, and enforcement shortcomings on ESG compliance management through a numerical simulation analysis. This study is expected to provide clearer improvement suggestions for policymakers and enterprises, thereby promoting the effective control of corporate carbon emissions.

For the issue of tax incentives on carbon governance of iron and steel enterprises under ESG objectives, an evolutionary game relationship exists between the government, iron and steel enterprises, and financial institutions. Therefore, we apply the three-party evolutionary game method (Shakil, 2021). First, we will analyze how the current tax policy affects enterprise carbon emission reduction decisions, especially how they adjust their operation mode to meet the requirements of sustainable development under the role of tax incentives and penalty mechanisms (Bruna et al., 2022). Second, this article will analyze legislative gaps and enforcement problems in the existing ESG legal compliance system. Specifically, this study focuses on loopholes in tax policies related to ESG compliance, the insufficient oversight of relevant laws and regulations during implementation, and the resulting legislative lag. These issues are particularly prominent in the current corporate carbon governance process, directly affecting the interface and implementation between tax incentives and the actual emission reduction effect of enterprises (Chen et al., 2023). Finally, drawing on successful cases at home and abroad, we will propose practical optimization suggestions to enhance the effectiveness of tax policies in promoting corporate carbon emission reductions (Alkaraan et al., 2022). Through in-depth research on this topic, this article aims to provide a reference for policymakers and enterprises, so as to better achieve carbon neutrality and promote sustainable economic development (Li and Zhu, 2024).

2 Related work

2.1 Background to ESG legal compliance management

With the increasingly serious problem of global climate change, enterprise carbon emission reduction has become an important area of research (Wang and Sarkis, 2017). In recent years, the gradual advancement of ESG legal compliance management has made the responsibility of enterprises in environmental protection increasingly prominent (Nirino et al., 2021). Relevant literature has extensively explored how companies can achieve carbon emission reduction while complying with ESG standards (Rao et al., 2023). In the global challenge of addressing climate change, carbon emission reduction by enterprises has become an important issue (Elmghaamez et al., 2024). Particularly in recent years, with the promotion of ESG legal compliance management, the role of corporations in environmental responsibility has become increasingly important (Chen and Xie, 2022). ESG investment has gradually become an important trend in the global financial market (Gangi et al., 2024). There is a positive correlation between corporate performance in environmental and social responsibility and financial performance (Naeem et al., 2022). This finding has prompted more investors to incorporate ESG factors into their decision-making process, thus driving companies to take more proactive steps in environmental protection (Liu et al., 2022). Another study points out that ESG compliance not only helps to reduce risk but also enhances the long-term value of companies (Yuan et al., 2022).

2.2 Tax incentives and corporate emission reductions

In recent years, a growing body of research has examined tax incentives and firms' carbon emission reductions (Arvidsson and Dumay, 2022). Tax incentives for highly polluting industries significantly increased the likelihood of firms adopting cleaner technologies, particularly in the iron, steel, and cement industries, in a study of the European Union's carbon trading market (Elamer and Boulhaga, 2024). Similarly, firms' carbon emission intensity per unit of output fell by 12% after taking advantage of tax breaks (Xie et al., 2019). However, some studies indicate that in the absence of effective regulation, some firms may use tax incentives for financial arbitrage rather than invest in low-carbon technologies (Zhou et al., 2022). This study further explores the impact of tax incentives on firms' emission reduction under different ESG legal compliance environments (Li et al., 2024).

2.3 Tripartite evolutionary games in carbon governance

In recent years, research on carbon governance and tripartite evolutionary games has deepened considerably. Studies show that government incentives effectively guide corporate green transformation (Yan, 2025), public supervision plays a key role in curbing corporate free-riding (Yu and Lu, 2024), and tax incentives under ESG compliance pressure not only alleviate short-term costs but also promote long-

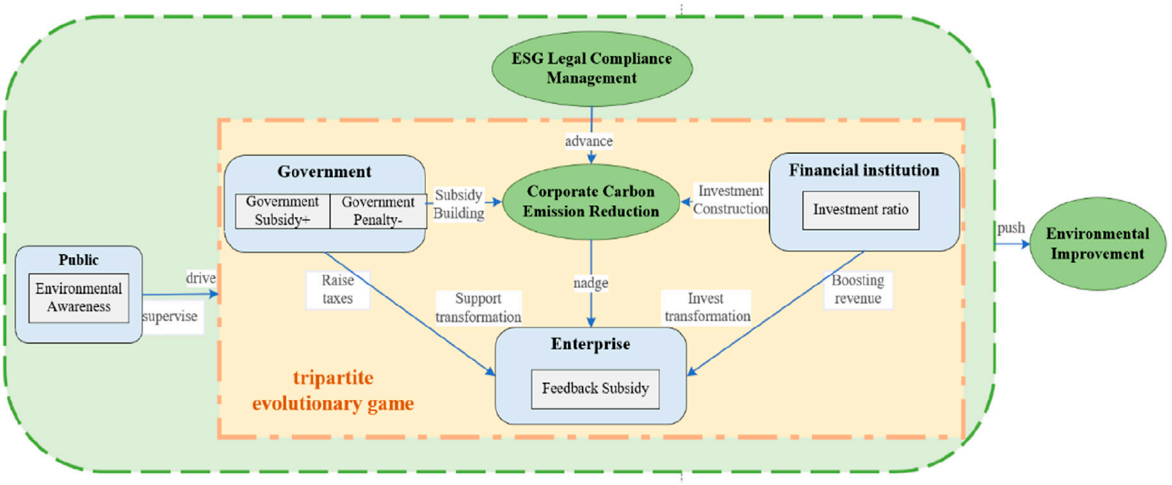


FIGURE 1
Framework of this research.

term stability in emission reduction (Jiang and Luo, 2025). Moreover, policy mixes such as carbon trading and tax subsidies can reduce carbon leakage and increase governance efficiency (Fan et al., 2024), while digital transformation strengthens information sharing and collaborative emission reduction across supply chains (Zou et al., 2024). Environmental regulation under the ESG framework also generates an innovation compensation effect (Wang, 2025). In addition, regional heterogeneity significantly influences policy outcomes (Zhang et al., 2024). Collectively, these findings highlight the complex interplay among tax incentives, ESG compliance, and corporate emission reduction, providing a solid foundation for the tripartite game model developed in this study.

In summary, based on the existing literature, this study combines ESG legal compliance management and tax incentive mechanisms (Galbreath, 2013; Ramírez-Orellana et al., 2023) and adopts a three-party evolutionary game model to provide new perspectives and methods for exploring corporate carbon emission reduction (Liang et al., 2022). Analysis indicates that the impact of the carbon tax policy on firms' decision to reduce emissions is particularly significant in high-energy-consumption industries, with the iron and steel industry reducing carbon emissions by as much as 18% (Wang et al., 2024). In contrast, enterprises in low-carbon industries responded more slowly, indicating that the effects of tax incentives are industry-specific (Li et al., 2024). In addition, different types of tax incentives, including direct carbon tax reductions, can quickly reduce carbon emissions in the short term (Rahman et al., 2023), while R&D subsidies are more effective in promoting long-term technological innovation (Cheng et al., 2024).

3 A game-theoretical model

3.1 Problem description

This study employs an evolutionary game model to analyze the interactions between government, steel firms, and regulatory agencies under tax incentives and ESG compliance frameworks. The rationale for selecting this modeling approach over alternative methodologies, such as classical Nash equilibrium-based static models or agent-based simulations, is as follows:

Dynamic adaptation: Unlike traditional game theory models that assume players make rational decisions instantaneously, the evolutionary game model captures the dynamic adaptation of strategies over time, which better reflects real-world decision-making processes in policy and corporate compliance. Learning and imitation mechanisms: The evolutionary framework enables strategy evolution through learning and imitation, making it well-suited for analyzing the gradual adoption of carbon reduction practices in response to tax incentives and regulatory pressures. Policy impact simulation: This model enables the examination of policy adjustments and their long-term impact on enterprise behavior, providing insights into the effectiveness of different tax structures in promoting ESG compliance. Given these advantages, the evolutionary game model provides a more comprehensive and realistic representation of corporate decision-making processes in the context of ESG policies.

This article's remaining sections are organized as follows (Figure 1): Section 2 reviews existing research in this area; Section 3 constructs a tripartite evolutionary game model; Section 4 presents evolutionary stabilization strategies; Section 5 analyzes impact elements through simulations; Section 6 provides discussion; and Section 7 provides conclusions with recommendation for practical strategies based on simulation results.

For the carbon governance of steel enterprises under ESG objectives, there exists an evolutionary game relationship between the government, steel enterprises, and financial institutions, in which the three parties consider their own interests and constantly imitate and

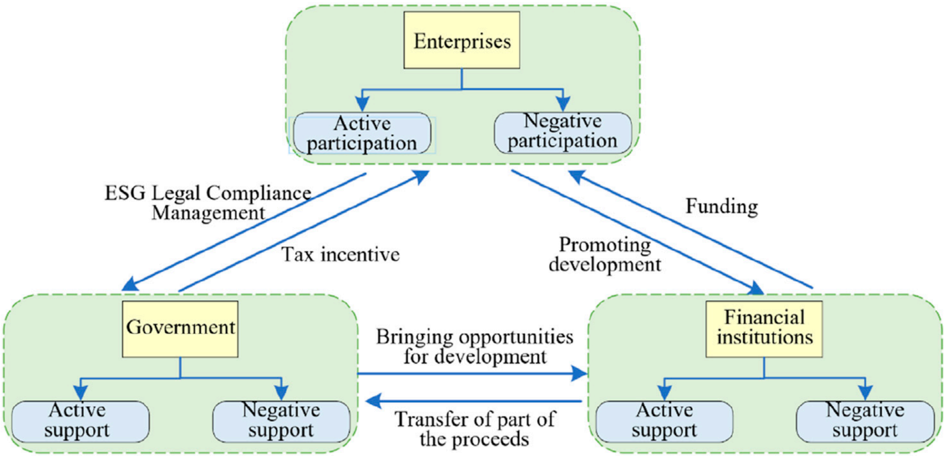


FIGURE 2
Interactive relationships among three stakeholders.

TABLE 1 **Variable definition.**

Variable	Definition
G	Funds disbursed to steel companies and governments when actively supported by financial institutions
C_0	Costs incurred when financial institutions actively support the enterprise's low-carbon transition
C_1	Costs of steel companies' negative engagement in carbon governance
C_2	Costs of negative government involvement in carbon governance
C	Total cost of active participation in carbon management by both steel companies and governments
E	Reduced cost inputs to steel companies and governments from the efforts of financial institutions when all three adopt proactive strategies
K_1	Reduction in steel company costs from proactive strategies by financial institutions when steel companies are negatively engaged in carbon governance
K_2	Reduced cost inputs to the government from proactive strategies by financial institutions when the government is negatively engaged in carbon governance
R_0	Total benefits when actively supported by financial institutions
R_1	Social benefits of carbon management activities in steel companies
R_2	Basic benefits received when the government grants a high level of incentives
R	The additional benefits, also known as synergies, that accrue when both steel companies and governments are actively involved in carbon management
L_1	Additional benefits to steel companies when governments are actively involved, and steel companies are passively involved in carbon governance
L_2	Additional social benefits to the government when the steel business is actively involved, and the government is passively involved in carbon governance
q	The coefficient of allocation of the policy subsidy between the steel firm and the government, with the allocation coefficient of the steel firm being q
d_1	Government regulatory cost coefficient
d_2	Enterprise technological transformation cost coefficient
α	For the distribution coefficients of the benefits of digital synergies in the production chain, the benefit distribution coefficients for steel companies are α

modify their strategic choices under the effect of changes in the external environment and the learning mechanism, forming an evolutionary game system (Rahman et al., 2023). In this system, steel enterprises and financial institutions can influence each other's strategic choices through the ratio of revenue sharing, while whether the government adopts positive incentive strategies will affect the strength of corporate

TABLE 2 **Payoff matrix of tripartite evolutionary game.**

Masterplan	Active support from financial institutions		Negative support from financial institutions	
	Active participation of enterprises	Negative business involvement	Active participation of enterprises	Negative business involvement
Active government participation	$R_0 - C_0 - G$ $R_1 + aR + qG - (d_1 + d_2)\ (C - E)$ $R_2 + (1 - a)R + (1 - q)G - (1 - d_1 - d_2)\ (C - E)$	$R_0 - C_0 - (1 - q)G$ $R_1 + L_1 - (C_1 - K_1)$ $R_2 + (1 - q)\ G - (1 - d_1 - d_2)\ (C - E)$	bR_0 $R_1 + aR - (d_1 + d_2)C$ $R_2 + (1 - a)R - (1 - d_1 - d_2)C$	bR_0 $R_1 + L_1 - C_1$ $R_2 - (1 - d_1 - d_2)\ C$
Negative government involvement	$R_0 - C_0 - qG$ $R_1 + qG - (d_1 + d_2)\ (C - E)$ $R_2 + L_2 - (C_2 - K_2)$	$R_0 - C_0$ $R_1 - (C_1 - K_1)$ $R_2 - (C_2 - K_2)$	bR_0 $R_1 - (d_1 + d_2)\ C$ $R_2 + L_2 - C_2$	bR_0 $R_1 - C_1$ $R_2 - C_2$

carbon governance and its social responsibility. The three influence each other and are inseparable (Cheng et al., 2024). Thus, the behavioral strategy evolution relationship among the three is formed as shown in Figure 2.

3.2 Model assumptions

First, about the main body of the game. The game subjects are government, steel enterprises, and financial institutions. Second, about the behavioral strategies among the three parties. The game subjects all adopt two behavioral strategies, the financial institution (S) adopts two strategies of active support (AS) and negative support (NS), the set of strategies is {positive support AS, negative support NS}, and sets the probability that the financial institution adopts the strategy AS, and the strategy of adopting NS as 1−x; the steel enterprise (P) and the government (R) both adopt active cooperation (AI) and negative input (NI) strategies, the set of strategies is {positive input AI, negative input NI}, and set the probability of adopting strategy AI for steel enterprises (P) and the government (R) as, and the probability of adopting strategy NI as 1-year and 1−z. Third, about the variable setting. For the problem of tax incentives for carbon governance in steel enterprises under ESG objectives, when state policy subsidies are considered, the variable settings of the game financial institutions (S), steel enterprises (P), and the government (R) are shown in Table 1.

To better reflect real-world conditions, the cost-sharing coefficients are distinguished as follows: d1 denotes the regulatory cost borne by the government, while d2 represents the technological transformation cost undertaken by enterprises. This distinction allows the model to more accurately capture the heterogeneous roles of the government and enterprises in carbon governance.

3.3 Game payoff matrix

The strategies of the government (G), steel firms (F), and regulatory agencies (R) interact dynamically in the model. The government provides tax incentives (S_g), steel firms decide on their level of emission reduction effort (S_f), and regulatory agencies engage in compliance monitoring (S_r). The expected payoffs for each player can be defined as follows:

$$\text{Government's Payoff Function: } U_G = \theta T - \lambda S_g - \gamma C,$$

where θT represents the tax revenue, λS_g represents the cost of tax incentives, and γC represents the enforcement cost.

$$\text{Steel Firms' Payoff Function: } U_F = \pi(Q) - C_r - f(S_r),$$

where $\pi(Q)$ is the profit function based on output Q, C_r is the cost of emission reduction, and f (S_r) is the penalty function imposed by regulatory agencies.

$$\text{Regulatory Agencies' Payoff Function: } U_R = \delta S_r - \omega M,$$

where δS_r represents the effectiveness of monitoring and ωM is the cost associated with regulatory enforcement.

Based on the model assumptions, the tripartite evolutionary game payoff matrix of financial institutions, steel companies, and the government as stakeholders under ESG objectives is shown in Table 2.

3.4 Replicating dynamic equations

We make the expected returns to financial institutions adopting positive and negative strategies, respectively, E_x, E_{1-x}. It is calculated that:

$$E_x = yz(R_0 - C_0 - G) + y(1-z)(R_0 - C_0 - qY) + (1-y)z(R_0 - C_0 - (1-q)G) + (1-y)(1-z)(R_0 - C_0), \tag{1}$$

$$E_{1-x} = yzbR_0 + y(1-z)bR_0 + (1-y)zbR_0 + (1-y)(1-z)bR_0. \tag{2}$$

The resulting dynamic equation for the replication of the financial institution's evolutionary game is

$$S(x) = \frac{dx}{dt} = x(1-x)\left(-yqG + (q-1)zG + R_0 - C_0 - bR_0\right). \tag{3}$$

Similarly, the expected returns from making steel firms adopt positive and negative strategies are, respectively, E_y, E_{1-y}. It is calculated that

$$E_y = xz\left(R_1 + aR + qG - d(C-E)\right) + x(1-z)\left(R_1 + qG - d(C-E)\right) + (1-x)z(R_1 + aR - dC) + (1-x)(1-z)(R_1 - dC), \tag{4}$$

$$E_{1-y} = xz\left[R_1 + L_1 - (C_1 - K_1)\right] + x(1-z)\left[R_1 - (C_1 - K_1)\right] + (1-x)z(R_1 + L_1 - C_1) + (1-x)(1-z)(R_1 - C_1). \tag{5}$$

The resulting dynamic equation for the replication of the evolutionary game for steel companies is

$$P(y) = \frac{dy}{dt} = y(1-y)\left(z(aR - L_1) + x(dE + qG - K_1) + C_1 - dC\right). \tag{6}$$

Similarly, the expected returns to making the government adopt a positive strategy and a negative strategy are E_z, E_{1-z}. It is calculated that

$$\begin{aligned} E_z = {} & xy\left(R_2 + (1-a)R + (1-q)G - (1-d)(C-E)\right) + x(1-y)\left(R_2 + (1-q)G - (1-d)(C-E)\right) + (1-x)y\left(R_2 + (1-a)R - (1-d)C\right) \\ & + (1-x)(1-y)\left(R_2 - (1-d)C\right), \end{aligned} \tag{7}$$

$$E_{1-z} = xy\left(R_2 + L_2 - (C_2 - K_2)\right) + x(1-y)\left(R_2 - (C_2 - K_2)\right) + (1-x)y(R_2 + L_2 - C_2) + (1-x)(1-y)(R_2 - C_2). \tag{8}$$

The resulting dynamic equation for the replication of the government's evolutionary game is

$$R(z) = \frac{dz}{dt} = z(1-z)\left(y\left((1-a)R - L_2\right) + x\left((1-d)E + (1-q)G - K_2\right) + C_2 - (1-d)C\right). \tag{9}$$

Finally, by integrating the replication dynamic equations of the three parties of the game (financial institutions, steel companies, and government), the replication dynamic equations of the whole dynamic system are obtained:

$$\begin{cases} S(x) = \dfrac{dx}{dt} = x(1-x)\left(-yqG - (1-q)zG + R_0 - C_0 - bR_0\right), \\ P(y) = \dfrac{dy}{dt} = y(1-y)\left(z(aR - L_1) + x(dE + qG - K_1) + C_1 - dC\right), \\ R(z) = \dfrac{dz}{dt} = z(1-z)\left(y\left((1-a)R - L_2\right) + x\left((1-d)E + (1-q)G - K_2\right) + C_2 - (1-d)C\right). \end{cases} \tag{10}$$

4 Evolutionary game analysis

In an asymmetric evolutionary game, where a sufficient condition for the evolutionary stability of an equilibrium point to hold is that the equilibrium point is a strict Nash equilibrium, and a strict Nash equilibrium is a pure-strategy equilibrium, it is only necessary to consider the stability of a pure-strategy equilibrium in an asymmetric evolutionary game by making the replicated dynamic equations $S(x) = 0$, $P(y) = 0$, $R(z) = 0$. Solving yields eight pure-strategy equilibria 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), and E_8 (1, 1, 1). In the evolution of the game with cooperative strategies among the main subjects, it is sufficient to consider the stability of eight pure-strategy equilibria. Based on this, we analyze the evolutionary stability of the strategies for each subject in the game model, starting with the analysis of the evolutionary stable strategies of financial institutions, enterprises, and government, followed by an analysis of the overall evolutionary stability of the system.

4.1 Evolutionary stability of financial institutions

Regarding the analysis of the strategies of financial institutions, we rely on the replication dynamic equation theorem, which states that when x is the evolutionary $S(x) = 0$, $S'(x) < 0$ strategy of the financial institution.

$$S(x) = \frac{dx}{dt} = x(1-x)\left(-yqG - (1-q)\,zG + R_0 - C_0 - bR_0\right), \tag{11}$$

$$S'(x) = \frac{dx}{dt} = (1-2x)\left(-yqG - (1-q)\,zG + R_0 - C_0 - bR_0\right). \tag{12}$$

When $S(x) = 0$, and $S'(x) < 0$, $x = 0$, $x = 1$, or $y^* = \frac{R_0 - C_0 - bR_0 - (1-q)zG}{qG}$, $z^* = \frac{R_0 - C_0 - bR_0 - yqG}{(1-q)G}$. We have expressed it for the sake of brevity. We will denote $\frac{R_0 - C_0 - bR_0 - (1-q)zG}{qG}$ as $\prod_a$ and denote $\frac{R_0 - C_0 - bR_0 - yqG}{(1-q)G}$ as $\prod_b$.

Proposition 1: When $y^{*}<y<1$, $x=0$ is a point of evolutionary stability. The probability of a firm actively fulfilling its carbon governance responsibilities is higher than $\prod_{a}$. The strategy for the evolutionary stability of financial institutions is negative support NS. Conversely, when $0<y<y^{*}$, $x=1$ is a point of evolutionary stability. When the probability that a firm actively fulfills its carbon governance responsibilities is less than $\prod_{b}$, the strategy for the evolutionary stability of financial institutions is active support AS.

Proposition 2: When $z^{*}<z<1$, $x=0$ is a point of evolutionary stability. When the probability of high positive government incentives is higher than $\prod_{b}$, the strategy for evolutionary stability of financial institutions is negative support NS. Conversely, when $0<z<z^{*}$, $x=1$ is a point of evolutionary stability. The probability of high positive government incentives is lower than $\prod_{b}$. The evolutionary strategy for financial institutions is active support AS.

4.2 Evolutionary stability of the firm

Regarding the analysis of the firm's evolutionary strategy, we rely on the replication dynamics equation theorem to derive that when $P(y)=0, P'(y)<0$, y is the evolutionary strategy of the firms.

$$P(y)=\frac{dy}{dt}=y(1-y)\left(z(aR-L_1)+x(dE+qG-K_1)+C_1-dC\right), \tag{13}$$

$$P'(y)=\frac{dy}{dt}=(1-2y)\left(z(aR-L_1)+x(dE+qG-K_1)+C_1-dC\right). \tag{14}$$

When $P(y)=0$ and $P'(y)<0$, $y=0$, $y=1$, or $z^{*}=\frac{dC-C_1-x(dE+qG-K_1)}{aR-L_1}$, $x^{*}=\frac{dC-C_1-z(aR-L_1)}{dE+qG-K_1}$. In our attempt to make the presentation more concise, the $\frac{dC-C_1-x(dE+qG-K_1)}{aR-L_1}$ is denoted by $\prod_{c}$, and the $\frac{dC-C_1-z(aR-L_1)}{dE+qG-K_1}$ is denoted by $\prod_{d}$.

Proposition 3: When $aR>L_1$, if $z^{*}<z<1$, we know that $y=1$ is the point of evolutionary stability. When the probability of high positive government incentives is higher than $\prod_{C}$, the evolutionary strategy of the firm is active support AI. If $0<z<z^{*}$, $y=0$ is the point of evolutionary stability. The probability of active government involvement is lower than $\prod_{c}$. The evolutionary strategy of the firm is negative support NI. On the contrary, when $aR<L_1$, if $z^{*}<z<1$, $y=0$ is the point of evolutionary stability. When the probability of active government cooperation is higher than $\prod_{c}$, the evolutionary strategy of the firm is negative support NI. $0<z<z^{*}$, $y=0$ is the point of evolutionary stability. When the probability of active government participation is lower than $\prod_{c}$, the evolutionary strategy of the firm is active support AI.

Proposition 4: When $dE+qG>K_1$, if $x^{*}<x<1$, we know that $y=1$ is the point of evolutionary stability. When the probability of active participation by a financial institution is higher than $\prod_{d}$, the evolutionary strategy of the firm is "active support AI." If $0<x<x^{*}$, $y=0$ is the point of evolutionary stability. When the probability of active participation by a financial institution is less than $\prod_{d}$, the evolutionary strategy of the firm is negative support (NI). On the contrary, when $dE+qG<K_1$, if $x^{*}<x<1$, $y=0$ is the point of evolutionary stability. When the probability of active participation by a financial institution is higher than $\prod_{d}$, the evolutionary strategy of the firm is "negative support NI." If $0<x<x^{*}$, $y=1$ is the point of evolutionary stability. When the probability of active participation by a financial institution is less than $\prod_{d}$, the evolutionary strategy of the firm is "active support AI."

4.3 Evolutionary stability of government

Regarding the analysis of the government's evolutionary strategy, we rely on the replication dynamics equation theorem to derive that when $R(z)=0, R'(z)<0$, z is the government's evolutionary strategy.

$$R(z)=\frac{dz}{dt}=z(1-z)\left(y((1-a)R-L_2)+x\left((1-d)E+(1-q)G-K_2\right)+\ C_2-(1-d)C\right), \tag{15}$$

$$R'(z)=\frac{dz}{dt}=(1-2z)\left(y((1-a)R-L_2)+x\left((1-d)E+(1-q)G-K_2\right)+\ C_2-(1-d)C\right). \tag{16}$$

When $R(z)=0$ and $R'(z)<0$, $z=0$, or $x^{*}=\frac{(1-d)C-C_2-y((1-a)R-L_2)}{(1-d)E+(1-q)G-K_2}$, $y^{*}=\frac{(1-d)C-L_2-x((1-d)E+(1-q)G-K_2)}{(1-a)R-L_2}$. For brevity, we will express $\frac{(1-d)C-C_2-y((1-a)R-L_2)}{(1-d)E+(1-q)G-K_2}$ as $\prod_{e}$ and express $\frac{(1-d)C-L_2-x((1-d)E+(1-q)G-K_2)}{(1-a)R-L_2}$ as $\prod_{f}$.

Proposition 5: When $(1-d)E+(1-q)G>K_2$, if $x^{*}<x<1$, $z=1$ is the point of evolutionary stability. When the probability of active participation by financial institutions is higher than $\prod_{e}$. The government's evolutionary strategy is active participation in AI. In the event that $0<x<x^{*}$, $z=0$ is the point of evolutionary stability. When the probability that a financial institution is actively involved is lower than $\prod_{e}$, the government's evolutionary stabilization strategy is passive participation in NI. On the contrary, when $(1-d)E+(1-q)G>K_2$, If $x^{*}<x<1$, $z=0$ is the point of evolutionary stability. When the probability of active participation by financial institutions is higher than that of $\prod_{e}$, the government's evolutionary strategy is passive participation in NI. If $0<x<x^{*}$, $z=1$ is the point of evolutionary stability. When the probability of active participation by financial institutions is lower than the probability of $\prod_{e}$, the government's evolutionary strategy is "active participation in AI."

TABLE 3 **Eigenvalues of the Jacobi matrix.**

Equilibrium point	Eigenvalue λ_1	Eigenvalue λ_2	Eigenvalue λ_3
E_1 (0, 0, 0)	$R_0 - C_0 - bR_0$	$C_1 - dC$	$C_2 - (1 - d)\ C$
E_2 (1, 0, 0)	$-R_0 + C_0 + bR_0$	$qG + C_1 - d\ (C - E) - K_1$	$(1 - q)\ G + C_2 - (1 - d)\ (C - E) - K_2$
E_3 (0, 1, 0)	$R_0 - C_0 - bR_0 - qG$	$dC - C_1$	$(1 - a)\ R + C_2 - (1 - d)\ C - L_2$
E_4 (0, 0, 1)	$R_0 - C_0 - b\ R_0 - (1 - q)\ G$	$aR + C_1 - dC - L_1$	$(1 - d)\ C - C_2$
E_5 (1, 1, 0)	$-\ R_0 + C_0 + bR_0 + qG$	$-qG - C_1 + d\ (C - E) + K_1$	$-(1 - d)\ (C - E) + (1 - a)\ R + (1 - q)G + (C_2 - K_2) - L_2$
E_6 (1, 0, 1)	$-R_0 + C_0 + b\ R_0 + (1 - q)\ G$	$-d\ (C - E) + aR + qG + (C_1 - K_1) - L_1$	$-(1 - q)\ G - C_2 + (1 - d)\ (C - E) + K_2$
E_7 (0, 1, 1)	$R_0 - C_0 - b\ R_0 - G$	$-aR - C_1 + dC + L_1$	$-(1 - a)\ R - C_2 + (1 - d)\ C + L_2$
E_8 (1, 1, 1)	$-R_0 + C_0 + b\ R_0 + G$	$d\ (C - E) - a\ R - qG - (C_1 - K_1) + L_1$	$(1 - d)\ (C - E) - (1 - a)\ R - (1 - q)\ G - (C_2 - K_2) + L_2$

TABLE 4 **Stability analysis of evolutionary strategic portfolios.**

Equilibrium point	Progressive stabilization condition
E_3 (0, 1, 0)	$R_0 - C_0 - b\ R_0 - q\ G < 0\ (1 - a)\ R + C_2 - (1 - d)\ C - L_2 < 0$
E_4 (0, 0, 1)	$R_0 - C_0 - b\ R_0 - (1 - q)\ G < 0\ aR + C_1 - d\ C - L_1 < 0$
E_7 (0, 1, 1)	$R_0 - C_0 - bR_0 - G < 0$ $-aR - C_1 + dC + L_1 < 0$ $-(1 - a)\ R - C_2 + (1 - d)\ C + L_2 < 0$
E_6 (1, 0, 1)	$-R_0 + C_0 + bR_0 + (1 - q)\ G < 0$ $-d\ (C - E) + aR + qG + (C_1 - K_1) - L_1 < 0$
E_5 (1, 1, 0)	$-R_0 + C_0 + bR_0 + qG < 0$ $-(1 - d)\ (C - E) + (1 - a)R + (1 - q)\ G + (C_2 - K_2) - L_2 < 0$
E_8 (1, 1, 1)	$-R_0 + C_0 + bR_0 + G < 0\ d\ (C - E) - aR - qG - (C_1 - K_1) + L_1 < 0$ $1 - d)\ (C - E) - (1 - a)\ R - (1 - q)\ G - (C_2 - K_2) + L_2 < 0$

Proposition 6: When $(1\text{-}a)\ R > L_2$, if $y^{*}<y < 1$, $z = 1$ is the point of evolutionary stability. When the probability of firms actively participating is higher than $\prod_f$, the government's evolutionary strategy is active participation in AI. If $0<y < y^{*}$, $z = 0$. It is a point of evolutionary stability. The probability of firms actively cooperating is lower than $\prod_f$. The government's evolutionary strategy is "passive participation in NI". On the contrary, when $(1\text{-}a)\ R < L_2$, if $y^{*}<y < 1$, $z = 0$ is the point of evolutionary stability. When the probability of firms actively cooperating is higher than $\prod_f$, the government's evolutionary strategy is passive participation in NI. If $0<y < y^{*}$, $z = 1$ is the point of evolutionary stability. The probability of firms actively cooperating is lower than $\prod_f$. The government's strategy for evolutionary stability is "active participation in AI".

4.4 System evolutionary stability

The replicated dynamic model uses the local stability analysis of Jacobian matrices, and the Jacobian matrices of the replicated dynamic equations are obtained as

$$J = \begin{bmatrix} A'11\ A'12\ \ \ A'13 \\ A'21\ A'22\ A'23 \\ A'31\ A'32\ A'33 \end{bmatrix}. \tag{17}$$

According to Friedman's method, the Jacobi matrix is known from Equation 1 as follows.

$$J=\begin{pmatrix} (1-2x)(yz(1-\alpha)R_4+L_2+S_2-C_2) & x(1-x)z((1-\alpha)R_4+L_2) & x(1-x)y(1-\alpha)R_4+L_2) \\ y(1-y)z(\alpha R_4+\Delta R_2) & (1-2y)(xz(\alpha R_4+\Delta R_1)2S_1+\Delta R_2-\Delta R_1-\beta C_3-(2-z)(C_1+I-S_1)) & y(1-y)x(\alpha R_4-\Delta R_2) \\ z(1-z)yL_1 & z(1-z)(I-\beta C3+xL_1) & (1-2x)(xyL_1+(y-2)(R_3-R_5)+I-(y-\beta)C_3) \end{pmatrix}$$

We can set $F(x) = F(y) = F(z) = 0$. We will know that E_1 (0, 0, 0), E_2 (0, 0, 1), E_3 (0, 1, 0), E_4 (1, 0, 0), E_5 (1, 1, 0), E_6 (1, 0, 1), E_7 (0, 1, 1), E_8 (1, 1, 1) is the local equilibrium point. When the equilibrium point is E_1 (0, 0, 0), we have

$$
\begin{aligned}
&A'11 = (1-2x)\big((1-b)R_0 - yqG - z(1-q)G - C_0\big), A'12 = -x(1-x)qG, A'13 = -x(1-x)(1-q)G,\\
&A'21 = y(1-y)(dE + qG - K_1), A'22 = (1-2y)\big(x((qG + d(E-C) - K_1)) + z(aR - L_1) + C_1\big)\\
&A'23 = \mathrm{y}(1-y)(aR - L_1), A'31 = z(1-z)\big((1-d)E + (1-q)G - K_2\big), A'32 = z(1-z)\big((1-a)R - L_2\big),\\
&\mathrm{A}'33 = (1-2z)\big(x\big((1-q)G + (1-d)(E-C) - k_2\big) + \ y\big((1-a)R - L_2\big) + C_2\big).
\end{aligned}
\tag{18}
$$

From the Lyapunov discriminant, the equilibrium is an evolutionary stable point (ESS) when all eigenvalues of the Jacobian matrix are negative; the equilibrium is a non-stable point when the sign of all eigenvalues of the Jacobian matrix is determined, and some eigenvalues are positive. Therefore, the 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) can be substituted into the Jacobian matrix J separately to obtain the corresponding eigenvalues (see Table 3).

In practice, the initial parameters should satisfy $C_1>d\,C$, $C_2>(1-d)\,C$, $C_1-K_1>d\,(C-E)$, $C_2-K_2>d\,(C-E)$. This means: regardless of whether financial institutions are actively involved or not, the cost of negative cooperation between enterprises and governments is always greater than the shared cost of positive cooperation. The reason for this is that enterprises can not only reduce costs and achieve precise control in the carbon governance chain, but they can also achieve economies of scale. In this scenario, the eigenvalues of the points E_1 (0, 0, 0), E_2 (1, 0, 0) do not satisfy the sign requirement of the Lyapunov discriminant for evolutionary stability. The eigenvalues of the points 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) also require certain conditions if they are to satisfy the discriminant (see Table 4).

Table 4 shows that the stable equilibrium of the evolution of each subject's strategy is influenced by a variety of factors, and a specific discussion of the stability of these six equilibria follows.

Scenario 1: When $R_0-C_0-bR_0-qG<0$ and $(1-a)\ R + C_2-(1-d)\ C-L_2 < 0$, financial institutions have lower returns to active support strategies than to passive support in cases where firms are actively engaged in carbon governance ($R_0-C_0-qG < bR_0$). The benefits of active government participation are lower than those of passive participation ($(1-a)\ R-(1-d)\ C < L_2-C_2$). Table 4 shows that the eigenvalues of the equilibrium points E_3 (0, 1, 0) are all negative. Therefore, {negative support, active participation, negative participation} is the evolutionary strategy.

Scenario 2: When $R_0-C_0-bR_0-(1-q)\ G < 0$ and $aR + C_1-dC-L_1<0$, financial institutions have lower returns to active support strategies than to passive support in the case of active government involvement in carbon governance ($R_0-C_0-(1-q)G < bR_0$). The benefits of active participation by firms are lower than the benefits of passive participation ($a\ R-d\ C < L_1-C_1$). Table 4 shows that the eigenvalues of the equilibrium points E_4 (0, 0, 1) are all negative. Therefore, {negative support, negative participation, active participation} is the evolutionary strategy.

Scenario 3: When $R_0-C_0-bR_0-G<0$, $-aR-C_1+dC + L_1 < 0$, and $-(1-a)\ R-C_2+(1-d)\ C + L_2 < 0$, financial institutions receive less for positive support strategies than for negative support when both firms and governments are actively involved ($R_0-C_0-G < bR_0$). The benefits of active participation are higher than those of passive participation for both businesses and financial institutions ($L_1-C_1<a\ R-d\ C$,$L_2-C_2<(1-a)R-(1-d)C$). From Table 4, the eigenvalues of the equilibrium points E_7 (0, 1, 1) are all negative. Thus, {negative support, active participation, active involvement} is the evolutionary strategy.

Scenario 4: When $-R_0+C_0+bR_0+(1-q)G<0$ and $-d\ (C-E)+a\ R+\ q\ G+(C_1-K_1)-L_1<0$, financial institutions have higher returns to active support strategies than to passive support with active government involvement ($bR_0<R_0-C_0-(1-q)\ G$). Firms' returns to an active participation strategy with active support from financial institutions are lower than the returns to passive participation ($a\ R-d\ (C-E) + q\ G < L_1-(C_1-K_1)$). Table 4 shows that the eigenvalues of the equilibrium points E_6 (1, 0, 1) are all negative. Thus, {positive support, negative involvement, active participation} is the evolutionary strategy.

Scenario 5: When $-R_0+C_0+bR_0+qG < 0$ and $-(1-d)(C-E)+(1-a)R+(1-q)G+(C_2-K_2)-L_2<0$. Financial institutions have higher returns to active support strategies than to passive support in the presence of active business participation ($bR_0<R_0-C_0-qG$). The benefits of active government involvement with the active support of financial institutions are lower than the benefits of passive involvement ($(1-a)\ R-(1-d)\ (C-E)\ +(1-q)\ G+<L_2-(C_2-K_2)$). Table 4 shows that the eigenvalues of the equilibrium points E_5 (1, 1, 0) are all negative. Therefore, {positive support, active participation, negative participation} is the evolutionary strategy.

Scenario 6: When $-R_0+C_0+bR_0+G < 0$, $d\ (C-E)-a\ R-q\ G-(C_1-K_1)+L_1 < 0$, and $(1-d)(C-E)-(1-a)R-(1-q)G-(C_2-K_2)+L_2 < 0$. Financial institutions have higher returns to a positive support strategy than to a negative support with active participation of both business and government ($bR_0<R_0-C_0-G$). The benefits of active participation are higher than those of passive participation for both businesses and financial institutions ($L_1-(C_1-K_1)<a\ R-d\ (C-E)+q\ G$,$L_2-(C_2-K_2)<(1-a)R-(1-d)(C-E)+(1-q)G$). Table 4 shows that the eigenvalues of the equilibrium points E_8 (1, 1, 1) are all negative. Therefore, {active support, active participation, active involvement} is the evolutionary strategy.

5 Simulation analysis

To further verify the validity of the evolutionary stability analysis, the model variables are parametrically set and substituted into the evolutionary game model. Then, the evolutionary game model of stakeholders' strategies is simulated using MATLAB R2021a software to analyze the evolutionary paths of the tripartite gaming of the financial institutions, enterprises, and the government in the system and to explore the impacts of contract coefficients, income distribution coefficients, cost-sharing coefficients, and subsidy policy on the strategies of the game subjects.

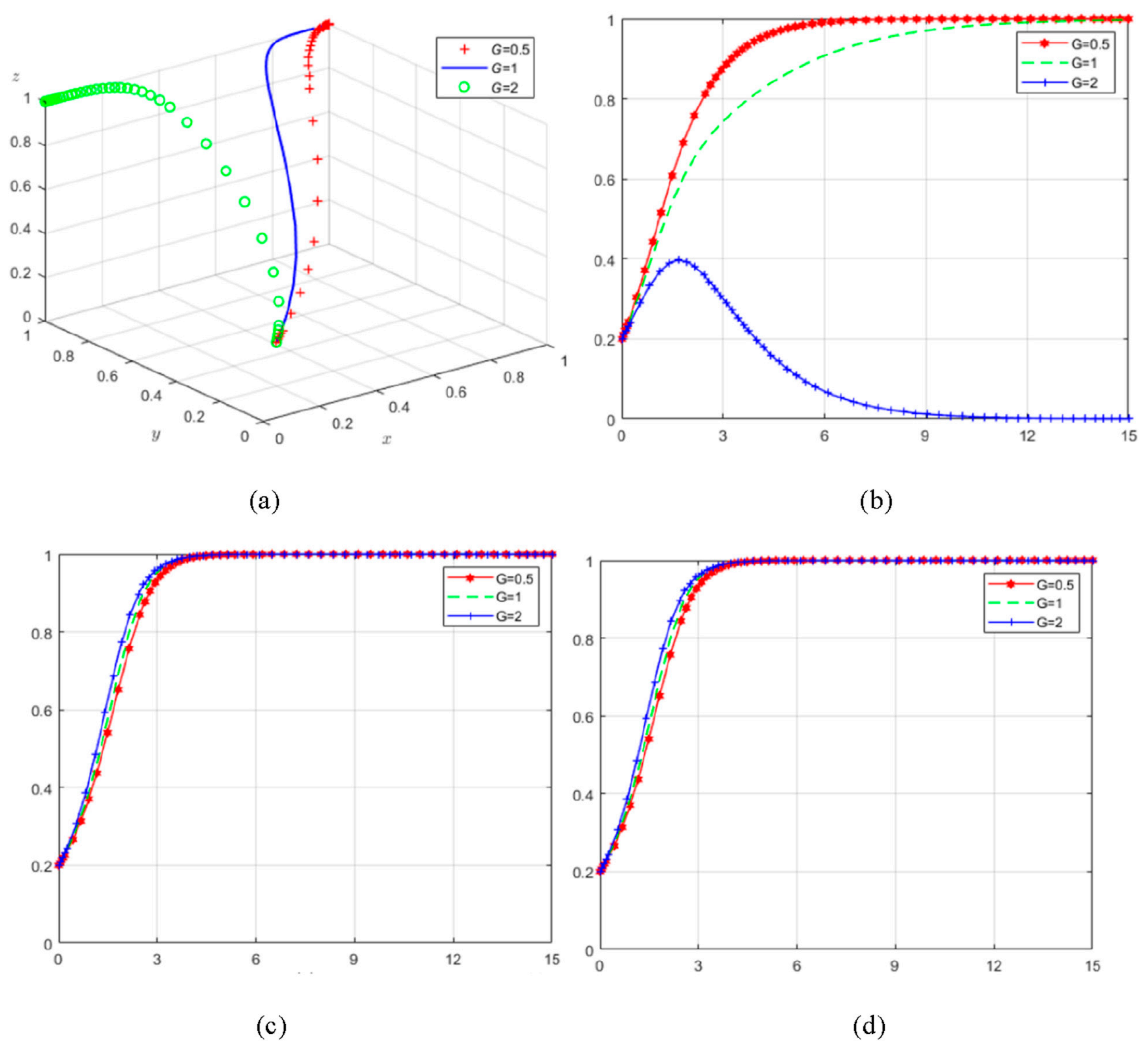


FIGURE 3
The impact of tax incentive subsidy coefficient (G) on the strategic evolution of stakeholders. **(a)** Three-dimensional plot showing the evolution trajectories of strategies under different G values (0.5, 1, 2). **(b)** Two-dimensional line plot depicting the convergence of the firm's strategy over time. **(c)** Two-dimensional line plot depicting the convergence of the government's strategy over time. **(d)** Two-dimensional line plot depicting the convergence of the financial institution's strategy over time.

To increase the practical relevance of this study, we supplemented the simulation analysis with illustrative cases from the steel industry. For instance, after receiving tax incentives, Baosteel Group significantly increased its investment in ultra-low emission technologies and introduced intelligent production lines, which led to an approximate 15% reduction in carbon intensity. This example confirms the positive role of tax incentives in driving corporate green transformation. In addition, we incorporated real-world cases concerning carbon leakage and regulatory arbitrage. Some steel enterprises have shifted production across regions or exploited tax loopholes to delay their emission reduction obligations, which undermines policy effectiveness and increases governance costs. These cases suggest that while tax incentives can be effective, they must be accompanied by cross-departmental regulatory coordination and dynamic evaluation mechanisms to prevent policy arbitrage and ensure the achievement of carbon governance objectives.

The data sources and their role in the modeling procedure are as follows: Tax incentive data: Collected from government policy documents and financial reports, these data inform the subsidy coefficient (S_g) and tax rate variables (T), which influence firms' strategic decisions. Corporate carbon emission data: Obtained from environmental disclosure reports of steel firms, this dataset is used to estimate baseline emission levels (E_0) and marginal reduction costs (C_r), which directly affect firms' payoff functions in the model. Regulatory compliance data: Sourced from monitoring agencies and ESG reports, this dataset helps define compliance probability (P_c) and penalty coefficients ($f(S_r)$), influencing the effectiveness of enforcement mechanisms in the model. These datasets are integrated into the evolutionary

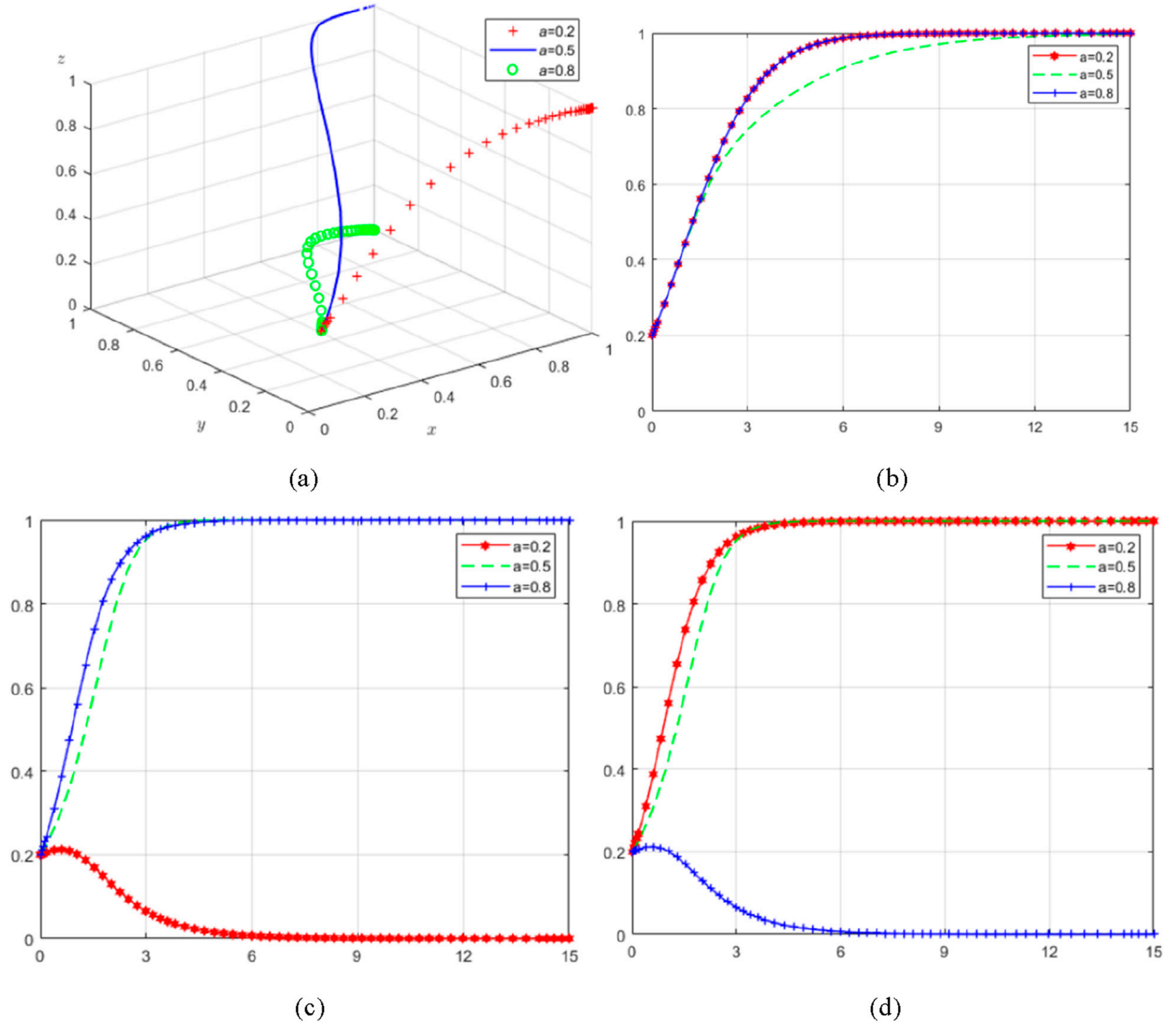


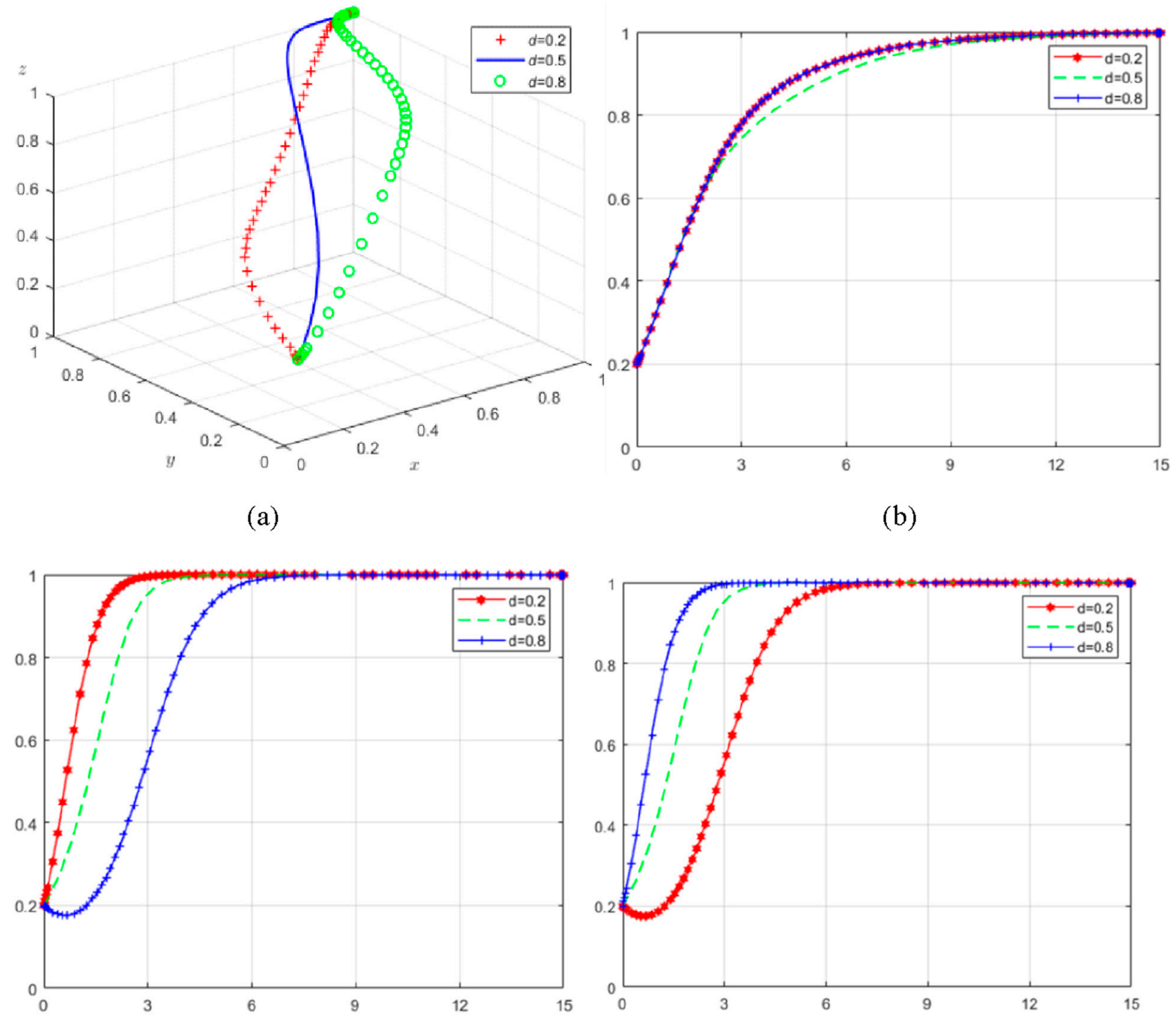
FIGURE 4
(α) on the strategic evolution of stakeholders. **(a)** Three-dimensional trajectory plot comparing strategy evolution under different α values (0.2, 0.5, 0.8). **(b)** Two-dimensional line chart showing the trend of the firm's strategy propensity under varying α. **(c)** Two-dimensional line chart showing the trend of the government's strategy propensity under varying α. **(d)** Two-dimensional line chart showing the combined or comparative trend of strategies under varying α.

game framework, enabling dynamic simulations of policy impacts and firm behavior. By explicitly incorporating real-world data, our model ensures a more robust and realistic representation of ESG policy effects on corporate carbon reduction strategies.

In conjunction with the six scenarios above on the evolutionary stakeholder game, the game model variables were as follows. The initial value of C_0, C_1, C_2, C, E, K_1, K_2, R_0, R, L_1, L_2, a, b, q, d, G are set to six groups: Array 1=(4, 3, 3, 5, 2.5, 1, 1, 6, 10, 4, 4, 0.7, 0.2, 0.6, 0.4, 1.5); Array 2=(4, 3, 3, 5, 2.5, 1, 1, 6, 10, 4, 4, 0.3, 0.2, 0.4, 0.6, 1.5); Array 3=(4, 3, 3, 5, 2.5, 1, 1, 6, 10, 4, 4, 0.5, 0.2, 0.5, 0.5, 1.5); Array 4=(4, 3, 3, 5, 2.5, 1, 1, 6, 10, 4, 4, 0.7, 0.1, 0.6, 0.4, 1); Array 5=(4, 3, 3, 5, 2.5, 1, 1, 6, 10, 4, 4, 0.3, 0.1, 0.4, 0.6, 1); Array 6=(4, 3, 3, 5, 2.5, 1, 1, 6, 10, 4, 4, 0.5, 0.1, 0.5, 0.5, 1). We then substituted the above parameters into the game model and performed an evolutionary path simulation analysis using MATLAB R2021a.

5.1 Tax incentive subsidy coefficients *G*

We set the values of the subsidy policy G to 0.5, 1, and 2 to determine the effect of the subsidy policy G on the strategy choices of the three parties of the game. As can be seen in Figure 3a, the ESS of the system evolves from (0,1,1) to (1,1,1) as the subsidy policy G increases. Specifically, as shown in Figures 3b–d, the change of subsidy policy G mainly brings about the change of financial institutions' evolutionary strategy. G is negatively correlated with *x*; that is, excessive subsidy will lead to financial institutions' tendency to "negatively support the NS" strategy, which is because the subsidy policy is issued by the financial institutions, thus increasing their costs. G is negatively correlated with x, y, and z, respectively. At the same time, G is positively correlated with y and z. As G increases, the speed at which y and z converge to



(a) (b)

(c) (d)

FIGURE 5
(a) Three-dimensional line plot with trajectories for different d values (0.2, 0.5, 0.8). **(b)** Two-dimensional line graph showing the evolution of the firm's strategy under different cost-sharing ratios. **(c)** Two-dimensional line graph showing the evolution of the government's strategy under different cost-sharing ratios. **(d)** Two-dimensional line graph showing the evolution of the financial institution's strategy or the system's overall convergence under different cost-sharing ratios.

1 accelerates, suggesting that increased subsidies can motivate enterprises and the government to reach strategic synergies more quickly because subsidy policies can increase the expected net profits of both. Therefore, even though policy subsidies can promote strategic synergies between firms and governments in the medium term, excessive subsidies should be avoided to achieve the desired system ESS (1, 1, 1).

5.2 Allocation coefficients for tax incentives *a*

The values of the income distribution coefficient *a* are set to 0.2, 0.5, and 0.8 to determine the effect of the income distribution coefficient a on the strategy choices of the three parties of the game. Figure 4a shows that the ESS of the system evolves toward (1, 0, 0), (1, 1, 1), and (1, 0, 1) when the income distribution coefficient is taken as 0.2, 0.5, and 0.8, respectively. In addition, as can be seen from Figures 4b–d, the evolutionary strategies of financial institutions do not change with the change in the coefficient of income distribution, *a*, and always converge to the AS strategy, whereas the change in the coefficient, a, leads to the change in the evolutionary strategies of firms and the government, and, specifically, a is positively correlated with y, and a is negatively correlated with z. That is, as the coefficient a increases, firms tend to choose the strategy of active participation in AI. Financial institutions, in contrast, tend to choose the strategy of passive participation in NI, because the expected net profits of both are affected by the coefficient a of the income distribution, which affects the stability of the ESS.

and thus the stability of ESS. Therefore, in the development of the ESS, it is possible to balance the benefits by adjusting the income distribution ratio between the enterprises and the government in the chain, so as to stimulate the active participation of the two and achieve the synergy of the strategies.

5.3 Cost-sharing factor *d*

The values of the cost-sharing coefficient are set to 0.2, 0.5, and 0.8 to determine the effect of the cost-sharing coefficient *d* on the strategy choices of the three parties of the game. As can be seen in Figure 5a, although the evolutionary path changes when the cost-sharing coefficient d changes, the ESS of the system remains at (1, 1, 1). Furthermore, as can be seen in Figures 5b–d, a change in the coefficient d does not bring about a change in the evolutionary stabilization strategy of the financial institutions, firms, or the government. The evolutionary stabilization strategy remains an active strategy over time, but when coefficient d is low, firms tend to move faster toward the active strategy, and the opposite is true for the government. Similarly, when coefficient d is high, the government tends to actively participate in the strategy faster, and firms do the opposite. Therefore, in practice, the process of reaching strategy synergy between firms and governments can be accelerated by adjusting the appropriate cost-sharing ratio.

6 Discussion

Based on the development model of ESG objectives, this study constructs a three-party evolutionary game model of financial institutions, enterprises, and the government and explores the influence of key decision variables on the evolution of the strategies of the game subjects. It is found that, first, the evolutionary game results will change when the initial values of the decision variables, such as the income distribution coefficient, the cost-sharing coefficient, and the subsidy policy, are changed. Second, the policy subsidy is an important factor affecting the active support of financial institutions. Appropriately lowering the contract coefficient and avoiding excessive policy subsidies are all conducive to the government, consumers, financial institutions, and other financial institutions tending to adopt positive strategies. Third, revenue-sharing coefficients, cost-sharing coefficients, and subsidy policies play an important role in the participation of firms and governments in decision-making, and high or low revenue-sharing coefficients and cost-sharing coefficients are not conducive to strategic synergies between firms and governments. In addition, a moderate increase in policy subsidies can accelerate the speed of strategic synergy between firms and governments.

The results suggest that tax incentives positively influence firms' willingness to reduce emissions, while ESG compliance mechanisms increase corporate environmental responsibility. However, the long-term sustainability of these effects warrants further examination.

Potential risks of sustained expansion: Regulatory overburden: As corporate carbon reduction policies evolve, excessive or misaligned regulations could lead to compliance fatigue, discouraging firms from proactively investing in sustainability. Economic trade-offs: While tax incentives encourage emissions reduction, over-reliance on financial incentives could create short-term gains at the expense of long-term commitment to green transformation. Carbon leakage risk: Expansion strategies might inadvertently shift emissions to less regulated regions rather than achieving actual reductions, undermining the policy's intended effects.

Mitigation strategies: Adaptive policy mechanisms: Governments should implement dynamic tax structures and flexible ESG compliance frameworks to adjust incentives based on firms' long-term sustainability performance. Sector-specific carbon accounting models: A differentiated carbon credit system tailored to high-emission industries like the steel sector can ensure equitable and effective emissions reduction measures. Technological investment: Firms should be encouraged to invest in low-carbon technologies and digital solutions to enhance their sustainability without over-reliance on external financial support.

7 Conclusion

This study examines the impact of tax incentives on corporate decisions to reduce carbon emissions within the ESG compliance framework, with a particular focus on the iron and steel industry. By developing a tripartite evolutionary game model, we systematically analyze the interactions among government, enterprises, and financial institutions under different policy scenarios. Key findings and contributions: Positive role of tax incentives: The findings indicate that well-structured tax incentives significantly increase firms' willingness to reduce emissions, particularly when coupled with stringent ESG compliance requirements. Differentiated policy effects: The effectiveness of tax incentives varies across firms depending on their initial carbon emission levels, compliance costs, and regulatory pressure, highlighting the need for targeted policy design. Strategic interactions and policy optimization: The study reveals that imbalanced policy allocation or inconsistent enforcement may lead to carbon leakage or regulatory arbitrage, weakening the intended effect of tax incentives.

Reasonable parameter setting can effectively improve the effectiveness of policy implementation and increase the motivation of enterprises to participate. Specifically, when formulating tax incentive policies, the government should fully consider the characteristics of the industry, the scale of enterprises, and the cost of carbon emissions to ensure the feasibility and effectiveness of the policies. For example, in high-carbon-emitting industries (such as the iron, steel, and cement manufacturing industries), appropriately increasing tax incentives, combined with strict regulatory measures, can effectively promote the low-carbon transformation of enterprises. At the same time, policy implementation should also maintain dynamic adjustments to adapt to market changes and technological advances to ensure that enterprises continue to benefit from reasonable incentives.

Building upon the simulation results and case analyses, this study refines the earlier recommendations on progressive tax incentives and strengthening ESG regulatory collaboration by proposing specific implementation pathways. First, regarding progressive tax incentives, a phased adjustment mechanism should be designed, such as setting the initial tax reduction at 20%, raising it to 25% in the medium term, and further increasing it to 30% in the later stage. This ensures that enterprises maintain continuous motivation for emission reduction across different development phases. Second, for cross-departmental regulatory collaboration, it is essential to establish information-sharing and joint enforcement mechanisms among environmental protection, taxation, and financial authorities. For example, creating a unified database of carbon emissions and taxation and conducting regular joint audits can help prevent policy arbitrage and carbon leakage. Finally, a dynamic evaluation mechanism should be introduced to periodically review and adjust policy effectiveness. A data-driven feedback system can ensure that policies remain adaptive to industrial transformation and evolving international regulations.

Despite the insights provided, this study has several limitations that also present opportunities for future research. First, as a theoretical simulation model, its findings depend on the underlying assumptions and parameter calibrations. Although we grounded our parameters in industry data, future work could employ more precise, firm-level panel data for calibration to increase accuracy. Second, the model focuses on the interaction among a representative government, a single steel enterprise, and a financial institution. It does not capture the competitive dynamics among multiple firms or the cross-border effects of international carbon policies, such as the EU's Carbon Border Adjustment Mechanism (CBAM), which could significantly alter strategic choices. Third, the model's applicability to small and medium-sized enterprises (SMEs) may be limited due to their different resource constraints and compliance capacities compared to the large steel firms primarily considered here.

Future research could extend this work in several directions: (i) developing a multi-agent game model that incorporates competition and collaboration among several firms within an industrial cluster; (ii) integrating international policy factors to assess their impact on domestic carbon governance; and (iii) conducting comparative case studies across different industries or regions to examine the heterogeneity of policy effects. Employing a multi-method approach that combines agent-based modeling with empirical validation could further strengthen the robustness and generalizability of the findings.

Data availability statement

Publicly available datasets were analyzed. The datasets used and analyzed during the current study are available from the corresponding authors on reasonable request.

Author contributions

ZQ: Data curation, Methodology, Supervision, Conceptualization, Writing – original draft, Writing – review and editing. YL: Writing – original draft. SL: Writing – review and editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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