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An analysis of optimal equilibrium in the carbon trading market - From a tripartite evolutionary game perspective

Wen-Jing Fan [a,*], Yao Fang [b], Rui-Bo Jiang [c]

[a] *Economics School, Hangzhou Normal University, Hangzhou 311121, China*
[b] *Zhejiang Branch, Agricultural Development Bank of China, Hangzhou 310003, China*
[c] *Economic and Management School, Zhejiang University of Water Resources and Electronic Power, Hangzhou 310018, China*

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ABSTRACT

As the climate crisis intensifies, achieving the global consensus of carbon peaking and carbon neutrality has become imperative. Carbon trading is an important financial measure to address the environmental crisis, and the realization of the dual-carbon goals requires the cooperation and joint efforts of all parties involved in the carbon emissions trading market. This study constructs a dynamic evolutionary game model involving enterprises, government, and financial institutions while considering consumers' influence. By solving for equilibrium points and conducting numerical simulations, we explore optimal strategy choices for each stakeholder. Our findings reveal that the success of enterprise low-carbon transition is contingent upon market dynamics and requires active cooperation from government, financial institutions, and the public. Furthermore, factors such as financial market efficiency and internal governance capacity significantly impact enterprises' transformation decisions by influencing low-carbon transition costs. Public feedback indirectly affects enterprise decisions through its influence on financial institutions' provision of green services. Additionally, gradual reduction of carbon quotas by government entities facilitates progress toward low-carbon transformation objectives.

1. Introduction

In recent years, the global concern over extreme weather events caused by excessive greenhouse gas emissions has escalated. If countries continue to follow current production trends, it is anticipated that the global temperature will surpass the 2-degree Celsius threshold outlined in the Paris Agreement within this century. The resulting consequences, such as damage to global food reserves, rising sea levels, and a significant decline in biodiversity, will have profound negative impacts on human livelihoods and productivity. In response, numerous countries have proposed comprehensive environmental strategies encompassing economic and political development while emphasizing the establishment of a worldwide carbon market (Yu, Cao, & Liu, 2021). For instance, on September 20, 2020, Chinese leaders introduced China's dual carbon targets, which have subsequently gained strategic significance for China's sustainable development. Subsequently, the National Development and Reform Commission of China outlined six key areas to achieve carbon neutrality, which include restructuring the energy sector, transforming the industrial landscape, enhancing energy efficiency, advancing low-carbon technologies, strengthening institutions and mechanisms for low-carbon development, and expanding ecological carbon sinks.

The realization of the carbon peak and carbon neutrality targets necessitates not only ideological transformation at the national macro level but also active cooperation and full participation from various micro subjects. Incentive measures implemented by the government to promote low-carbon transformation, financial support provided by financial institutions for green investments, and the transition of high-polluting enterprises' development models are all indispensable elements in achieving the dual carbon targets. Furthermore, public awareness and feedback regarding pollution issues and green transformation will impact the process of implementing the low-carbon targets. Game theory is a crucial research methodology for analyzing the behavior of multiple agents and equilibrium outcomes. In the field of carbon trading, scholars have employed game theory to examine conflicts and cooperation among market entities (Fang, He, & Tian, 2022; Zhou, Xiao, & Zhao, 2023). However, literatures employing game theory to examine carbon trading markets predominantly concentrates on the two-party game between government and enterprises or upstream and downstream enterprises in the supply chain, and rarely include financial

* Corresponding author.
E-mail address: wenjingfanhznu@163.com (W.-J. Fan).

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institutions as active participants. Relevant studies (Chen, Ma, & Bai, 2023) show that financial institutions can increase the liquidity of carbon quota trading, reduce the risks of all parties, improve the efficiency of carbon market, and thus promote enterprises to successfully carry out low-carbon transformation. Therefore, it is imperative to incorporate financial institutions into game-theoretic analyses of carbon trading market and conduct a more comprehensive analysis of the factors affecting the low-carbon transformation of society.

Considering the paramount significance of the low-carbon transformation and the research gap in this area, this paper aims to analyze the behavioral strategies of governments, financial institutions, and enterprises within the carbon trading market using dynamic evolutionary game theory and to determine the optimal modes for attaining the low-carbon targets through analysis and simulation of equilibrium results. The marginal contributions of this paper are primarily manifested in the following two aspects. Firstly, the game analysis approach of the carbon trading market mainly employs the classical model for static game analysis and seldom adopts the evolutionary game method for research, thereby causing the relevant research to lack realistic assumptions and sufficient mechanism analysis. Secondly, whereas the literature utilizing game theory to examine the carbon trading market has focused mainly on government–enterprise games, this paper incorporates financial institutions and considers public reactions. The incorporation of financial institutions into the model enhances the diversity of strategies, offering governments and enterprises fresh incentives for emission reduction and risk management. This also improves the efficacy of price mechanisms and the efficiency of carbon trading markets, thereby influencing equilibrium outcomes. For instance, whether financial institutions provide green financial services impacts the likelihood of enterprises undergoing low-carbon transformation, while their provision of such services is influenced by government incentives and public feedback.

2. Literature review

Academic research on the carbon trading market has primarily focused on the operational mechanisms (Sovacool, 2011; Svendsen & Vesterdal, 2003), the pricing of carbon emission rights (Paolella & Taschini, 2008; Springer, 2003; Zhang, Chen, Wu, & Zhu, 2021; Zhao, Han, Ding, & Calin, 2018), and risk management (Blyth & Bunn, 2011; Evans, Mehling, Ritz, et al., 2021; Wu, Chen, & Hu., C., 2021). Some scholars have employed game theory to analyze the decision-making behavior of governments and enterprises in achieving market equilibrium within the carbon trading market (Fang et al., 2022; Xu & Lv, 2014; Zhou et al., 2023); however, few studies have incorporated financial institutions into their analysis or considered the impact of public feedback on enterprise performance. There are two main branches of literature of strong relevance to this study. The first branch is the research on the operational mechanisms of the carbon trading market, which aids in understanding the specific operations of the carbon trading market and the effectiveness of emissions trading system. The second branch is the literature using game theory to analyze the decision-making behavior of micro entities in the carbon trading market, which is an important reference for our study.

2.1. Operation mechanism of the carbon trading market

Carbon emission rights are considered to be a public good with negative externalities (Stavins, 2011). Currently, there are three types of government policy tools aimed at reducing carbon emissions: traditional administrative orders, carbon taxes, and emissions trading system. Among these options, emissions trading system is a market-based mechanism that combines control of the total amount of emissions and a trading system to establish the carbon emissions trading market (Aldy, Krupnick, Newell, et al., 2010). Scholars studying the mechanisms of this market have primarily focused on designing the trading mechanism itself, the initial quota allocation methods, and the pricing of carbon emissions, as well as analyzing the effectiveness of emissions trading system.

In terms of the design of carbon trading market mechanisms, various scholars have proposed different plans for carbon emission reduction in accordance with the specific economic, environmental, and management contexts of different countries. For instance, the European Union has established a straightforward greenhouse gas emission trading mechanism that addresses issues such as carbon emission quotas, trading methods, target ranges, enforcement measures, and others (Svendsen & Vesterdal, 2003). Sovacool (2011) identified shortcomings in eight typical carbon trading markets and advocated for the adoption of more equitable and effective public policies to address environmental degradation and climate change concerns. Chen and Lu (2016) developed an emissions trading scheme specifically tailored to China's emissions trading market by considering aspects such as the legal foundations, basic framework design, relevant institutional arrangements, and regulatory policies.

In terms of the allocation of the initial carbon emission rights, there are three primary allocation methods: free distribution, public auction, and fixed-price sales. Scholars' opinions have diverged regarding the efficacy of these three methods. The primary advantage of free allocation, also known as the “grandfather system,” lies in its potential to reduce entry barriers within the emission trading market and enhance market participants' enthusiasm (Gagelmann, 2008). By allocating emission quotas based on historical emission levels, this approach not only satisfies the emissions requirements of production units but also incentivizes energy conservation and emission reduction by allowing surplus quotas to be sold for profit. Consequently, enterprises can benefit from market flexibility, while mitigating any adverse impact that carbon trading may have on economic development (Cong & Wei, 2010; Lee, Lin, & Lewis, 2008). Burtraw and McCormack (2017) argued that public auctioning of quotas can encourage and direct social capital toward industries with more advantageous emission reduction prospects, thereby enabling enterprises to achieve cost-effective emissions reductions. Hu, Peng, and Chen (2018) argued that the free distribution method is suitable for agglomeration areas with low energy consumption industries, whereas the public auction method can achieve optimal resource allocation efficiency in densely populated regions with high energy consumption industries. Through empirical research on the return data of carbon futures, Zhang et al. (2021) found that investor attention is a non-negligible pricing factor in carbon market.

Research on the efficiency of carbon emissions trading systems generally concurs that this approach leads to a reduction in carbon emissions and is more effective than carbon taxes (Bai & Ru, 2022). Bushnell, Chong, and Mansur (2013) investigated the effects of the EU ETS (European Union's Emissions Trading System) for CO_2 on firms and found that several industrial sectors benefited from the EU ETS rather than being adversely affected by CO_2 regulation. Schmalensee and Stavins (2017) analyzed 30 years of experience with emissions trading systems and concluded that well-designed cap-and-trade systems, if appropriately implemented, can cost-effectively achieve their primary objective of meeting targeted emissions reductions. Key elements for successful design and implementation include: avoiding prior approval of trades, establishing a robust cap, ensuring compliance, provisions for banking allowances, and price collars. Bai and Ru (2022), using a panel sample of the largest 100 countries worldwide to exploit variations in ETS implementations, discovered that ETS adoption significantly reduced greenhouse gas emissions by 12.1 %. In contrast, the introduction of carbon taxes has a less effective impact on emissions reduction and fails to boost the usage of renewable energy. Additionally, Wang and Kuusi (2024)‘s study with new OECD data indicates that some carbon leakage has indeed occurred due to the EU ETS, resulting in higher carbon content in imports to the EU.

2.2. Game theory analysis of carbon trading markets

In recent years, game theory has been employed by scholars to analyze the behavioral strategies and market equilibrium in the carbon trading market. Based on the significance of market participants, relevant studies using game theory to analyze the carbon trading market mainly focus on the game between government and enterprise or the game between upstream and downstream enterprises. A small number of studies also include consumers or third-party monitoring agencies in the analysis, but relatively few studies include financial institutions in the analysis and consider consumer feedback simultaneously.

Some studies have analyzed the game between government and enterprises in carbon trading markets. Cao, Han, and Qi (2011) developed a three-stage dynamic game model between the government and enterprises, in accordance with the imperatives of low-carbon development. They computed the equilibrium solution of this model, which revealed both the essential prerequisites for enterprises to achieve a low-carbon development mode and the significant impact of government incentives on these enterprises. Similarly, Jiao, Chen, and Li (2017) examined an evolutionary game between local governments and enterprises under the constraint of carbon emissions. Their findings revealed that the impact of carbon quotas on local government supervision strategies was contingent upon the magnitude of market revenue derived from enterprises' unit emission reduction efforts, whereas factors such as government supervision costs and emission reduction effectiveness parameters exhibited a negative influence on local government supervision strategies. Cheng, An, Dong, et al. (2019) investigated the evolutionary dynamics of technological innovation behavior in renewable energy power generation enterprises and government incentives within the framework of carbon trading mechanisms. Their findings suggest that advancements in the carbon market can facilitate technological innovation among renewable energy power generation enterprises by leveraging market forces. Furthermore, the liberalization of electricity pricing can contribute to promoting technological innovation within the power generation industry.

Other scholars have studied the game theoretical problem of upstream and downstream enterprises and the various factors that affect the operation of the carbon trading market from the perspective of supply chains. Tong, Mu, Zhao, et al. (2019) considered an evolutionary game model under the influence of a cap-and-trade policy, revealing that emission caps, carbon credit market prices, and consumer preferences for low-carbon products are crucial determinants affecting retailers' and manufacturers' behavior. Xu, Wang, and Zhao (2018) studied the supply chain decision problem under the low-carbon economy and showed that the simultaneous development of the economy and the environment requires the government to formulate corresponding policies to solve environmental problems. Xia, Zhu, and Lu (2022) established decentralized and centralized decision-making models to consider the influence of outsourcing. Their results showed that under certain conditions, enterprises could improve profits by increasing unit outsourcing fees, and the profits of each member could be effectively distributed using the Shapley value method. Utilizing a manufacturer-led Stackelberg model, Sun and Zhong (2023) examined the influence of fairness concerns on carbon emission reduction (CER) and discovered that such concerns negatively affect the level of CER, indicating that they are not invariably advantageous for maximizing social utility. Furthermore, Ma, Pan, Zhang, et al. (2024) developed a Stackelberg model for the electricity market under two combination policy scenarios, CET-FIP (Carbon Emissions Trading-Feed in Premiums) and CET-RPS (Carbon Emissions Trading-Renewable Portfolio Standards), and compared their impact on the renewable energy industry. Their findings indicate that, in comparison to a single renewable energy development policy, both CET-RPS and CET-FIP policies can effectively reduce carbon emissions; in the long term, the CET-RPS policy demonstrates greater emission reduction capability while the CET-FIP policy yields stronger economic benefits.

In addition, limited studies incorporate third-party validation agencies or consumers into the government-enterprise game framework to analyze the equilibrium outcomes of the tripartite game in the carbon trading market. Xu and Lv (2014) incorporated government, enterprises, and consumers into a comprehensive game analysis framework, which revealed that measures such as reducing low-carbon regulation costs, increasing penalties for polluting behaviors, and enhancing national awareness regarding low-carbon practices are conducive to promoting low-carbon transformations. Based on the same logic, Zhou and Hu (2022) proposed specific strategies for enterprises with high carbon emissions from three aspects: enterprise low-carbon technology R&D, the establishment of a government reward and punishment mechanism, and the implementation of a supervision system. In response to persistent inaccuracies in carbon emission data within logistics enterprises, Wu, Liu, Yang, et al. (2022) developed a tripartite evolutionary game model encompassing government entities, third-party validation agencies, and logistical firms. Their findings indicate that heightened scrutiny from third-party validators may inadvertently facilitate collusive behavior among logistics enterprises. Moreover, an optimal 10 % to 20 % increase in carbon pricing by the government serves as both an incentive for rigorous validation efforts by third parties and a means of reducing governmental oversight costs. Feng and Ge (2024) developed a dynamic model of the tripartite evolutionary game involving the central government, local government, and high-pollution enterprises. Their empirical findings indicate that effective fiscal policy can facilitate green low-carbon transition, with fiscal decentralization playing a moderating role.

In summary, there is a relatively mature academic literature on the operating mechanisms of carbon trading markets, and the research has indicated that the decision-making behavior of the main participants in the carbon trading market is crucial to the realization of carbon emissions reduction goals. The literature employing game theory to analyze carbon trading has focused primarily on two-party games involving governments and enterprises, interenterprise games, or consumer interactions, with financial institutions rarely included. Currently, numerous studies have emphasized the crucial role of financial institutions in facilitating the green transformation of enterprises and carbon trading markets (Acheampong, 2019; Chen, Manu, & Asante, 2023). Campiglio (2016) explores the potential impact of monetary policies and macroprudential financial regulation, suggesting that adjusting banks' incentives and constraints could effectively increase credit creation for low-carbon sectors. Zafar, Zaidi, Sinha, Gedikli, and Hou (2019) investigated the impact of disaggregated financial development on carbon emissions, finding that a higher banking development index reduces carbon emissions in G-7 countries but increases them in N-11 countries. Given the importance of financial institutions in the low-carbon transformation and the lack of relevant research, this paper intends to analyze the behavioral strategies adopted by the government, financial institutions, and enterprises in the carbon trading market using a dynamic evolutionary game theory.

3. Model setting and hypothesis

3.1. The market participants

In the process of industrial low-carbon transformation, governments, enterprises, and financial institutions will adopt diverse strategies based on their own interests and their counterparties' behaviors to maximize their individual gains. The ultimate choices made by each participant will directly impact the achievement of low-carbon goals. Simultaneously, the public, as consumers of green products and beneficiaries of ecological improvements, will provide varying degrees of positive or negative feedback to the three participating entities in this game. Therefore, this paper considers the influence exerted by the public on the dynamic interplay among the market participants. A logical relationship diagram depicting the market participants and the basic assumptions regarding their relationships is presented below, see Fig. 1.

3.2. Modeling assumptions

Before establishing the game theoretical model, we make the following assumptions based on China's carbon trading market.

Assumption 1. The three key participants in the carbon trading market, namely government, enterprises, and financial institutions, will converge toward a final equilibrium. All three are characterized as “boundedly rational” individuals who can choose appropriate strategies based on their understanding of others' behavior and the cognition of their own benefits. Specifically, the government's strategic choice revolves around whether to enforce strict supervision over the entire system; enterprises must decide whether to undertake green and low-carbon transformations; and financial institutions need to determine if they should provide green and low-carbon financial services to diverse financial subjects.

Assumption 2. The establishment of a carbon market primarily relies on government macro-control, with the government holding the authority to determine carbon quotas for enterprises, denoted as T. The adoption of green innovative production by enterprises will result in changes in their carbon emissions. When enterprises engage in green innovative production, their allocated carbon emission quota will be lower than the government's free allocation. Consequently, they can sell surplus quotas to generate funds (K). Conversely, when enterprises do not adopt green innovative production, their carbon emission quota will exceed the government's free allocation. In such cases, they must incur a certain cost (A) to purchase additional carbon quotas. P represents the trading price of carbon allowances. Typically, companies delegate management of their carbon assets to relevant financial institutions, which receive remuneration based on a predetermined coefficient. Furthermore, the trading price (P) and allocation quotas (T) set by government directly influence each enterprise's specific demands or supplies within this marketplace. The higher P results in reduced demands among heavily polluting firms whereas increased government-allocated carbon quotas correspondingly diminish their respective needs.

Assumption 3. The set of strategic behaviors of an enterprise can be succinctly summarized as [low-carbon transition, no transition]. In the case where an enterprise opts for a low-carbon transition, it will allocate R&D funds to establish a dedicated low-carbon team, thereby enhancing product quality, improving corporate reputation, mitigating negative societal feedback, reducing carbon dioxide emissions, and consequently altering revenue streams accordingly. It is assumed that when an enterprise chooses a low-carbon transition, it achieves revenue denoted as R1 and incurs the costs associated with such a transformation, represented by C2. We denote the corresponding carbon emissions as T1. Conversely, if an enterprise decides against low-carbon transformation (opting for no transition), its revenue becomes R2 without any expenditure on transformative measures; however, this choice exposes the company to negative public feedback, denoted by D2. Furthermore, when the government oversees and facilitates the enterprises' transition toward low-carbon production, the enterprises become eligible for a government subsidy, S1. Conversely, failure to adopt low-carbon production methods will result in a prescribed penalty, F1.

Assumption 4. The set of government strategic behaviors can be briefly summarized as [strict regulation, loose regulation]. When enterprises undertake low-carbon transformation, the government can acquire revenue W1; however, if enterprises fail to engage in low-carbon transformation, the government will obtain revenue W2. In the case where the government opts for strict regulation of the carbon trading market, it can adopt two measures: first, subsidizing market participants engaged in carbon trading (through capital subsidies or tax reductions); and second, penalizing market participants involved in carbon trading (by imposing excess emission fees and potential future carbon tax policies). Specifically, subsidies provided by the government for enterprises' low-carbon transformation efforts are denoted as S1, whereas subsidies granted to financial institutions offering green services are denoted as S2. Fines imposed by the government on enterprises that fail to undertake low-carbon transformation are represented by F1; fines levied on financial institutions that neglect their responsibility to provide green services are indicated by F2. Regulatory costs incurred by the government are denoted as C. Under a regime of loose regulation, no subsidies or fines are implemented and nor are any regulatory costs borne. In the case of loose regulation, if enterprises do not conduct low-carbon transformation, the government will receive negative feedback from the public, denoted as D1. During the gradual process of integrating enterprises into the carbon trading market, the government has the authority to restrict an enterprise's carbon emission quota, T.

Assumption 5. The set of strategic behaviors of financial institutions can be succinctly summarized as [green services, traditional services]. Financial institutions incur certain costs when providing green financial services, but they receive positive public feedback and earn service fees based on a specific coefficient (θ). In addition, offering financial services for the green transformation of enterprises allows financial institutions to generate additional income (B1), and they receive positive feedback from the public (D3). Furthermore, by providing green financial services, financial institutions can help reduce the cost of green innovation for enterprises (C5). In such cases, if the government opts for strict

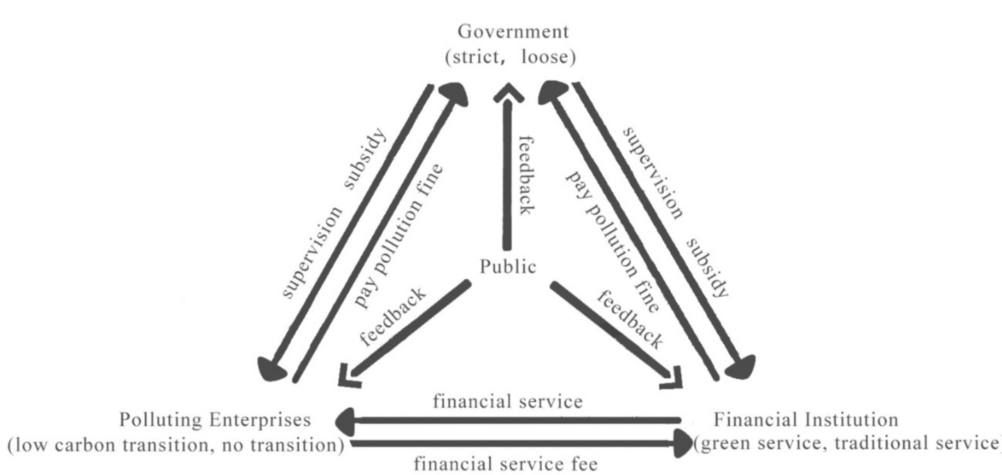

Fig. 1. The logical relationships of the low-carbon market participants.

regulation, financial institutions may receive subsidies from the government (S2). Conversely, if financial institutions choose not to provide green financial services, their own income is represented by B, and they do not incur any costs associated with the green financial services. In this scenario, if the government chooses strict regulation, financial institutions would be subject to fines (F2).

Table 1 below provides the definitions of the model parameters in this paper.

3.3. Model construction and dominant strategy analysis

3.3.1. Model construction

Assuming that the probability of an enterprise opting for low-carbon transformation production is denoted by x, then the complementary probability of not choosing low-carbon transformation production is $1 - x$ $(0 < x < 1)$. Similarly, let y represent the probability of a green financial institution choosing to provide green financial services, and let $1 - y$ represent the complementary probability of not providing such services. Likewise, z and $1 - z$ denote the probabilities of government selecting strict regulation and loose regulation, respectively. Table 2 presents the payoff matrix illustrating the evolutionary game outcomes of the carbon trading market based on these assumptions.

The replication dynamic equation, serving as a dynamic system that captures the evolving patterns of players, effectively portrays the behavioral trajectory exhibited by game participants. The basic principle is that strategies with better-than-average results will gradually be adopted by more individuals in a large number of rational parties, and eventually converge to a stable strategy (Friedman, 1988). The computational approach for deriving the replication dynamic equation is as follows:

$$\frac{dw(t)}{dt} = w(t)[E_t(A) - \overline{E_t}]$$

where w(t) represents the proportion of participants opting for a specific strategy A at time t, and dw(t)/dt denotes the growth rate of this proportion. $E_t(A)$ signifies the expected return associated with choosing strategy A, and E_t represents the average expected return of both

Table 1
Parameter definitions.

Parameter	Description
W1, W2	Government benefits from enterprises engaging in low-carbon transformation and not engaging in transformation
C	Government costs in regulating the low-carbon transformation of enterprises and the service behavior of financial institutions
S1, S2	Government subsidies to enterprises and financial institutions for conducting green business
F1, F2	Government fines on enterprises and financial institutions for not engaging in green business
D1	Public feedback on governmental actions
T	Carbon emission quota set by the government for enterprises
R1, R2	Enterprises benefits from low-carbon transformation and no transformation
C2	Enterprises cost of low-carbon transformation
D2	Public feedback on enterprises' behavior
T1	Enterprises carbon emissions under low-carbon transformation
T2	Enterprises carbon emissions under no transformation
A	Cost of purchasing carbon quotas
K	Revenue from selling carbon quotas
B1	Additional income earned by financial institutions through green business
C3	Costs incurred by financial institutions due to green business operations
B	Revenues earned by financial institutions when they only provide traditional services
D3	Positive feedback from the public to financial institutions providing green services
C5	Reduction of low-carbon transformation costs of enterprises when financial institutions provide green financial services
θ	Share of financial service fees based on carbon trading volume

Table 2
The payoff matrix of the evolutionary game.

Game subjects, behaviors, and benefits				Financial institutions	
				Green service (y)	Traditional service (1–y)
Government	Strict (z)	Enterprise	Low-carbon transition (x)	W1–C–S1–S2 R1–C2 + C5 + S1 + K B1–C3 + B + θ*K + S2 + D3	W1–C–S1 + F2 R1–C2 + S1 + K B–F2
			No transition (1–x)	W2–C–S2 + F1 R2–D2–F1–A B–C3 + θ*A + S2 + D3	W2–C + F1 + F2 R2–D2–F1–A B–F2
	Loose (1 – z)	Enterprise	Low-carbon transition (x)	W1 R1–C2 + C5 + K B − C3 + B1 + θ*K + D3	W1 R1–C2 + K B
			No transition (1–x)	W2–D1 R2–D2–A B–C3 + θ*A + D3	W2–D1 R2–D2–A B

strategies. We analyze the strategic choices made by all stakeholders by calculating replication dynamic equations applicable to enterprises, financial institutions, and governments in the carbon trading market.

The expected returns for enterprises engaging in low-carbon transformation and those not undertaking such transformation are denoted by E(lc) and E(nt), respectively. The corresponding replication dynamic equations and expected returns are presented below.

$$E\ (lc) = z*S1 + y*C5 + R1 - C2 + k,$$

$$E\ (nt) = -z*F1 + R2 - D2 - A,$$

$$F\ (x) = dx/dt = x\ (1-x)\ [z\ (F1 + S1) + yC5 + R1 - R2 - C2 + k + D2 + A].$$

The expected returns of financial institutions that provide green financial services and traditional financial services only are denoted by E (gf) and E(tf), respectively. Subsequently, the expressions for expected returns and replication dynamic equation can be formulated as follows:

$$E\ (gf) = z*S2 + x*B1 + x*\theta*K + B - C3 + \theta*A + D3 - \theta*A*x,$$

$$E\ (tf) = B - F2*z,$$

$$F\ (y) = dy/dt = y\ (1-y)\ (z*S2 + x*B1 + *\theta*K*x - C3 + \theta*A + D3 - \theta*A*x + F2*z).$$

The expected returns of government under strict and loose regulations are denoted by E(sr) and E(lr), respectively. Then, expected returns and the replication dynamic equation can be formulated as follows:

$$E\ (sr) = x*W1 - S1*x - S2*y + W2 - W2*x - C - F1*x + F1 + F2 - F2*y,$$

$$E\ (lr) = x*W1 + W2 - D1 - W2*x + D1*x,$$

$$F\ (z) = dz/dt = z\ (1-z)\ (-S1*x - F1*x - D1*x - S2*y + D1 - C + F1 + F2 - F2*y).$$

3.3.2. Analysis of the dominant strategies of the three participants

3.3.2.1. Enterprise strategy selection. According to the stability analysis, the enterprise choosing low-carbon transformation in the stable state requires that its replication dynamic equation F(x) is 0 and its first-order derivative is less than 0, as shown below:

$$F(x) = x(1\text{–}x)\,[z(F1+S1)+yC5+R1\text{–}R2\text{–}C2+k+D2+A] = 0,$$

$$d\,F(x)/dx = (1\text{–}2x)\,[\,(F1+S1)\,z+C5{*}y+R1\text{–}R2\text{–}C2+K+D2+A\,] < 0.$$

Let G(y) be defined as $(F1+S1)z+C5{*}y+R1\text{–}R2\text{–}C2+K+D2+A$. Because G(y) is an incremental function of y, when $y = [R2+C2\text{–}K\text{–}D2\text{–}A\text{–}(F1+S1)\,z\text{–}R1\,]/C5 = y^*$ G(y) equals 0, dF(x)/dx always equals 0, and the determination of a stable strategy for the enterprise becomes indeterminate. Conversely, when $y < y^*$, $x = 1$ represents the evolutionary stable strategy (ESS) point and when $y > y^*$, $x = 0$ signifies the desired evolutionary stable equilibrium strategy and the ESS point. Based on this analysis, Fig. 2 illustrates the phase diagram depicting the evolutionary strategy of enterprises.

According to the above results, an increase in parameters C5, S1, R1, F1, K, D2, and A leads to a higher likelihood of enterprises engaging in a low-carbon transformation. Conversely, an increase in parameters R2 and C2 results in a greater probability of enterprises opting not to pursue a low-carbon transformation. Therefore, the primary inference drawn from this study is as follows:

When there is an increase in green financial services, government subsidies, government fines, carbon market revenue, and positive public feedback, the benefits of green production are enhanced, thereby increasing the likelihood of a low-carbon transformation by enterprises. Conversely, when the benefits of not undergoing low-carbon transformation escalate and the costs associated with low-carbon production rise, the probability of achieving a low-carbon transition diminishes.

3.3.2.2. Financial institution strategy. According to the stability analysis, the probability of financial institutions choosing to provide green services is stable, which requires that the replication dynamic equation F(y) is 0 and its first-order derivative is less than 0, as shown below:

$$F(y) = y(1\text{–}y)\,(z{*}S2+x{*}B1+{*}\theta{*}K{*}x\text{–}C3+\theta{*}A+D3\text{–}\theta{*}A{*}x+F2{*}z) = 0,$$

$$d\,F(y)/dy = (1\text{–}2y)\,[(S2+F2)z+(B1+\theta{*}K\text{–}\theta{*}A)x\text{–}C3+\theta{*}A+D3\,)] < 0.$$

We set $J(z) = (S2 + F2)z + (B1 + \theta{*}K\text{–}\theta{*}A)x - C3 + \theta{*}A + D3)$. Because J(z) is an incremental function of z, when $z = [C3\text{–}\theta{*}A\text{–}D3\text{–}(B1+\theta K\text{–}\theta{*}A)x\,]/(S2+F2) = z^*$, J(z) is 0, dF(y)/dy is always equal to 0, and the stable strategy of the financial institutions cannot be determined. For $z < z^*$ ($z > z^*$), achieving $y = 0$ ($y = 1$) represents the desired evolutionary stable equilibrium strategy. Based on this analysis, Fig. 3 presents a phase diagram depicting the evolutionary strategies of the financial institutions.

Through the calculation of volume, an increase in parameters A, D3, B1, and K is associated with a higher probability of financial institutions offering green services. Conversely, an increase in parameter C3 is associated with a lower probability of financial institutions providing green services. Therefore, the second inference of this study suggests that:

The likelihood of financial institutions offering green financial services is positively correlated with their additional income from conducting green services as well as the costs and revenues related to carbon quota transactions by enterprises. In addition, this likelihood is positively correlated with public feedback on government actions and negatively correlated with the costs incurred by financial institutions for implementing green services.

3.3.2.3. Government strategy. Based on the stability analysis, the probability of the government opting for strict supervision in a stable state requires that its replication dynamic equation F(z) is 0 and its first-order derivative is negative.

$$F(z) = z(1\text{–}z)\,(\text{–}S1{*}x\text{–}F1{*}x\text{–}D1{*}x\text{–}S2{*}y+D1\text{–}C+F1+F2\text{–}F2{*}y) = 0,$$

$$d\,F(z)/dz = (1\text{–}2z)\,[(\text{–}S1\text{–}F1\text{–}D1)x\text{–}(S2+F2)y+D1\text{–}C+F1+F2\,] < 0.$$

We set $H(x) = (—S1 - F1 - D1)x - (S2 + F2)y + D1 - C + F1 + F2$. Because H(x) is a subtraction function of x, when $x = [(\text{–}D1\text{–}F1\text{–}F2 + (S2+F2)y)/(\text{–}S1\text{–}F1\text{–}D1) = x^*$, H(x) is 0, dF(z)/dz. is always equal to 0, and the stable strategy of the government cannot be determined. When $x < x^*$ ($x > x^*$), $z = 1$ ($z = 0$) is the desired evolutionary stable equilibrium strategy. According to the analysis, the phase diagram of the evolutionary strategy of the government is constructed in Fig. 4.

According to the calculation of volume, an increase in parameters D1, F1, and F2 is positively correlated with the probability of the government opting for strict regulations. Conversely, an increase in parameters S2 and C is positively correlated with the likelihood of the government choosing looser regulations. Consequently, the third inference of this study is that:

The probability of strict regulation by the government is positively correlated with public feedback on governmental actions and penalties imposed on noncompliant enterprises and financial institutions involved in environmentally unfriendly practices. In addition, it is negatively correlated with subsidies provided by the government to financial institutions as well as the regulatory costs incurred by them.

Based on these three inferences, if achieving comprehensive low-carbon transformation among enterprises is deemed essential, it is imperative for governments to establish stringent reward–punishment mechanisms, and for financial institutions to offer efficient green financial services facilitating enterprise transformation. Furthermore, individuals must enhance their environmental awareness and actively choose eco-friendly products.

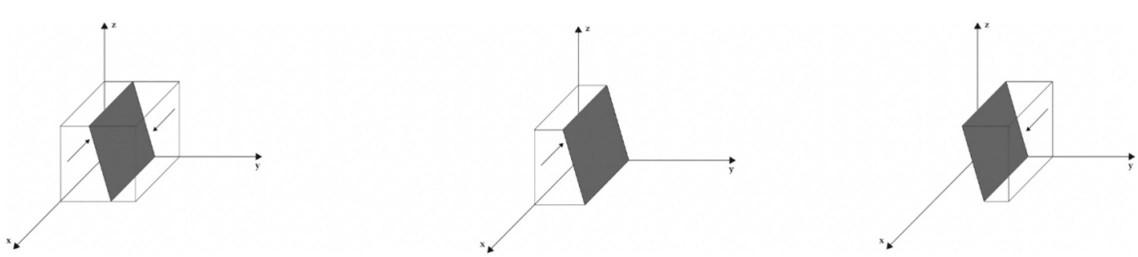

Fig. 2. Phase diagram of enterprise strategy selection.
Notes: The directions of the arrows indicate the strategies chosen by the enterprises, with "1" representing low-carbon transformation and "0" indicating selecting not to pursue a low-carbon transformation. The size of each segment reflects the probability of the strategy selection by enterprises, with larger segments indicating a higher probability.

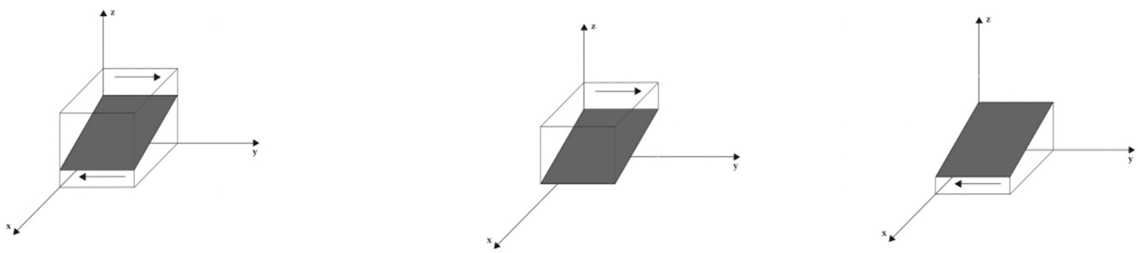

Fig. 3. Phase diagram of the strategic choices of the financial institutions.

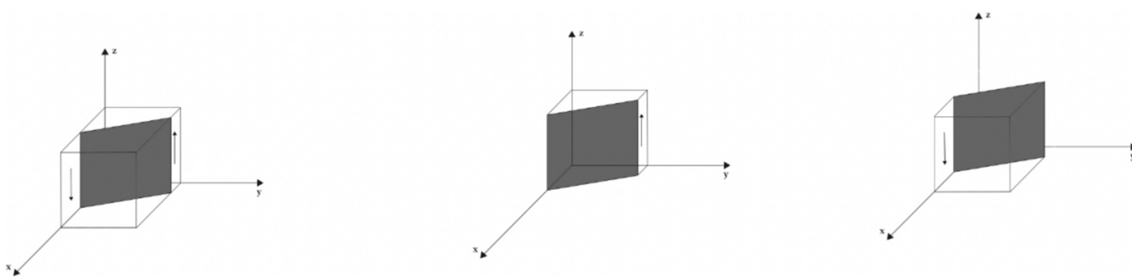

Fig. 4. Phase diagram of the strategic choices of the government.

3.4. Equilibrium point and stability analysis based on enterprise strategy

3.4.1. Strategy equilibrium point

Based on the constructed game theoretical model and the strategy analysis, we employed MATLAB (Matrix Laboratory) to compute the equilibrium points of the three-party evolutionary game. The results calculated for the evolutionary game equilibrium points are summarized in Table 3.

3.4.2. Analysis of equilibrium stability

The multi-agent evolutionary game is characterized by its asymmetry, resulting in the equilibrium of the ESS being a pure strategy equilibrium rather than a hybrid game equilibrium (Zhao, Hao, Yang, et al., 2020). Therefore, building on the literature, this study primarily focuses on investigating the stability of eight pure strategy equilibrium points, as presented above. Following Lyapunov's first law, if all eigenvalues of the Jacobian matrix possess negative real parts, the equilibrium point is considered asymptotically stable; conversely, if at least one eigenvalue has a positive real part, the equilibrium point becomes unstable. In cases where all eigenvalues have negative real parts except for an eigenvalue with a zero real part, the equilibrium point enters a critical state where its stability cannot be determined solely by examining eigenvalue signs. The stability analysis results for these pure strategy equilibria from Table 3 using Lyapunov's first law are summarized in Table 4.

According to the criteria mentioned above, E1 and E5 are possible strategy equilibrium points, and the corresponding equilibrium conditions are as follows: if ① is true, then $A - C2 + D2 + K + R1 - R2 < 0$, $D3 - C3 + \theta A < 0$, and $D1 - C + F1 + F2 < 0$; if ② is true, then $C2 - A - C5 - D2 - K - R1 + R2 < 0$, $C3 - B1 - D3 - \theta K < 0$, and $- C - S1 - S2 < 0$.

If the conditions of ① are met, namely if E1 represents the evolutionary stable equilibrium point, enterprises will opt against undertaking low-carbon transformation, and financial institutions will refrain from providing green services, thereby deviating from the initial intention of achieving dual carbon goals.

The condition under which E1 will not tend toward stability is that at least one of the three equations in ① is greater than 0, which necessitates that (i) the sum of benefits derived by the enterprise from low-carbon transformation, the income generated from selling carbon quotas, and the positive feedback from the public exceed the combined costs of low-carbon transformation and the benefits obtained from abstaining from such transformation; (ii) the feedback received by the government from the public and the fines levied by the government exceed the total regulatory costs it incurs; or (iii) feedback received by financial institutions from the public and benefits gained through their participation in carbon markets outweighs the costs associated with providing green services.

If the conditions of ② are satisfied, namely, if E5 represents the evolutionary stable equilibrium point, then enterprises will opt for implementing low-carbon transformation strategies, and financial institutions will choose to offer green services. This collaborative effort among multiple market entities will facilitate the attainment of the dual carbon objectives.

The stability of E5 is contingent on the three equations in ② being less than 0. In this regard, it is imperative to enhance enterprise returns to facilitate low-carbon transformation, streamline access to green financial services for enterprises, and foster positive public feedback on the enterprises' environmentally friendly practices. In addition, it is essential to increase the costs for enterprises to procure carbon quotas while reducing the expenses incurred during low-carbon transformation endeavors and increasing the potential losses associated with abstaining from such transformations. Simultaneously, efforts should be made to improve the financial institutions' returns from the provision of green financial services and to garner favorable public responses to their actions while minimizing the costs associated with offering these services. Concurrently, the government plays a pivotal role in facilitating the green transformation of enterprises primarily through market-oriented mechanisms such as carbon quota regulations and penalties for non-environmentally friendly practices.

Based on the analysis of equilibrium points E1 and E5, we can derive the fourth inference of this study as follows.

To promote enterprises' adoption of low-carbon transformation, financial institutions' provision of green services, and the government's implementation of loose regulations, it is crucial to enhance the benefits associated with low-carbon transformation for enterprises while reducing the costs incurred by abstaining from such transformation. Similarly, it is essential to increase the advantages for financial institutions engaging in green financial services while minimizing the costs associated with conducting sustainable business practices. Finally, fostering positive feedback from the public in response to the green transformations of both enterprises and financial institutions should be prioritized.

Table 3
Equilibrium points of the evolutionary game.

X-axis	Y-axis	Z-axis
−(D3–C3 + F2 + S2 + θA)/(B1–θA + θK)	− (A − C2 + D2 + F1 + K + R1 − R2 + S1)/C5	1
0	0	0
1	0	0
0	1	0
0	0	1
1	1	0
1	0	1
0	1	1
1	1	1
−(C–D1–F1 + S2)/(D1 + F1 + S1)	1	−(A–C2 + C5 + D2 + K + R1–R2)/(F1 + S1)
/	/	/
(D1–C + F1 + F2)/(D1 + F1 + S1)	0	−(A–C2 + D2 + K + R1–R2)/(F1 + S1)
0	(D1–C + F1 + F2)/(F2 + S2)	−(D3–C3 + θA)/(F2 + S2)
1	−(C–F2 + S1)/(F2 + S2)	–B1–C3 + D3 + K*θ)/(F2 + S2)
−(D3–C3 + θA)/(B1 −θA + θK)	−(A–C2 + D2 + K + R1–R2)/C5	0

Notes: "/" means the formula is too lengthy and not displayed.

Table 4
Stability assessment of equilibrium points in evolutionary game theory.

Equilibrium point	Eigenvalue of matrix	Symbol	Stability	Condition
E1 (0,0,0)	A–C2 + D2 + K + R1–R2	×	ESS	①
	D3–C3 + θA	−		
	D1–C + F1 + F2	−		
E2 (1,0,0)	C2–A–D2–K–R1 + R2	×	Instability point	/
	B1–C3 + D3 + θK	+		
	F2–C–S1	−		
E3 (0,1,0)	A–C2 + C5 + D2 + K + R1–R2	×	Instability point	/
	C3–D3–θA	+		
	D1–C + F1–S2	−		
E4 (0,0,1)	A–C2 + D2 + F1 + K + R1–R2 + S1	×	Instability point	/
	D3–C3 + F2 + S2 + θA	+		
	C–D1–F1–F2	×		
E5 (1,1,0)	C2–A–C5–D2–K–R1 + R2	×	ESS	②
	C3–B1–D3–θK	−		
	–C–S1–S2	−		
E6 (1,0,1)	C2–A–D2–F1–K–R1 + R2–S1	−	Instability point	/
	B1–C3 + D3 + F2 + S2 + θK	+		
	C–F2 + S1	+		
E7 (0,1,1)	A–C2 + C5 + D2 + F1 + K + R1–R2 + S1	+	Instability point	/
	C3–D3–F2–S2–θA	−		
	C–D1–F1 + S2	+		
E8 (1,1,1)	C2–A–C5–D2–F1–K–R1 + R2–S1	−	Instability point	/
	C3–B1–D3–F2–S2–θK	−		
	C + S1 + S2	+		

Note: In the table, − and + are negative and positive signs, respectively, and × indicates that additional constraints are required to determine whether the sign is positive or negative.

4. Numerical simulation

Building on the theoretical analysis presented in the previous section, this section employs MATLAB to conduct numerical simulations on the evolutionary behavior of the three parties within the game theoretical system. Next, we investigate how different parameter variations influence the equilibrium outcomes of the game.

From the successful initiation of China's national emissions trading market on July 16, 2021, until October 2023, a total of 365 million tons of carbon allowances have been traded in the market, with a cumulative transaction value amounting to 19.45 billion yuan. Based on these data, we set the initial value of the carbon price at 50 yuan/ton and the initial value of the carbon quota at 20 ($\times 10^7$ tons). In addition, we assume that parameters A and B have an initial value of 1 ($\times 10^7$ tons). Relevant parameters are defined using carbon emissions (tons) as the fundamental unit. Unless specifically stated otherwise, the unit for the following parameter values is "yuan/ton".

In the current carbon emission market context, the cost (C2) of low-carbon transformation for enterprises is approximately 60 (Fang et al., 2022). The regulatory cost (C) imposed by the government on enterprises and financial institutions is lower than the cost of low-carbon transformation for enterprises, estimated at 55. Government subsidy (S1) for enterprise's low-carbon transformation typically covers a portion of the transformation cost and is set at 15. Enterprises' return without low-carbon transformation stands at 100, while after adopting emission reduction measures, it generally increases by 20 % (Zhou et al., 2023), resulting in a post-reduction return set at 120. Public feedback regarding green production from enterprises (D2) is strong, whereas feedback on government failure to meet regulatory expectations (D1) is relatively weak; thus, these two feedback values are set at 20 and 10 respectively.

The involvement of financial institutions can enhance the efficiency of green financial services, thereby reducing enterprise's green transformation costs as indicated by Campiglio (2016), with an estimated reduction in enterprise transformation costs (C5) following implementation of green business activities being set at 20. Additional income obtained by financial institutions after engaging in green business amounts to 20; meanwhile, subsidies received from the government for conducting green business stand at 15. Positive public feedback garnered through these efforts amounts to D3 = 10. The additional cost incurred by financial institutions to provide green services totals C3 = 30.Furthermore, financial institutions can offer investment and financing services to enterprises within the carbon trading market to generate certain income represented as θ equaling 10 % of carbon market trading volume. Failure on part of both enterprises and financial institutions to engage in green practices may result in corresponding fines levied by the government amounting F1 = 20 and F2 = 30 respectively. Based on initial carbon allowances value and prevailing carbon trading prices, we can set $T = 48$, T1 = 46 and T2 = 44.

4.1. The evolutionarily stable equilibrium point

Finally, the main strategy selection for three-party simulation analysis in MATLAB with these parameter settings is presented below.

Based on the two- and three-dimensional evolution game simulation diagrams presented in Figs. 5 and 6, respectively, it is evident that the three players' decisions are based on maximizing their individual benefits over time based on the operation of the existing parameters. Consequently, regardless of the initial conditions, the simulations converge to an equilibrium point of (1, 1, 0). This finding underscores that enterprises can only achieve sustainable development and maximize their benefits by adopting low-carbon transformation strategies, financial institutions can solely optimize their gains by offering green services, and governments can only achieve benefit maximization by refraining from subsidizing or regulating.

4.2. Effects of main parameters on evolutionary results

4.2.1. Effect of low-carbon transformation costs

The expenses (C2) incurred by enterprises during their adoption of low-carbon transformation significantly impact the success of this transformation. As depicted in Fig. 7, escalating costs tend to discourage enterprises from pursuing green, low-carbon transformations over time. Consequently, it is imperative for governmental bodies and financial institutions to support R&D as well as green innovation initiatives undertaken by enterprises through diverse means, thereby reducing the costs associated with low-carbon transformations and enhancing their overall benefits by assisting in achieving society's overarching carbon reduction objectives.

4.2.2. Effect of carbon trading revenue and cost

The carbon trading market primarily influences the decision-making process of enterprises and other participants by affecting the cost (A) of purchasing carbon quotas and the revenue (K) generated from selling carbon quotas. As depicted in Fig. 8, the dynamic evolution in three dimensions demonstrates that changes in parameter K will drive enterprises and financial institutions to make different decisions. When K equals 30 or 40, enterprises and financial institutions opt to avoid low-carbon transformation and the provision of green services, respectively; however, when K exceeds 50, they choose green low-carbon transformation and offer green financial services. This indicates that although it may be challenging for the government to maximize its own interests through low-carbon subsidies and incentive policies, it can influence the

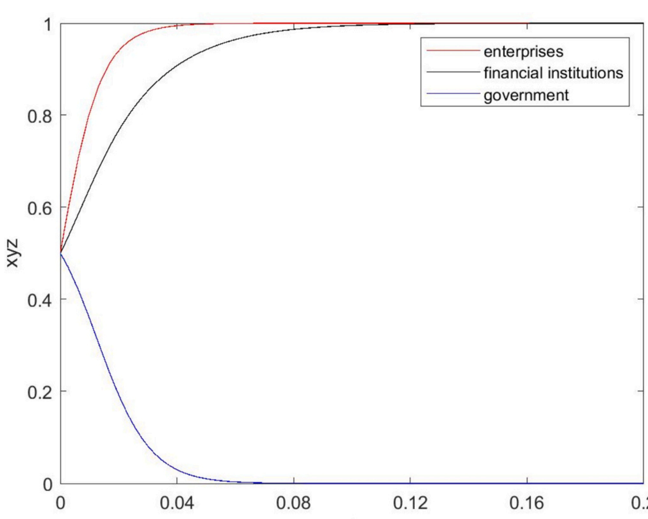

Fig. 5. The two-dimensional evolutionary process of the three key market players.

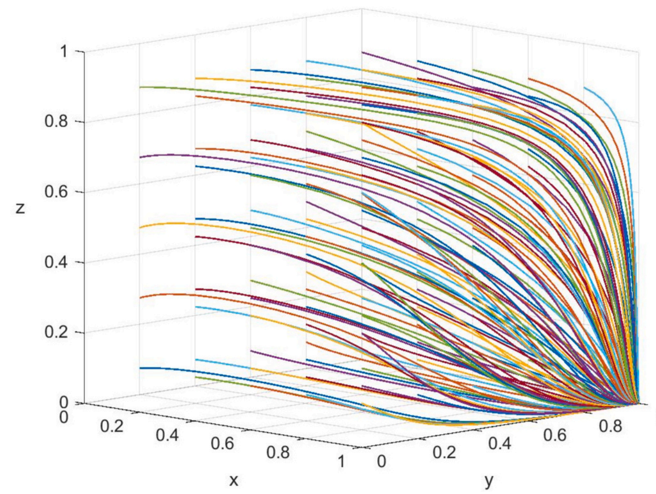

Fig. 6. The three-dimensional evolutionary process of the three key market players.

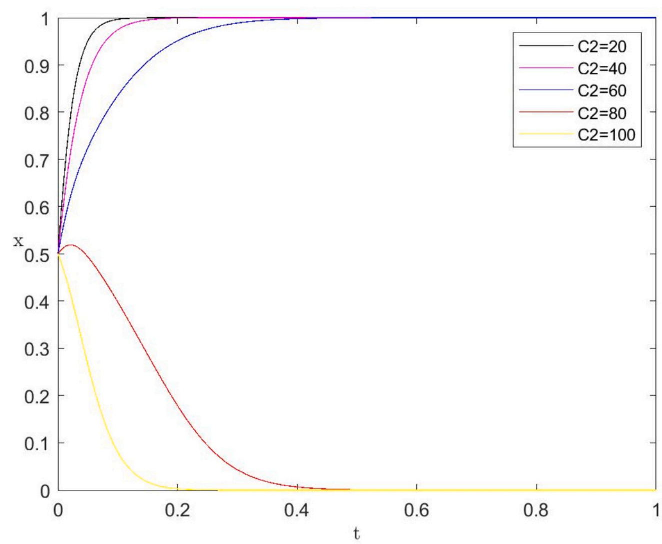

Fig. 7. The simulation diagram depicting the influence of parameter C2 on enterprises' low-carbon transformation decisions.

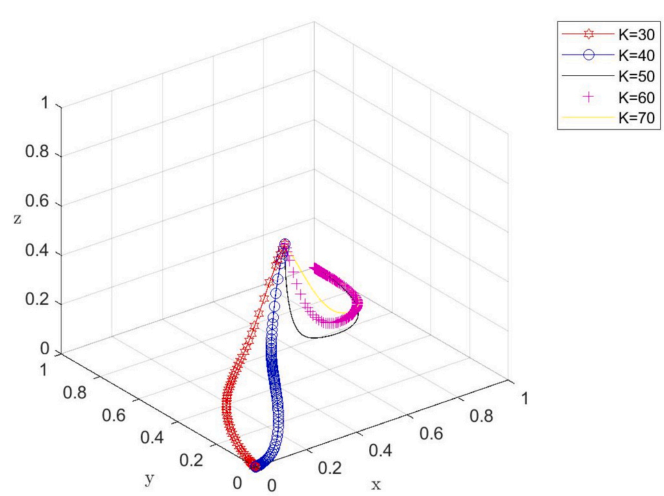

Fig. 8. Effect of variations in parameter K on the decision-making of the three parties.

price of carbon trading by adjusting carbon quotas, thereby promoting low-carbon transformations among enterprises and financial institutions. Fig. 9 reveals that variations in parameter A influence whether enterprises undertake low-carbon transformations. When A exceeds 30, enterprises decide to adopt low-carbon production methods. Moreover, as the value of A increases further, the pace at which enterprises embrace green low-carbon transformations accelerates accordingly—which is consistent with how cost factor A influences enterprises' transition to a low-carbon model. Therefore, gradually reducing carbon quotas would enable governments to enhance the benefits derived from adopting a low-carbon approach as well as increase the costs associated with not pursuing such transformations—with such a strategy aimed at achieving the overall goals of transitioning to a sustainable economy.

4.2.3. Effect of public feedback

With the escalating prominence of environmental issues, there is increasing public concern regarding the environmental performance of enterprises. The influence of public feedback on low-carbon transformation primarily manifests in their evaluation of enterprises' and financial institutions' low-carbon behavior (D2 and D3).[1]

In theory, more positive feedback from the public on enterprises' behaviors that promote low-carbon transformation enhances the likelihood that the enterprises will implement low-carbon production practices. However, the simulation results depicted in Fig. 10 indicate that public feedback on enterprises' low-carbon production does not significantly impact their decision-making process for low-carbon transformation. This could be attributed to the relatively lesser importance placed on public feedback compared with other factors that influence the enterprises' transitions to a low-carbon model. Conversely, the simulation outcomes presented in Fig. 11 demonstrate that public feedback can indeed affect financial institutions' decision-making processes to provide green services. A greater positive response from the public to low-carbon behavior increases the probability of financial institutions offering green financial services. In essence, it can be inferred that public feedback indirectly influences enterprises' adoption of a low-carbon approach. Therefore, it becomes imperative to enhance general awareness among individuals about environmentally friendly practices and encourage active participation in the enterprises' pursuit of a sustainable future with reduced carbon emissions.

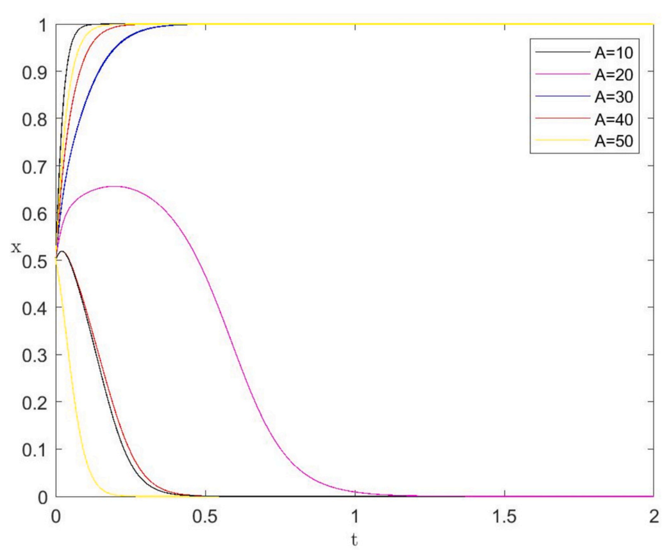

Fig. 9. Effect of variations in parameter A on enterprise decision-making.

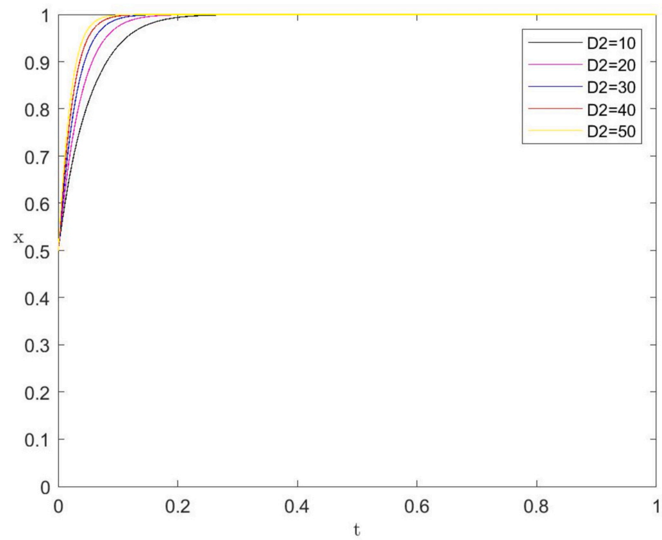

Fig. 10. Effect of changes in parameter D2 on enterprise decisions.

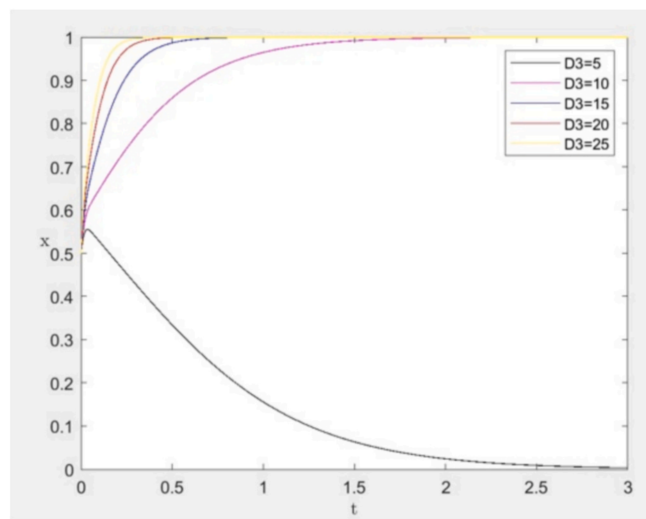

Fig. 11. Effect of changes in parameter D3 on financial institutions' decisions.

5. Conclusions and implications

5.1. Conclusions

As an important strategic goal, carbon emissions' reduction requires collaborative efforts from government, financial institutions, and enterprises. The strategies evolved by all three parties affect whether carbon emissions are reduced, and thus influence the adverse effects of excessive greenhouse gas emissions on the world environment. In this paper, we construct a multi-agent dynamic evolutionary game model, which incorporates government, financial institutions, and enterprises and also considers the influence of consumers. We conduct a simulation using MATLAB to explore the changes in strategies and analyze the influencing factors among all parties involved in the process of reducing carbon emissions.

Our main conclusions are as follows. First, when there is an increase

[1] We examined the impact of public feedback (D1) on government strategy in the context of loose governmental regulations in the absence of low-carbon transition. However, no statistically significant outcomes were observed. Owing to spatial constraints, the depiction and examination of this content have been omitted.

in green financial services, government subsidies, government fines, carbon market revenue, and positive public feedback, the benefits of green production are enhanced, thereby increasing the likelihood of low-carbon transformation by enterprises. Conversely, when the benefits of not undergoing low-carbon transformation escalate and the costs associated with low-carbon production rise, the probability of achieving a low-carbon transition diminishes. Second, the likelihood of financial institutions offering green financial services is positively correlated with their additional income from conducting green services as well as the costs and revenues related to carbon quota transactions by enterprises. In addition, it is positively correlated with public feedback on government actions, and negatively correlated with the costs incurred by financial institutions for implementing green services. Third, the probability of strict regulation by the government exhibits a positive correlation with public feedback on governmental actions and penalties imposed on noncompliant enterprises and financial institutions involved in environmentally unfriendly practices. Furthermore, it displays a negative correlation with subsidies provided by the government to financial institutions as well as regulatory costs incurred by them.

In general, the stable and favorable equilibrium of enterprises opting for low-carbon transition, financial institutions opting to offer green services, and governments adopting loose regulations is the result of mutual influence and trade-offs among market participants. It is crucial to enhance the benefits associated with low-carbon transformation for enterprises while increasing the costs incurred by not undertaking such transformation. Similarly, it is essential to increase the advantages for financial institutions engaging in green financial services while minimizing the costs associated with conducting sustainable business practices. In addition, fostering positive public feedback on the green transformations of both enterprises and financial institutions should be prioritized.

5.2. Policy implications

Therefore, some implications of our results are proposed as follows.

First, the government should effectively utilize policy tools such as carbon quotas and low-carbon subsidies to facilitate the low-carbon transformation of enterprises through a coordinated approach involving both carbon trading markets and administrative measures. Reasonable low-carbon subsidies or high-carbon fines can incentivize high-polluting enterprises to produce more environmentally friendly products in the short term, but, ultimately, clear and well-defined carbon quota setting in combination with a robustly designed carbon trading market are more conducive to promoting long-term enterprise-level decarbonization.

Second, the government should foster a conducive environment for enterprises to enhance their investment in green innovation and optimize the advantages of low-carbon transformation. The reduction of costs associated with a low-carbon transition and the amplification of benefits serve as pivotal catalysts encouraging high-polluting industries to embrace eco-friendly production practices. Hence, it is imperative for governments to incentivize businesses through green innovation subsidies and bolster the efficacy of the green innovation service system. In addition, enhancing intellectual property protection laws and augmenting carbon emission reduction benefits can further fortify the gains derived from a low-carbon transformation.

Moreover, it is imperative to encourage the active participation of financial institutions in the carbon trading market to effectively reduce transaction costs for enterprises. The accessibility of green financial services plays a crucial role in enterprises' low-carbon transformation, and the willingness of financial institutions to provide such services depends on striking a balance between costs and benefits. Therefore, during the initial stages of establishing the carbon trading market, it is essential for the government to subsidize financial institutions engaged in green finance activities, support professional training programs for carbon trading personnel, and facilitate the establishment of specialized carbon financial institutions. These measures will enhance both convenience for enterprises accessing green financial services and their likelihood of successful low-carbon transformation.

It is also crucial to enhance the publicity given to low-carbon goals to bolster public awareness of and positive responses toward low-carbon production. The findings of this study demonstrate that public feedback significantly influences the likelihood of enterprises adopting low-carbon practices and financial institutions offering green services, thereby impacting society's overall transition toward a low-carbon economy. Consequently, the government should actively promote the concept of low-carbon life, improve the public's recognition of low-carbon production, and encourage the public to provide positive feedback on the low-carbon behaviors of all participants, indirectly facilitating the achievement of our goal of a low-carbon transformation.

From the perspective of cooperation between parties in the carbon trading market, it is necessary to establish a collaborative mechanism to facilitate the sharing of information, collectively address challenges encountered during the low-carbon transition process, and form a unified front to drive low-carbon development. All stakeholders are encouraged to engage in joint research and development initiatives, particularly in the realm of low-carbon technologies and clean energy, with the aim of expediting innovation and application in this field. It is important to explore risk-sharing mechanisms such as establishing green funds or guarantee mechanisms to mitigate financial risks for enterprises undergoing the low-carbon transition. A collaborative platform involving governments, businesses, financial institutions, and research organizations, should be created to foster information exchange, resource integration and coordinated action aimed at fully harnessing the incentives associated with carbon pricing. Additionally, an information-sharing mechanism encompassing low-carbon technologies, market dynamics, policy changes etc., should be established to enable stakeholders to stay informed about industry trends and opportunities while enhancing market liquidity for carbon allowances.

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CRediT authorship contribution statement

Wen-Jing Fan: Writing – original draft, Formal analysis, Funding acquisition, Writing – review & editing. **Yao Fang:** Formal analysis, Validation, Software. **Rui-Bo Jiang:** Visualization, Software, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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