Sustainable Futures 10 (2025) 100894

Contents lists available at ScienceDirect

Sustainable Futures

journal homepage: www.sciencedirect.com/journal/sustainable-futures

Green game among government, enterprises, and the public: A study on the dynamics of enterprise green transformation from the perspective of Tripartite evolution

Yanan Zhao, Lili Zhang *, Siyao Li

School of Maritime Economics and Management, Dalian Maritime University, Dalian 116026, PR China

ARTICLE INFO

Keywords:
Green transformation
Evolutionary game
Environmental regulations
Government subsidies

ABSTRACT

This study utilizes a tripartite evolutionary game model to analyze the strategic decisions and their influencing factors among governments, businesses, and the public during the green transformation of enterprises. Our research demonstrates that by modifying environmental regulations and subsidy levels, it is feasible to attain an optimal system equilibrium state, characterized by either stringent or lenient governmental oversight, active public participation, and the green transformation of enterprises. Furthermore, when financial incentives surpass regulatory costs, local governments are inclined to implement more stringent measures. Enterprises are incentivized to adopt environmentally sustainable practices when the economic advantages derived from emission trading and tax savings exceed the costs associated with emission reduction. Public engagement in conservation efforts intensifies when subsidies for participation exceed the related costs, underscoring the significance of effective incentives and an understanding of public attitudes. These findings provide valuable decision-making support for policymakers and corporate leaders, offering practical guidance for advancing corporate green transformation and achieving sustainable development objectives.

1. Introduction

1.1. Background and motivation

In the context of globalization and environmental crises, corporate green transformation has emerged as a critical pathway to achieving sustainable development [1–3]. In light of the severe challenges posed by climate change, finite resources, and increasingly stringent regulatory frameworks, businesses must take proactive measures to mitigate their negative environmental impacts through technological innovation and improvements in management practices. Concurrently, the growing consumer demand for environmentally friendly products is compelling companies to integrate green principles into product design, production processes, and supply chain management [4–6]. Green transformation not only reflects corporate social responsibility but also represents an inevitable choice for enhancing competitiveness and meeting market demands [7,8]. Therefore, researching how businesses can effectively implement green transformation is of paramount importance for promoting harmonious economic, social, and environmental development.

Governments, as the primary facilitators and regulators of green transformation, guide and encourage businesses to achieve green transformation through the formulation of environmental regulations and policy measures. For instance, the Chinese government has strengthened its supervision of high-polluting industries in recent years and vigorously promoted clean energy. Businesses play a pivotal role in green transformation, bearing the brunt of transition costs and risks. At the same time, their green transformation efforts are influenced by government regulations and policies, necessitating decision-making guided by government directives. The public, as a significant participant in green transformation, influences the decisions of businesses and governments through consumer choices and behavioral feedback. The enhancement of environmental awareness among the public and changes in consumer preferences will drive businesses to adjust their production methods and influence government policy formulation.

Nevertheless, the interaction mechanisms among governments, businesses, and the public during the green transformation process remain ambiguous. In the formulation of environmental regulations and policies, governments must take into account the cost-bearing capacity of businesses as well as the level of public acceptance. Concurrently, businesses must weigh costs against benefits, considering both

* Corresponding author.
E-mail addresses: zhao3226870051@163.com (Y. Zhao), lilizhang@dlmu.edu.cn (L. Zhang), lisiyao0726@163.com (S. Li).

https://doi.org/10.1016/j.sftr.2025.100894
Received 22 February 2024; Received in revised form 2 September 2024; Accepted 18 June 2025
Available online 21 June 2025

government regulations and public demand while pursuing green transformation. The public, in turn, must evaluate the effectiveness of government policies and the progress of business transformation when engaging in green initiatives. Therefore, analyzing the strategic choices and interaction mechanisms among governments, businesses, and the public within the context of green transformation carries significant theoretical and practical implications.

1.2. Research questions and major findings

This study aims to delve deeply into the dynamic evolutionary process and influencing factors of strategic choices among governments, enterprises, and the public in corporate green transformation by constructing a tripartite evolutionary game model. Specifically, the research primarily addresses the following questions:

(1) Does an ideal system equilibrium state exist, characterized by stringent or lenient government regulation, public participation, and corporate green transformation? If such a state exists, what are the conditions for its realization?
(2) What effects do environmental regulations(such as emissions trading and environmental taxes) and government subsidies (including subsidies from both central and local governments) have on the strategic choices of the three parties involved?

To address the aforementioned questions, this paper constructs a tripartite evolutionary game model involving local governments, enterprises, and the public. It determines the evolutionary stable points of the system and the conditions for their existence. Furthermore, numerical simulations are employed to analyze the impacts of environmental regulations and government subsidies on the strategic choices of the three main parties. The key findings are as follows:

Firstly, under specific conditions, all eight pure strategy equilibrium points have the potential to become evolutionarily stable points. This implies that by adjusting relevant parameters, the evolutionary system can be guided towards a desirable equilibrium, thereby facilitating the green transformation of enterprises. This provides a directional guideline for policymaking and implementation, enabling stakeholders to better understand and drive the green transformation process. Secondly, when the combined benefits of local government subsidies and emissions trading revenue exceed the cost of emission reduction, enterprises will consistently choose green transformation as their evolutionarily stable strategy. Similarly, when the sum of central government subsidies and environmental tax revenue surpasses the cost of strict regulation, local governments will always opt for strict regulation as their stable strategy. For the public, if their participation subsidies exceed the cost of participation, their evolutionarily stable strategy will always be to engage in green transformation. Thirdly, increasing the price of emissions trading, the environmental tax rate, and local government subsidies can promote green transformation in enterprises. On the other hand, enhancing central government subsidies and the environmental tax rate encourages local governments to adopt strict regulatory measures. Additionally, increasing subsidies for the public can also motivate them to actively participate in green transformation.

1.3. Contribution statements and organization

This study addresses critical issues in the corporate green transformation process by investigating how to effectively motivate the collaborative participation of governments, businesses, and the public through appropriate policy instruments. Our objective is to construct a tripartite evolutionary game model that elucidates the stability conditions and influencing factors governing the strategic choices of all parties under varying environmental policies and subsidy mechanisms. The novelty of this research lies not only in uncovering the stability conditions and influencing factors of strategic choices for the three primary stakeholders across diverse scenarios but also in demonstrating, through numerical simulation, the potential effects of policy parameter adjustments on promoting corporate green transformation and achieving sustainable development goals. This multidimensional analytical approach provides novel insights and decision support for understanding and advancing green transformation, thereby offering more precise and practical guidance for policymakers and corporate decision-makers.

The remaining sections of this paper are organized as follows: Section 2 provides a literature review. Section 3 introduces the tripartite evolutionary game model, including model construction, solution, and analysis. Section 4 analyzes the evolutionary outcomes and presents relevant propositions. Section 5 conducts numerical simulations to analyze the effects of relevant factors on the evolutionary system. Finally, Section 6 concludes the paper.

2. Literature review

The following research areas are closely related to this study. We concisely review them as follows.

2.1. Roles of government, enterprises, and the public in green transformation

In exploring the process of green transformation, the focal point of research has been on the roles played by government, enterprises, and the public, as well as their interrelationships. A careful review and analysis of existing literature reveal the critical functions of these three entities in driving green transformation and the mechanisms of their interactions.

Firstly, the government plays an indispensable leading role in green transformation [9–11]. As the representative of the public interest, the government is responsible for formulating environmental policies, providing financial support, and implementing environmental regulation. Through measures such as setting strict emission standards, promoting the use of renewable energy, and implementing green taxation, the government can guide enterprises and the public toward more environmentally friendly production and consumption patterns. At the same time, the government also bears the important responsibility of overseeing enterprises' compliance with environmental regulations and protecting the environmental rights and interests of the public.

Secondly, enterprises play a dual role as both implementers and beneficiaries in green transformation [12,13]. Facing environmental regulations and market pressures, enterprises need to adopt measures such as technological innovation, process optimization, and product greening to reduce their environmental impact and enhance their competitiveness. Some advanced enterprises have already integrated environmental protection concepts into their core businesses, achieving win-win economic and environmental benefits through the development of environmentally friendly products and improved resource utilization efficiency. However, some enterprises resist green transformation due to short-sighted behavior or cost considerations, which requires joint efforts from the government and all sectors of society to promote change.

Lastly, the public plays multiple roles as consumers, supervisors, and participants in green transformation [14–16]. With increasing environmental awareness, the public is paying more attention to environmental issues and expressing their environmental aspirations through actions such as purchasing environmentally friendly products and participating in environmental activities. This social pressure encourages enterprises to attach greater importance to environmental issues and actively participate in green transformation. At the same time, the public can also promote greater attention to environmental issues from the government and enterprises by supervising corporate behavior and participating in environmental decision-making.

Taken together, the government, enterprises, and the public form an interrelated and interacting relationship in green transformation.

However, existing studies often focus on the analysis of a single entity while neglecting the mechanisms of their interactions. Unlike previous research, this study will place greater emphasis on analyzing the interactive relationships and influencing factors among the government, enterprises, and the public. We will adopt an evolutionary game approach to deeply explore their strategic choices, interaction mechanisms, and influencing factors in the process of green transformation.

2.2. Application of evolutionary game models in green transformation research

In the realm of green transformation research, evolutionary game models serve as a potent analytical tool, extensively employed to delve into the strategic choices and interplay mechanisms among diverse entities such as governments, enterprises, and the public in the context of environmental protection. By combing through and analyzing existing literature, the application of evolutionary game models in green transformation research primarily centers around the following aspects.

Firstly, evolutionary game models are harnessed to dissect the strategic selections and evolutionary trajectories of enterprises throughout the green transformation journey [16–22]. These investigations typically fashion evolutionary game models encompassing diverse strategic options (e.g., environmental investments, technological innovations), simulating the strategic evolution of enterprises to explore the impacts of various factors (such as government policies, market demands, technological innovation) on their green transformation endeavors. These studies are instrumental in unveiling the behavioral patterns of enterprises during the green transition, providing a theoretical foundation for informed policy formulations by governments.

Secondly, evolutionary game models also find application in examining the game-theoretic dynamics between governments and enterprises concerning environmental matters [23–26]. In these frameworks, governments and enterprises emerge as the primary players, analyzing their strategic decisions and mutual influences in shaping and executing environmental policies. These models afford researchers a deeper comprehension of the collaborative and conflicting interactions between governments and enterprises, guiding the crafting of effective environmental policy frameworks.

Moreover, certain studies leverage evolutionary game models to scrutinize the emergence and evolution of public environmental behaviors [27–30]. These models account for the diverse perspectives and behavioral preferences of the public vis-à-vis environmental issues, simulating their strategic evolution to identify avenues for fostering positive environmental actions. Such investigations hold significant importance in bolstering public environmental consciousness and catalyzing green transformations.

Distinguishing our research from existing endeavors, we aspire to construct a more holistic and nuanced evolutionary game model that accurately portrays the strategic choices and interaction mechanisms of various stakeholders throughout the green transformation process. Concurrently, we emphasize the integration of model outcomes with pragmatic policy development, aiming to deliver more targeted and actionable policy recommendations for facilitating green transformations.

2.3. Impact of environmental regulation and government subsidies on green transformation

During the process of green transformation, environmental regulation, and government subsidies emerge as two crucial external factors that significantly influence the pathway and outcomes of green transitions for both enterprises and society at large. From the perspective of environmental regulation [31], existing research generally concurs that stringent environmental policies can propel enterprises towards adopting more environmentally friendly production methods and technological innovations, thereby mitigating environmental pollution and resource wastage [32–36]. By establishing emission standards and imposing pollution taxes, environmental regulations raise the cost of non-compliance, thus encouraging a shift towards green production. Simultaneously, these regulations steer consumers towards more environmentally friendly products and services, further promoting market greening. However, some studies caution that excessively strict environmental regulations might increase production costs, undermining the competitiveness of enterprises and potentially hindering green transformation efforts [37–39].

On the other hand, government subsidies constitute a pivotal tool in facilitating green transformation [40–43]. Through financial subsidies, tax incentives, and other means, governments incentivize enterprises to invest in green technologies and environmental projects [44]. Such subsidies lower the costs and risks associated with green transitions, enhancing the willingness and effectiveness of enterprises to pursue green transformation. Additionally, government subsidies catalyze the development and dissemination of green technologies, accelerating the green transformation process across society. Nevertheless, the implementation of government subsidies necessitates careful consideration of recipient selection, subsidy amount determination, and effectiveness evaluation to ensure the efficient utilization of subsidy funds and the smooth progression of green transformation [45–47].

In synthesis, while existing research tends to focus on analyzing the impact of individual factors, it often overlooks the interplay between environmental regulation and government subsidies, as well as their connections with other factors. In contrast, this study aims to comprehensively consider various forms of environmental regulations and subsidies, delving deeper into the specific mechanisms and effects of these factors on green transformation. To highlight the literature positioning and research gaps, we summarize the critical difference between our work and the aforementioned closely related studies in Fig. 1.

3. The model

In the context of green transformation, there exist complex behavioral interactions and logical relationships among the government, enterprises, and the public [48,49]. Firstly, as the leader and regulator, the government guides and promotes the green transformation of enterprises through the formulation of environmental regulations and policy measures [50,51]. The government's behavior is influenced by factors such as the strictness of its regulations, the environmental tax rates imposed, and transfer payments to local governments. The level of government regulation and tax rates directly affect the costs and benefits of enterprises, thereby influencing their decision to adopt green transformation. Additionally, the government can also incentivize and facilitate green transformation through cost subsidies for enterprises and encouragement subsidies for the public.

Secondly, enterprises, as the main actors in green transformation, are influenced by various factors [12,13]. The decision of whether to pursue green transformation is often driven by considerations of costs and benefits. Green transformation entails higher costs for enterprises, but it also brings additional revenue and competitive advantages. Business decisions are also influenced by the government's regulatory efforts, cost subsidies, and vertical transfer payments. Furthermore, enterprises are influenced by public attention and demands, as public concern and support for environmental issues can drive enterprises to adopt green transformation.

Lastly, the public, as an important influencing factor in business green transformation, has an impact on both enterprises and the government [52,53]. Public participation and support can drive enterprises to adopt green transformation through their attention to environmental issues and demands for environmentally friendly products. Public participation can also push enterprises to intensify their green transformation efforts by reporting environmental violations. Additionally, the government and enterprises can encourage public participation through subsidies and rewards.

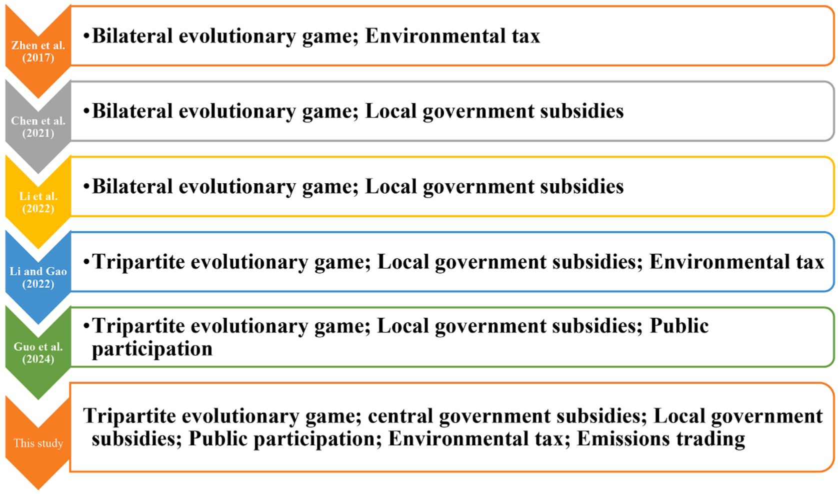

Fig. 1. The critical difference between our work and the closely related studies.

In summary, there are mutual influences and interactions among the government, enterprises, and the public in terms of their behaviors. Government regulations and policy measures directly affect business decisions regarding green transformation, while business decisions are influenced by the government's regulatory efforts and subsidy policies, as well as public attention and demands. Public participation and support can influence the behaviors of enterprises and the government, thereby promoting the implementation of green transformation. The logical relationships among the various actors are depicted in Fig. 2.

There are multiple reasons why evolutionary game models are used to study the strategic choices and interaction mechanisms among the government, enterprises, and the public in the context of green transformation. Firstly, green transformation involves multiple stakeholders, and their decisions and behaviors are often dynamically evolving. Evolutionary game models can capture the strategy evolution and outcomes of all parties in the process of continuous learning and adaptation. Secondly, evolutionary game theory can consider long-term interests and sustainable development factors. The decisions and behaviors involved in green transformation have long-term impacts on the economy and the environment. Evolutionary game models can better analyze the strategic choices of all parties under long-term interest considerations. Lastly, evolutionary game models help understand and explain real-world behavioral phenomena. Through model construction and analysis, we can uncover the reasons for the interactions and strategic choices among the government, enterprises, and the public, as well as their impacts on green transformation. The research framework of this study is illustrated in Fig. 3.

In conclusion, evolutionary game models provide a powerful tool for in-depth research on the strategic choices and interaction mechanisms among various parties in green transformation. They offer theoretical guidance and policy recommendations for achieving sustainable development.

3.1. Model assumptions and symbol explanation

This paper makes the following assumptions under the setting of bounded rationality for the government, enterprises, and the public.

Assumption 1. The local government provides free emission allowances e to the enterprises within its jurisdiction. The emissions of the enterprise before and after green transformation are Q_1 and Q_2, respectively, with $Q_2 < e < Q_1$. When the emissions of the enterprise exceed the allocated allowances, it needs to purchase additional allowances from the emission trading market at a unit price p determined by the market. Therefore, the enterprise needs to pay $p(Q_1 - e)$ before the green transformation and gains additional profits of $p(e - Q_2)$ after the transformation. The emission reduction achieved by the green transformation is $\Delta e = Q_1 - Q_2$, and the environmental benefits obtained by the public from emission reduction are $B = a\Delta e$, where a represents the emission reduction efficiency ([17]b; Raymond, 2016).

Assumption 2. The enterprise incurs a lower cost C_1 if it does not undergo green transformation, while a higher cost $C_2\left(C_2 = C_1 + \varphi\Delta e^2\right)$ is required for the green transformation, where φ represents the coefficient of emission reduction affecting the cost of green transformation. The local government provides a certain cost subsidy $T = b\varphi\Delta e^2$ to the enterprises that choose to undergo green transformation, where b is the cost subsidy coefficient. If the enterprise chooses not to undergo green transformation, it will not be eligible to receive the cost subsidy provided by the local government.

Assumption 3. The environmental tax rate is θ. When the local government chooses strict regulation (loose regulation), the regulatory cost and the collected environmental tax are denoted as C and θQ_i (δC and $\delta\theta Q_i$), respectively, where $i \in \{1, 2\}$. Here, $\delta(0 < \delta < 1)$ represents the degree of regulatory stringency by the local government. A smaller δ indicates looser regulation, which is manifested in the decrease in the

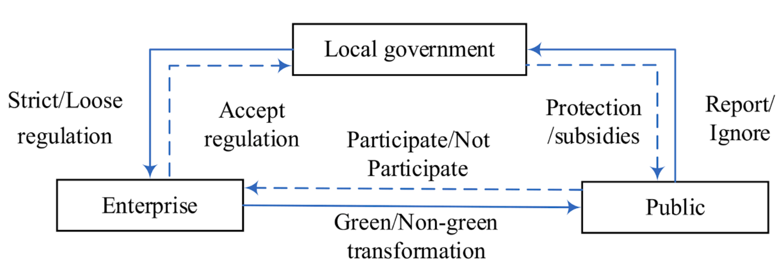

Fig. 2. Logic relationship diagram of tripartite evolutionary game.

Fig. 3. The research framework of this study.

supervision cost and the environmental tax rate imposed by the local government [54]. The central government's vertical transfer payments to the local government mainly depend on the local government's pollution control performance and pollution control funding. The more funding the local government invests in pollution control within its jurisdiction, and the better the emission reduction effect within a certain range, the larger the amount of vertical transfer payments from the central government to the local government. ϵC and $\epsilon\delta C$ represent the vertical transfer payments from the central government to the local government before and after the green transformation, respectively.

Assumption 4. The public can choose whether to participate in the green transformation of enterprises. Public participation is reflected from two perspectives: public attention and public reporting [55]. Public attention refers to the expression of their environmental demands by the public through their concern about environmental pollution issues. It reflects an increase in public environmental awareness and can promote product sales, thereby exerting long-term invisible guidance on corporate green innovation [56]. Public reporting refers to the public reporting of environmental violations by enterprises, which in turn forces enterprises to undergo green transformation. It is assumed that when the public participates in the green transformation of enterprises, they incur participation costs M, and the local government provides subsidies N for public participation. In addition, public participation enables the enterprise to obtain additional benefits F. If the public does not participate, they will not incur participation costs, and the green transformation of the enterprise will not yield additional benefits.

Assumption 5. The probability of the local government choosing strict regulation is denoted as $x(0 \le x \le 1)$, and the probability of choosing loose regulation is $1 - x$. The probability of an enterprise choosing green transformation is denoted as $y(0 \le y \le 1)$, and the probability of not choosing green transformation is $1 - y$. The probability of public participation is denoted as $z(0 \le z \le 1)$, and the probability of the public not participating is $1 - z$. Both x, y and z are functions of time t.

The symbols used in this paper are explained as shown in Table 1.

3.2. Payoff matrix for the game

Based on the assumptions mentioned above, we obtain the payoff matrix for the tripartite evolutionary game between the government, enterprises, and the public, as shown in Table 2.

Table 1
Symbol explanation.

Symbol	Explanation
e	The amount of emissions allocated for free by the local government to enterprises in its jurisdiction.
Q_1 and Q_2	The amount of emissions before and after the green transformation of the enterprise.
p	The price of emissions trading per unit.
Δe	$\Delta e = Q_1 - Q_2$, the emission reduction achieved through the green transformation of the enterprise.
B	$B = a\Delta e$, the environmental benefits obtained by the public through emission reduction, where a is the emission reduction efficiency.
C	The cost of strict supervision by the local government.
C_1 and C_2	The cost before and after the green transformation of the enterprise, where $C_2 = C_1 + \varphi\Delta e^2$, and φ is the coefficient that affects the cost of emission reduction.
T	$T = b\varphi\Delta e^2$, the cost subsidy provided by the local government to green transformation enterprises, where b is the cost subsidy coefficient.
θ	The environmental tax rate.
δ	The degree of supervision by the local government.
ϵ	The coefficient of central government subsidies.
M	The cost borne by the public for participating in green innovation by enterprises.
F	The additional benefits obtained by the enterprise through public participation in green transformation.
N	The subsidy provided by the local government to the public when they participate.
x, y, z	The probabilities of strict government supervision, enterprise green transformation, and public participation, respectively.

3.3. The equilibrium points of evolutionary games

Based on the above game payoff matrix, the expected payoff and average expected payoff under strict regulation and loose regulation for the government are as follows.

$$\begin{aligned} U_x^1 &= yz(\theta Q_2 + \epsilon C - C - T) + y(1-z)(\theta Q_2 + \epsilon C - C - T) \\ &\quad + (1-y)z(\theta Q_1 + \epsilon C - C) + (1-y)(1-z)(\theta Q_1 + \epsilon C - C) \\ &= -Ty + C(-1+\epsilon) + (\theta - y\theta)Q_1 + y\theta Q_2 \end{aligned} \quad (1)$$

Table 2
Payoff matrix for the tripartite evolutionary game.

		Enterprise	Public	
			Participation z	Non-participation $1-z$
Local government	Strict regulation x	Green transformation y	$\theta Q_2+\epsilon C-C-T$ $T+p(e-Q_2)+F-C_2-\theta Q_2$ $B+N-M$	$\theta Q_2+\epsilon C-C-T$ $T+p(e-Q_2)-C_2-\theta Q_2$ B
		Non-green transformation $1-y$	$\theta Q_1+\epsilon C-C$ $p(e-Q_1)-C_1-\theta Q_1$ $N-M$	$\theta Q_1+\epsilon C-C$ $p(e-Q_1)-C_1-\theta Q_1$ 0
	Loose regulation $1-x$	Green transformation y	$\delta\theta Q_2+\delta\epsilon C-\delta C-T$ $T+p(e-Q_2)+F-C_2-\delta\theta Q_2$ $B+N-M$	$\delta\theta Q_2+\delta\epsilon C-\delta C-T$ $T+p(e-Q_2)-C_2-\delta\theta Q_2$ B
		Non-green transformation $1-y$	$\delta\theta Q_1+\delta\epsilon C-\delta C$ $p(e-Q_1)-C_1-\delta\theta Q_1$ $N-M$	$\delta\theta Q_1+\delta\epsilon C-\delta C$ $p(e-Q_1)-C_1-\delta\theta Q_1$ 0

$$\begin{aligned}U_x^2 &= yz(-T-C\delta+C\delta\epsilon+\delta\theta Q_2)+y(1-z)(-T-C\delta+C\delta\epsilon+\delta\theta Q_2)\\&\quad+(1-y)(1-z)(-C\delta+C\delta\epsilon+\delta\theta Q_1)+(1-y)z(\\&\quad-C\delta+C\delta\epsilon+\delta\theta Q_1)\\&=-Ty+C\delta(-1+\epsilon)-(-1+y)\delta\theta Q_1+y\delta\theta Q_2\end{aligned} \tag{2}$$

$$\begin{aligned}U_x &= xU_x^1+(1-x)U_x^2\\&=-Ty-C(x(-1+\delta)-\delta)(-1+\epsilon)\\&\quad+(x(-1+\delta)-\delta)\theta((-1+y)Q_1-yQ_2)\end{aligned} \tag{3}$$

The dynamic replicator equation for the local government is as follows.

$$\begin{aligned}F_1 &= \frac{dx}{dt}=x\left(U_x^1-U_x\right)\\&=(-1+x)x(-1+\delta)(C(-1+\epsilon)+(\theta-y\theta)Q_1+y\theta Q_2)\end{aligned} \tag{4}$$

The expected payoff and average expected payoff for green transformation and non-green transformation of the enterprise are as follows.

$$\begin{aligned}U_y^1 &= x(1-z)\left(-C_1+p(e-Q_2)+\varphi(Q_1-Q_2)^2-\theta Q_2\right)\\&\quad+xz\left(F-C_1+p(e-Q_2)+\varphi(Q_1-Q_2)^2-\theta Q_2\right)+(1-x)(1-z)\big(\\&\quad-C_1+p(e-Q_2)+\varphi(Q_1-Q_2)^2-\delta\theta Q_2\big)\\&\quad+(1-x)z\left(F-C_1+p(e-Q_2)+\varphi(Q_1-Q_2)^2-\delta\theta Q_2\right)\\&=ep+T+Fz-C_2-(p+(x+\delta-x\delta)\theta)Q_2\end{aligned} \tag{5}$$

$$\begin{aligned}U_y^2 &= x(1-z)(-C_1+p(e-Q_1)-\theta Q_1)+xz(-C_1+p(e-Q_1)-\theta Q_1)\\&\quad+(1-x)(1-z)(-C_1+p(e-Q_1)-\delta\theta Q_1)+(1-x)z(\\&\quad-C_1+p(e-Q_1)-\delta\theta Q_1)\\&=ep-C_1-(p+(x+\delta-x\delta)\theta)Q_1\end{aligned} \tag{6}$$

$$\begin{aligned}U_y &= yU_y^1+(1-y)U_y^2\\&=ep+Ty+Fyz+(-1+y)C_1-yC_2\\&\quad+(p+(x+\delta-x\delta)\theta)((-1+y)Q_1-yQ_2)\end{aligned} \tag{7}$$

The dynamic replicator equation for the enterprise is as follows.

$$\begin{aligned}F_2 &= \frac{dy}{dt}=y\left(U_y^1-U_y\right)\\&=-((-1+y)y(T+Fz+C_1-C_2+(p+(x+\delta-x\delta)\theta)(Q_1-Q_2)))\end{aligned} \tag{8}$$

The expected payoff and average expected payoff for the public's participation and non-participation are as follows.

$$\begin{aligned}U_z^1 &= (-M+N)(1-x)(1-y)+(-M+N)x(1-y)+(B-M+N)(1-x)y\\&\quad+(B-M+N)xy\\&=-M+N+By\end{aligned} \tag{9}$$

$$U_z^2=B(1-x)y+Bxy=By \tag{10}$$

$$U_z=zU_z^1+(1-z)U_z^2=By+(-M+N)z \tag{11}$$

The dynamic replicator equation for the public is as follows.

$$F_3=\frac{dz}{dt}=z\left(U_z^1-U_z\right)=(M-N)(-1+z)z \tag{12}$$

Let

$$\begin{cases}F_1=(-1+x)x(-1+\delta)(C(-1+\epsilon)+(\theta-y\theta)Q_1+y\theta Q_2)=0\\F_2=-((-1+y)y(T+Fz+C_1-C_2+(p+(x+\delta-x\delta)\theta)(Q_1-Q_2)))=0,\\F_3=(M-N)(-1+z)z=0\end{cases}$$

The equilibrium point of evolutionary game can be obtained by solving the equations simultaneously, and is shown in Table 3.

Table 3
Equilibrium points of the tripartite evolutionary game.

Equilibrium Point	x	y	z
E_1	$\frac{p+\delta\theta+(-1+b)\varphi(Q_1-Q_2)}{\theta-\delta\theta}$	$-\frac{C-C\epsilon-\theta Q_1}{\theta(Q_1-Q_2)}$	0
E_2	0	0	0
E_3	1	0	0
E_4	0	1	0
E_5	1	1	0
E_6	$\frac{F+(p+\delta\theta+(-1+b)\varphi(Q_1-Q_2))(Q_1-Q_2)}{(-1+\delta)\theta(Q_1-Q_2)}$	$-\frac{C-C\epsilon-\theta Q_1}{\theta(Q_1-Q_2)}$	1
E_7	0	0	1
E_8	1	0	1
E_9	0	1	1
E_{10}	1	1	1

3.4. Stability analysis of equilibrium points

According to the methods proposed by Friedman [57] and Lyapunov [58], the stability conditions of equilibrium points in evolutionary games can be determined using the Jacobian matrix. The Jacobian matrix of the evolutionary system is as follows:

$$J=\begin{bmatrix}\frac{dF_1}{dx} & \frac{dF_1}{dy} & \frac{dF_1}{dz}\\ \frac{dF_2}{dx} & \frac{dF_2}{dy} & \frac{dF_2}{dz}\\ \frac{dF_3}{dx} & \frac{dF_3}{dy} & \frac{dF_3}{dz}\end{bmatrix}=$$

$$\begin{bmatrix}(-1+2x)(-1+\delta)(C(-1+\epsilon)+(\theta-y\theta)Q_1+y\theta Q_2) & (-1+x)x(-1+\delta)\theta(-Q_1+Q_2) & 0\\ -((-1+y)y(1-\delta)\theta(Q_1-Q_2)) & (1-2y)(Fz+(p+(x+\delta-x\delta)\theta+(-1+b)\varphi(Q_1-Q_2))(Q_1-Q_2)) & -F(-1+y)y\\ 0 & 0 & (M-N)(-1+2z)\end{bmatrix}$$

If the eigenvalues of Jacobian matrix corresponding to the equilibrium point are all negative, then this equilibrium point is the stable point of evolutionary game. From this, the stability conditions of each equilibrium point can be judged, as shown in Table 4 **(See page 41)**.

4. Evolutionary results analysis

Based on the above analysis, the following proposition is obtained.

Proposition 1. *When $M > N$ and $C\epsilon + \theta Q_1 < C$, if $\Delta e(p+\delta\theta) + (-1+b)\varphi\Delta e^2 < 0$, then E_2 is a stable point, meaning that the strategy combination {loose regulation, non-green transformation, non-participation} is the evolutionarily stable strategy for the system. Otherwise, if $\Delta e(p+\delta\theta) + (-1+b)\varphi\Delta e^2 > 0$, then E_4 is a stable point, meaning that the strategy combination {loose regulation, green transformation, non-participation} is the evolutionarily stable strategy for the system.*

Proposition 1 states that when the public participation subsidy is less than the participation cost, and the sum of central government subsidies and local government environmental taxes is less than the strict regulation cost of the local government, the relationship between the emission trading profit and the saved environmental taxes and the cost of emission reduction will determine the evolutionarily stable strategy for the system. Specifically, if it is less than the cost of emission reduction, then the strategy combination {loose regulation, non-green transformation, non-participation} will become the evolutionarily stable strategy for the system. This means that the enterprise chooses not to undergo green transformation, operates under loose regulation, and the public does not participate in green transformation. In this case, the enterprise may consider the cost of emission reduction to be high and unable to obtain sufficient economic benefits from green transformation, thus choosing to continue using traditional, higher-emission production technologies. This may reflect the economic evaluation made by the enterprise regarding the cost of emission reduction and environmental pressure.

Additionally, if it is greater than the cost of emission reduction, then the strategy combination {loose regulation, green transformation, non-participation} will become the evolutionarily stable strategy for the system. This means that the enterprise chooses to undergo green transformation, operates under loose regulation, and the public does not participate in green transformation. In this case, the enterprise may consider the cost of emission reduction to be relatively low, and through green transformation, it can achieve higher economic benefits, while the environmental regulations under loose regulation can reduce its operating costs.

Table 4
Stable conditions for equilibrium points in the tripartite evolutionary game.

Equilibrium point	Eigenvalues of jacobian matrix at equilibrium point	Stability Condition
E_1	$\left\{-M+N,-\frac{\sqrt{C^2p^2\theta^2Q_1^4+2C^2p^2\delta\theta^2Q_1^4-C^2p^2\delta^2\theta^2Q_1^4+2b\delta^2\theta^4\varphi^2Q_1Q_2^7-b^2\delta^2\theta^4\varphi^2Q_1Q_2^7}}{(-1+\delta)\theta^2(Q_1-Q_2)^2},\frac{\sqrt{C^2p^2\theta^2Q_1^4+2C^2p^2\delta\theta^2Q_1^4-C^2p^2\delta^2\theta^2Q_1^4+2b\delta^2\theta^4\varphi^2Q_1Q_2^7-b^2\delta^2\theta^4\varphi^2Q_1Q_2^7}}{(-1+\delta)\theta^2(Q_1-Q_2)^2}\right\}$	Unstable point
E_2	$\{-M+N,-((-1+\delta)(-C+C\epsilon+\theta Q_1),\ p+\delta\theta+(-1+b)\varphi(Q_1-Q_2))(Q_1-Q_2)\}$	$M > NC\epsilon + \theta Q_1 < Cand\ \Delta e(p+\delta\theta)+(-1+b)\varphi\Delta e^2 < 0$
E_3	$\{-M+N,(-1+\delta)(-C+C\epsilon+\theta Q_1,\ p+\theta+(-1+b)\varphi(Q_1-Q_2))(Q_1-Q_2)\}$	$M > Nand\ C\epsilon+\theta Q_1 > Cand\ \Delta e(p+\theta)+(-1+b)\varphi\Delta e^2 < 0$
E_4	$\{-M+N,-((-1+\delta)(-C+C\epsilon+\theta Q_2)),-((p+\delta\theta+(-1+b)\varphi(Q_1-Q_2))(Q_1-Q_2))\}$	$M > Nand\ C\epsilon+\theta Q_2\langle Cand\ \Delta e(p+\delta\theta)+(-1+b)\varphi\Delta e^2\rangle 0$
E_5	$\{-M+N,(-1+\delta)(-C+C\epsilon+\theta Q_2),-((p+\theta+(-1+b)\varphi(Q_1-Q_2))(Q_1-Q_2))\}$	$M > Nand\ C\epsilon+\theta Q_2 > Cand\ \Delta e(p+\theta)+(-1+b)\varphi\Delta e^2 > 0$
E_6	$\left\{M-N,\frac{\sqrt{C^2F^2\theta^2Q_1^2+2C^2F^2\delta\theta^2Q_1^2-C^2F^2\delta^2\theta^2Q_1^2+2b\delta^2\theta^4\varphi^2Q_1Q_2^7-b^2\delta^2\theta^4\varphi^2Q_1Q_2^7}}{(-1+\delta)\theta^2(Q_1-Q_2)^2},-\frac{\sqrt{C^2F^2\theta^2Q_1^2+2C^2F^2\delta\theta^2Q_1^2-C^2F^2\delta^2\theta^2Q_1^2+2b\delta^2\theta^4\varphi^2Q_1Q_2^7-b^2\delta^2\theta^4\varphi^2Q_1Q_2^7}}{(-1+\delta)\theta^2(Q_1-Q_2)^2}\right\}$	Unstable point
E_7	$\{M-N,-((-1+\delta)(-C+C\epsilon+\theta Q_1)),F+(p+\delta\theta+(-1+b)\varphi(Q_1-Q_2))(Q_1-Q_2)\}$	$M < Nand\ C\epsilon+\theta Q_1 < Cand\ F+\Delta e(p+\delta\theta)+(-1+b)\varphi\Delta e^2 < 0$
E_8	$\{M-N,(-1+\delta)(-C+C\epsilon+\theta Q_1),F+(p+\theta+(-1+b)\varphi(Q_1-Q_2))(Q_1-Q_2)\}$	$M < Nand\ C\epsilon+\theta Q_1 > Cand\ F+\Delta e(p+\theta)+(-1+b)\varphi\Delta e^2 < 0$
E_9	$\{M-N,-((-1+\delta)(-C+C\epsilon+\theta Q_2)),-F-(p+\delta\theta+(-1+b)\varphi(Q_1-Q_2))(Q_1-Q_2)\}$	$M < Nand\ C\epsilon+\theta Q_2\langle Cand\ F+\Delta e(p+\delta\theta)+(-1+b)\varphi\Delta e^2\rangle 0$
E_{10}	$\{M-N,(-1+\delta)(-C+C\epsilon+\theta Q_2),-F-(p+\theta+(-1+b)\varphi(Q_1-Q_2))(Q_1-Q_2)\}$	$M < Nand\ C\epsilon+\theta Q_2 > Cand\ F+\Delta e(p+\theta)+(-1+b)\varphi\Delta e^2 > 0$

Proposition 2. *when $M > N$and $C\epsilon + \theta Q_2 > C$, if $\Delta e(p+\theta) + (-1+b)\varphi\Delta e^2 < 0$, then $E_3$is a stable point, meaning that the strategy combination {strict regulation, non-green transformation, non-participation} is the evolutionarily stable strategy for the system. Otherwise, if $\Delta e(p+\theta) + (-1+b)\varphi\Delta e^2 > 0$, then E_5 is a stable point, meaning that the strategy combination {strict regulation, green transformation, non-participation} is the evolutionarily stable strategy for the system.*

Proposition 2 states that when the public participation subsidy is less than the participation cost, and the sum of central government subsidies and local government environmental taxes is greater than the cost of strict regulation, the relationship between the emission trading profits and the saved environmental taxes and the emission reduction cost will still determine the evolutionarily stable strategy for the system. Specifically, if it is less than the emission reduction cost, then the strategy combination {strict regulation, non-green transformation, non-participation} is the evolutionarily stable strategy for the system. This means that enterprises choose to operate under strict regulation without undergoing green transformation, and the public chooses not to participate in related activities. In this case, enterprises may consider the emission reduction cost to be high and lack economic incentives, making it more economically reasonable for them to not undergo green transformation.

On the contrary, if it is greater than the emission reduction cost, then the strategy combination {strict regulation, green transformation, non-participation} is the evolutionarily stable strategy for the system. This means that enterprises choose to undergo green transformation under strict regulation, and the public chooses not to participate. In this case, enterprises may believe that green transformation can yield higher economic benefits and that stricter regulatory measures can better control the market.

Proposition 3. *States that when$M < N$ and $C\epsilon + \theta Q_1 < C$,if $F + \Delta e(p+\delta\theta) + (-1+b)\varphi\Delta e^2 < 0$ then$E_7$is a stable point, meaning that the strategy combination {loose regulation, non-green transformation, participation} is the evolutionarily stable strategy for the system. Otherwise, if$F + \Delta e(p+\delta\theta) + (-1+b)\varphi\Delta e^2 > 0$, then E_9 is a stable point, meaning that the strategy combination {loose regulation, green transformation, participation} is the evolutionarily stable strategy for the system.*

Proposition 3 states that in the case where public participation subsidies exceed participation costs, and the sum of central government subsidies and local government environmental taxes is less than the cost of strict regulation, the relationship between the additional benefits brought to the enterprise by public participation, emissions trading profits, savings in environmental taxes, and the cost of emission reduction will determine the system's evolutionarily stable strategy. Specifically, if the sum is less than the cost of emission reduction, the strategy combination {loose regulation, non-green transformation, participation} becomes the evolutionarily stable strategy. In this case, the enterprise chooses to continue using traditional high-emission production techniques under loose regulation, while the public chooses to participate in related activities. The enterprise may perceive the cost of emission reduction as high and unable to offset the gap through additional benefits, emissions trading, and savings in environmental taxes. Therefore, it continues to use traditional, higher-emission technologies. On the other hand, if the sum is greater than the cost of emission reduction, the strategy combination {loose regulation, green transformation, participation} becomes the evolutionarily stable strategy. This means that the enterprise chooses to undergo green transformation to achieve higher economic benefits at a lower cost of emission reduction, and operates in a loose regulation environment. At the same time, the public also chooses to participate in green transformation activities.

Proposition 4. *When $M < N$ and $C\epsilon + \theta Q_2 > C$, if $F + \Delta e(p+\theta) + (-1+b)\varphi\Delta e^2 < 0$, then E_8 is a stable point, meaning that the strategy combination {strict regulation, non-green transformation, participation} is the system's evolutionarily stable strategy. Otherwise, if $F + \Delta e(p+\theta) + (-1+b)\varphi\Delta e^2 > 0$, then E_{10} is a stable point, meaning that the strategy combination {strict regulation, green transformation, participation} is the system's evolutionarily stable strategy.*

Proposition 4 describes the relationship between the additional benefits brought to the enterprise by public participation, emission trading profits, and saved environmental taxes, and the cost of emission reduction. It determines the system's evolutionarily stable strategy. Specifically, when the sum of the enterprise's additional benefits, emission trading profits, and saved environmental taxes is less than the cost of emission reduction, the system's evolutionarily stable strategy is {strict regulation, non-green transformation, participation}. This means that the enterprise chooses to continue using traditional non-green transformation technologies under strict regulation and the public chooses to participate in related activities. In this case, the enterprise may consider the cost of emission reduction to be high and unable to offset the gap through additional benefits, emission trading, and saved environmental taxes. Therefore, it chooses to continue using traditional, higher-emission technologies. Conversely, when the sum is greater than the cost of emission reduction, the system's evolutionarily stable strategy is {strict regulation, green transformation, participation}. This indicates that the enterprise chooses to undergo green transformation, operates under strict regulation, and the public also chooses to participate in related activities. In this case, the enterprise may perceive that under strict regulation, the cost of emission reduction is relatively low, and higher economic benefits can be obtained through green transformation.

By$C\epsilon + \theta Q_1 > C\epsilon + \theta Q_2$, and $min\{\Delta e(p+\delta\theta) + (-1+b)\varphi\Delta e^2, F + \Delta e(p+\delta\theta) + (-1+b)\varphi\Delta e^2, \Delta e(p+\theta) + (-1+b)\varphi\Delta e^2, F + \Delta e(p+\theta) + (-1+b)\varphi\Delta e^2\} = \Delta e(p+\delta\theta) + (-1+b)\varphi\Delta e^2$, $max\{\Delta e(p+\delta\theta) + (-1+b)\varphi\Delta e^2, F + \Delta e(p+\delta\theta) + (-1+b)\varphi\Delta e^2, \Delta e(p+\theta) + (-1+b)\varphi\Delta e^2, F + \Delta e(p+\theta) + (-1+b)\varphi\Delta e^2\} = F + \Delta e(p+\theta) + (-1+b)\varphi\Delta e^2$, combined propositions 1–4, it can be concluded that when $\Delta e(p+\delta\theta) + (-1+b)\varphi\Delta e^2 > 0$, the evolutionarily stable strategy for the enterprise is always green transformation; when $F + \Delta e(p+\theta) + (-1+b)\varphi\Delta e^2 < 0$, the evolutionarily stable strategy for the enterprise is always non-green transformation.

The same method can be used to determine that when $M < N$, the evolutionarily stable strategy for the public is always to participate. When $M > N$, the evolutionarily stable strategy for the public is always not to participate. When $C\epsilon + \theta Q_2 > C$, the evolutionarily stable strategy for the local government is always strict regulation; when $C\epsilon + \theta Q_1 < C$, the stable strategy for the local government is always loose regulation

Based on the preceding analysis, we derive Proposition 5.

Proposition 5. *When $C\epsilon + \theta Q_2 > C$, the evolutionarily stable strategy for local governments is always strict regulation. When $\Delta e(p+\delta\theta) + (-1+b)\varphi\Delta e^2 > 0$, the evolutionarily stable strategy for enterprises is always green transformation. When $M < N$, the evolutionarily stable strategy for the public is always participation.*

Fig. 4 effectively depicts the results of Proposition 5.

5. Numerical simulation

To validate the results of the aforementioned proposition and uncover additional managerial insights, this section utilizes Mathematica 13 for numerical simulation. The simulation will examine the effects of local government subsidies on enterprise green transformation, emissions trading, environmental taxes, central government subsidies for local government regulation, and subsidies provided to participating stakeholders within the evolutionary system. In this model, there are no intricate correlations among the variables; thus, the settings primarily reflect the magnitude relationships, with parameters adjustable as per actual conditions. Without loss of generality, it is assumed that the

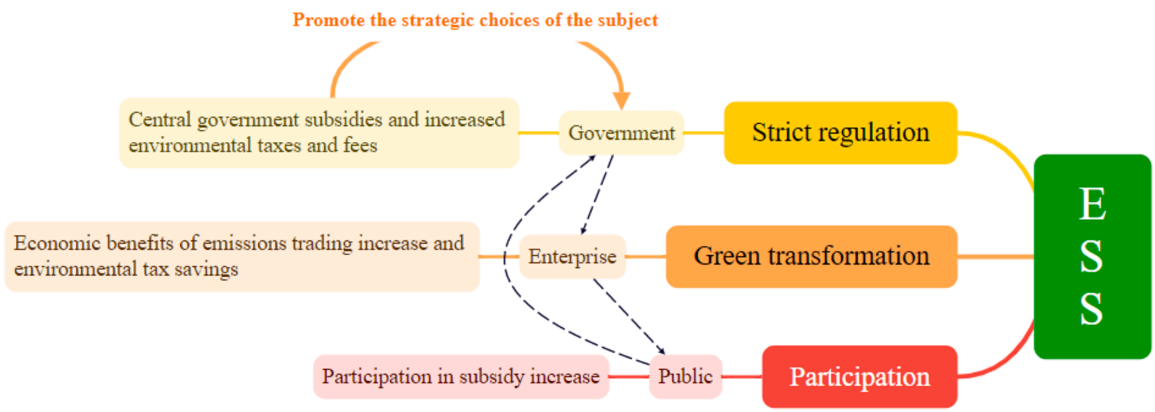

Fig. 4. Result analysis summary chart.

initial probabilities of evolution for local governments, enterprises, and the public are all 0.5.

5.1. The impact of local government subsidies on the evolutionary system

The Environmental Protection Tax Law in China stipulates that the tax amount for taxable air pollutants ranges from 1.2 yuan to 12 yuan per pollution equivalent, while the tax amount for water pollutants ranges from 1.4 yuan to 14 yuan per pollution equivalent. The specific determination and adjustment of applicable tax amounts can be decided within the statutory range by the Standing Committee of the People's Congress at the local level. Therefore, here we assume an environmental tax rate of $\theta = 1.3$.

In addition, the trading price of pollutant discharge permits is determined by the market and varies among provinces and cities. For example, in Jiangsu Province, the prices are set at 300 yuan/ton for chemical oxygen demand, 400 yuan/ton for ammonia nitrogen, 200 yuan/ton for sulfur dioxide, and 300 yuan/ton for nitrogen oxides. In contrast, in Fujian Province, the prices are set at 1300 yuan/ton for chemical oxygen demand, 1500 yuan/ton for ammonia nitrogen, 800 yuan/ton for sulfur dioxide, and 1100 yuan/ton for nitrogen oxides. Therefore, here we assume a trading price of pollutant discharge permits, $p = 400$.

The remaining parameter settings are as follows: $M = 20$, $N = 10$, $C = 100, Q_1 = 120$, $Q_2 = 100$, $\delta = 0.5$, $\epsilon = 0.5$, $\varphi = 25$, $F = 20$. By adjusting the magnitude of the local government subsidy coefficient b for green transformation of enterprises, the influence of the local government subsidy coefficient on the evolutionary system is revealed, as shown in Fig. 5.

Fig. 5 depicts the influence of the local government subsidy coefficient b on the stable strategies of the evolutionary system. Specifically, when b is small (e.g., $b = 0.1$ or 0.15), satisfying the condition for E_3 to be a stable point, the system's stable strategy is {strict regulation, non-green transformation, non-participation}. When b is larger (e.g., $b = 0.2$

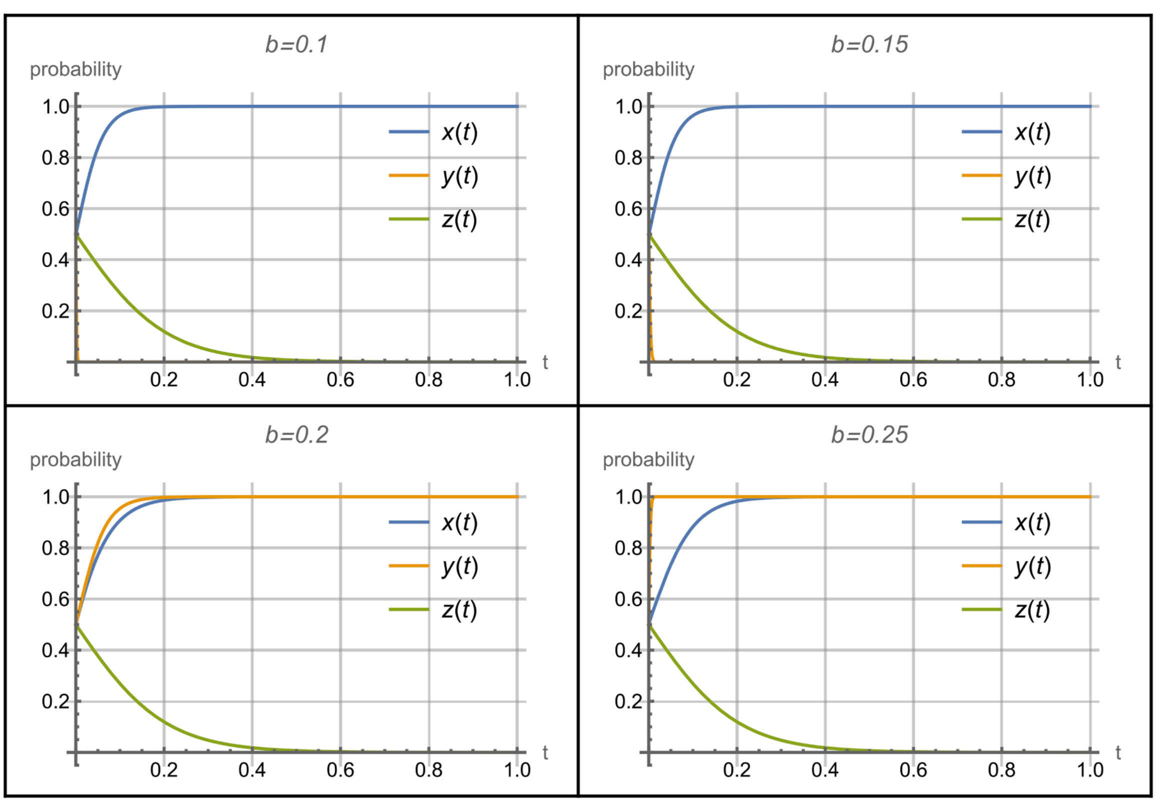

Fig. 5. The impact of local government subsidy coefficient b on the evolutionary system.

or 0.25), satisfying the condition for E_5 to be a stable point, the system's stable strategy changes to {strict regulation, green transformation, non-participation}. It can be observed that as b increases, the stable strategy of the enterprises transitions from non-green transformation to green transformation. Therefore, the magnitude of the local government subsidy coefficient directly affects the decision of enterprises to undergo green transformation. When the subsidy coefficient is low, enterprises may perceive that the cost of transformation outweighs the subsidy benefits, or that the subsidy level is insufficient to offset the transformation costs, resulting in a lack of sufficient incentive for transformation. Hence, the government needs to moderately increase the subsidy coefficient to incentivize enterprises to undergo green transformation. A moderate incentive mechanism can drive enterprises to actively respond to environmental demands and achieve environmental protection and sustainable development goals. The government should exercise caution when adjusting the subsidy coefficient to balance the relationship between enterprise transformation costs, subsidy benefits, and environmental protection goals. Combining increased regulatory efforts with higher subsidy levels can ensure that enterprises operate in compliance after undergoing green transformation, preventing moral hazards and improper behavior. Additionally, the government should strengthen environmental education, promotion, and public participation to enhance public awareness and engagement in environmental issues, thereby promoting the realization of sustainable development.

5.2. *The impact of emission trading on the evolutionary system*

In this sub-section, the impact of environmental taxes on the evolutionary system is revealed by adjusting the pollutant trading price p. The parameter settings are as follows:$M = 20,\ N = 10,\ C = 100, Q_1 = 120,\ Q_2 = 100,\ \delta = 0.5,\ \epsilon = 0.3, b = 0.18, \theta = 1.3,\ \varphi = 25,\ F = 20$. The simulation results are shown in Fig. 6.

Fig. 6 shows the impact of pollutant trading prices p on the stable strategies of the evolutionary system. Specifically, when p is low (e.g., $p = 380$ or 400), the system's stable strategy is {strict regulation, non-green transformation, non-participation}, satisfying the condition for E_3 to be a stable point. Conversely, when p is high (e.g.,$p = 420$ or 440), the system's stable strategy transitions to {strict regulation, green transformation, non-participation}, satisfying the condition for E_5 to be a stable point. Therefore, as p increases, the evolutionary stable strategy of the enterprises shifts from non-green transformation to green transformation. This is because higher pollutant trading prices impose economic pressure on enterprises, incentivizing them to adopt green transformation measures to reduce emissions and environmental impact. Pollutant trading systems are market-based environmental management mechanisms that encourage enterprises to reduce emissions and improve environmental efficiency through the introduction of trading and pricing mechanisms for pollutant rights. As the price of pollutant trading increases, enterprises need to pay higher costs to obtain emission permits, which becomes an economic burden for non-environmentally friendly enterprises. In order to reduce costs, avoid fines, and comply with environmental regulations, enterprises will adopt more green transformation measures, improve production processes, enhance emission efficiency, and even innovate products to meet market demands. Furthermore, higher pollutant trading prices also promote technological innovation and cooperation among enterprises. Enterprises can seek more environmentally friendly and efficient technologies and methods, collaborate with other enterprises to collectively reduce environmental impact, share pollutant rights, and achieve economic benefits.

5.3. *The impact of environmental taxes on the evolutionary system*

In this sub-section, the impact of the environmental tax on the evolutionary system is revealed by adjusting the size of the environmental tax rate θ. The parameter settings are as follows:$M = 20,\ N = 10,\ C = 400, Q_1 = 120,\ Q_2 = 100,\ \delta = 0.5,\ \epsilon = 0.3, b = 0.18,\ \varphi = 25,\ F = 20, p = 400$. The simulation results are shown in Fig. 7.

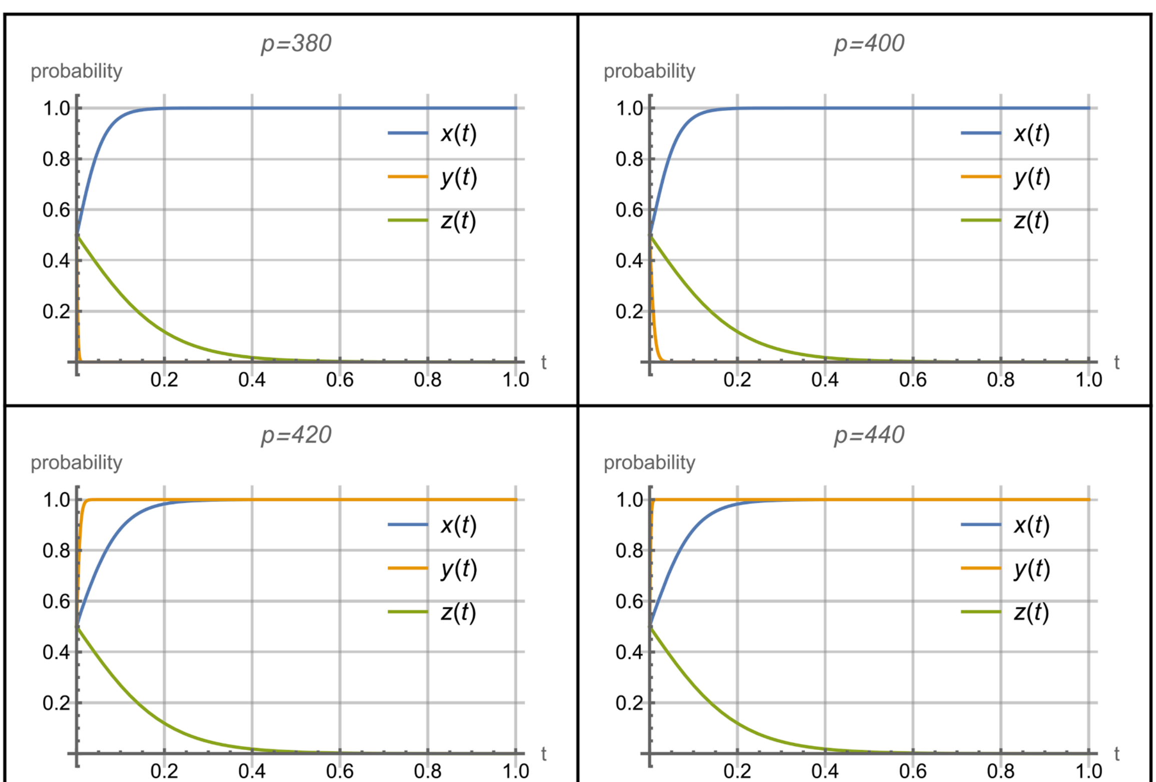

Fig. 6. The impact of emission trading price p on the evolutionary system.

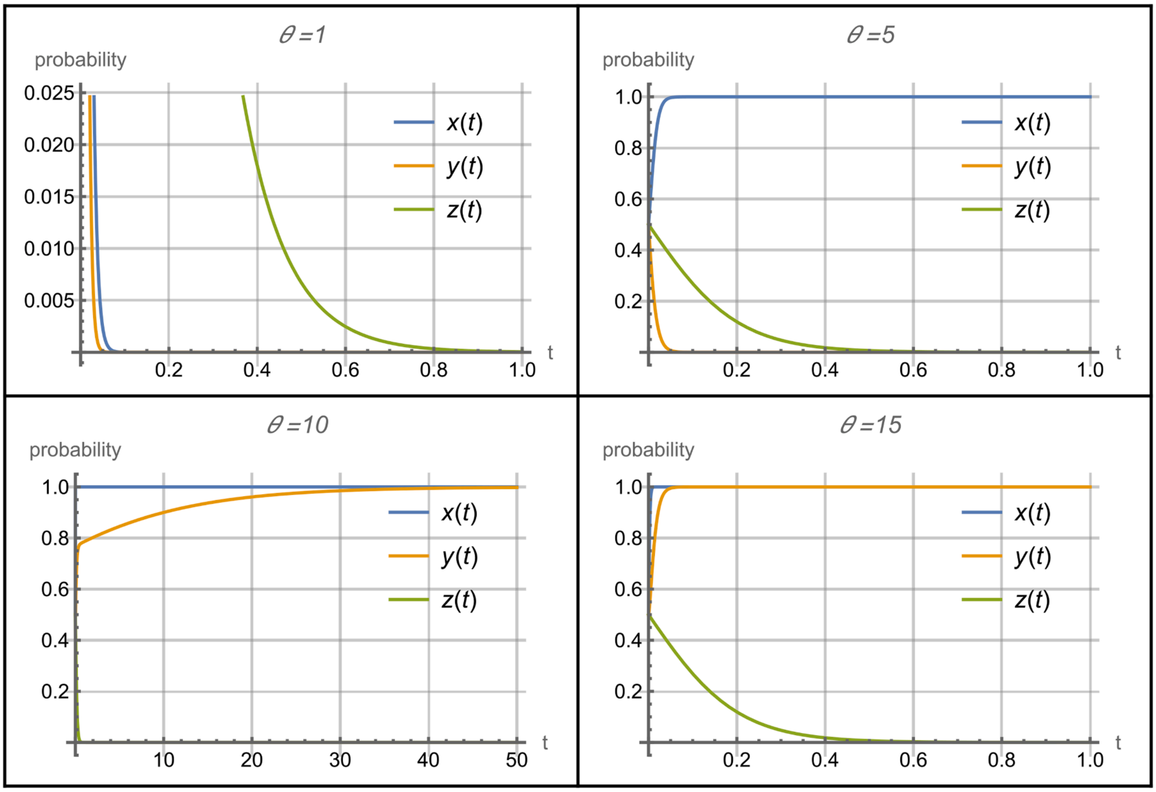

Fig. 7. The impact of environmental tax rate θ on the evolutionary system.

Fig. 7 depicts the influence of the environmental tax rate θ on the stable strategies of the evolutionary system. Specifically, when θ is low, for example, $\theta = 1$, the system evolves to a stable strategy of "loose regulation, non-green transformation, non-participation" at the stable point E_2. As θ increases, for instance, $\theta = 5$, the system evolves to a stable strategy of "strict regulation, non-green transformation, non-participation" at the stable point E_3. With further increases in θ, such as $\theta = 10$ or 15, the system evolves to a stable strategy of "strict regulation, green transformation, non-participation" at the stable point E_5. Therefore, as θ increases, the evolutionary stable strategy for local governments shifts from loose regulation to strict regulation, while the evolutionary stable strategy for enterprises shifts from non-green transformation to green transformation. As the environmental tax rate increases, local governments are more inclined to adopt stricter regulatory measures to promote improvements in enterprises' environmental behavior. High tax rates encourage governments to take more stringent

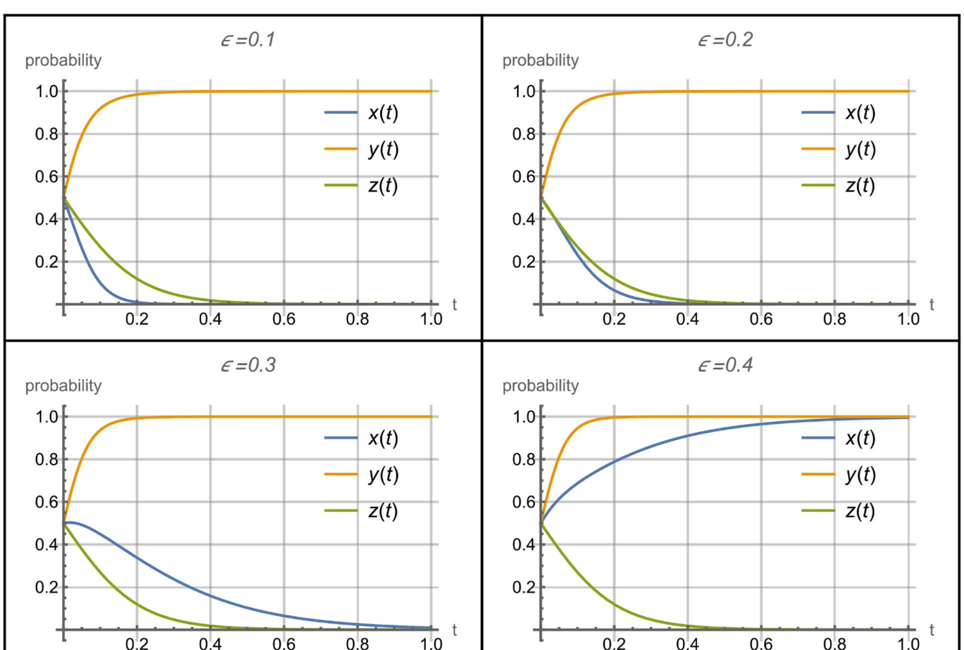

Fig. 8. The impact of central government subsidy coefficient ϵ on the evolutionary system.

measures to ensure that enterprises proactively adopt environmental protection measures and reduce negative impacts on the environment. At the same time, enterprises are more inclined to adopt green transformation strategies to reduce the burden of environmental taxes. High environmental taxes provide clear economic incentives, driving enterprises to invest and innovate in order to reduce environmental pollution and adopt more environmentally friendly business practices. Therefore, increasing the environmental tax rate can effectively mobilize the enthusiasm of enterprises and local governments to participate in environmental protection, promoting more sustainable development.

5.4. The impact of central government subsidies on the evolutionary system

This sub-section reveals the impact of central government subsidies on the evolutionary system by adjusting the coefficient ϵ, which represents the subsidy ratio from the central government to local governments. The parameter settings are as follows:$M = 20,\ N = 10,\ C = 200,\ Q_1 = 120,\ Q_2 = 100,\ \delta = 0.5,\ b = 0.18, \theta = 1.3,\ \varphi = 25,\ F = 20, p = 400$. The simulation results are shown in Fig. 8.

Fig. 8 illustrates the impact of the coefficient ϵ, representing the central government subsidies to local governments, on the stable strategies of the evolutionary system. Specifically, when ϵ is small, such as $\epsilon = 0.1,\ 0.2$, or 0.3, the condition for E_4 to be a stable point is satisfied, and the system's stable strategies are {loose regulation, green transformation, non-participation}. When ϵ is larger, such as $\epsilon = 0.4$, the condition for E_5 to be a stable point is satisfied, and the system's stable strategies become {strict regulation, green transformation, non-participation}. Therefore, as ϵ increases, the evolutionary stable strategy of local governments shifts from loose regulation to strict regulation. This is because the central government incentivizes local governments through subsidies to adopt stricter environmental regulatory measures to protect the environment and promote sustainable development. By increasing the amount of environmental regulatory subsidies, the central government sends a clear signal to local governments, emphasizing the importance and urgency of environmental protection. In order to obtain more subsidy funds, local governments will strengthen their environmental regulation of enterprises to ensure compliance with environmental laws and policy requirements. Strict regulatory measures can encourage enterprises to adopt more environmentally friendly measures, reduce negative impacts on the environment, and promote low-carbon and sustainable development. In addition, strict environmental regulation also helps enhance the image and reputation of local governments. By using subsidy funds for environmental regulation, local governments can not only improve local environmental quality but also enhance their reputation and influence in the field of environmental protection, attracting more investment and talent.

5.5. The impact of public participation subsidies on the evolutionary system

The sub-section reveals the impact of subsidies provided by local governments on the evolutionary system by adjusting the size of the subsidy N given to participating individuals. The parameter settings are as follows: $M = 20,\ \epsilon = 0.3,\ C = 100, Q_1 = 120,\ Q_2 = 100,\ \delta = 0.5,\ b = 0.18, \theta = 1.3,\ \varphi = 25,\ F = 20, p = 400$.The simulation results are shown in Fig. 9.

Fig. 9 depicts the impact of public participation subsidies N on the stable strategies of the evolutionary system. Specifically, when N is small, such as $N = 16$ or 18, and the condition for E_5 being a stable point is satisfied, the system's evolutionarily stable strategies are {strict regulation, green transformation, non-participation}. When N is large, such as $N = 22$ or 24, and the condition for E_{10} being a stable point is satisfied, the system's evolutionarily stable strategies change to {strict regulation, green transformation, participation}. Therefore, as N increases, the evolutionarily stable strategy of the public shifts from non-participation to participation.

The green transformation subsidies provided by local governments

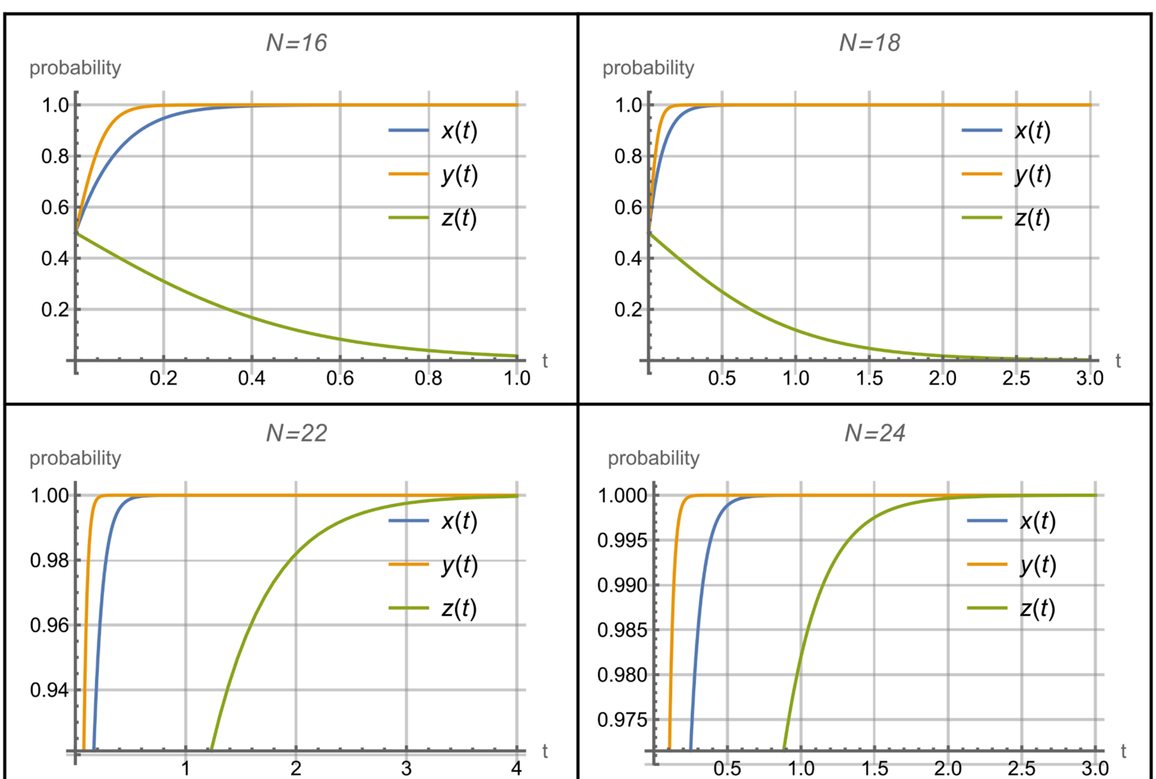

Fig. 9. The impact of public participation subsidies N on the evolutionary system.

have incentivized the public to actively engage in green transformation actions, promoting environmental protection and sustainable development. As the subsidy amount increases, the public receives more economic and policy support to adopt environmental measures and improve environmental quality. This further stimulates public participation, as they become more concerned about environmental issues and actively participate in green transformation actions. The ways in which the public participates are diverse, including engaging in activities organized by environmental protection organizations, volunteering, purchasing eco-friendly products, and taking individual actions to conserve resources and reduce environmental pollution. The public recognizes the importance of environmental protection for their own interests and responsibilities, and they contribute to achieving the goal of environmental sustainability through practical actions. At the same time, public participation in green transformation also has a positive impact on the image and reputation of local governments. By encouraging public engagement in green transformation, local governments demonstrate their commitment to environmental protection and provide proactive environmental policies and actions. The active involvement of the public further strengthens the leadership and influence of local governments in the field of environmental protection.

6. Conclusions

With the increasing prominence of environmental issues and the growing demand for sustainable development in society, enterprises are shifting towards green development to balance economic benefits and environmental protection. Green transformation is a complex and challenging process involving government policy support, corporate strategic choices, and public participation. This paper aims to conduct in-depth research on the decision factors and interactions in corporate green transformation, extract collaborative governance strategies involving multiple stakeholders, and provide theoretical and practical guidance for promoting sustainable development and social responsibility.

The innovations of this paper are twofold. Firstly, by developing a tripartite evolutionary game model, this study integrates the government, enterprises, and the public into a cohesive analytical framework to thoroughly investigate their interactions and impacts in the context of green transformation. This approach surpasses traditional single or dual-subject research perspectives and aligns more closely with the complexities of real-world scenarios. Secondly, the paper rigorously examines the influence of environmental regulations and government subsidies on the strategic choices of these three stakeholders. Through model resolution and simulation analysis, it elucidates the mechanisms and specific impacts of various factors, thereby providing a more precise reference for policy formulation.

6.1. Summary of findings

The main findings of this paper are as follows. Firstly, under specific conditions, all eight pure strategy equilibria have the potential to become stable points in the evolutionary game. This means that by adjusting relevant parameters, the evolutionary system can be guided towards the ideal equilibrium point, thereby promoting corporate green transformation. This provides guidance for policy formulation and implementation, enabling stakeholders to better understand and promote the process of green transformation. Secondly, when the sum of subsidies from local governments and the benefits of pollution rights trading for enterprises exceeds the emission reduction cost, enterprises will always choose green transformation as the evolutionarily stable strategy. Similarly, when the sum of subsidies from the central government and the revenue from environmental taxes exceeds the cost of strict regulation, local governments will always choose strict regulation as the evolutionarily stable strategy. For the public, when their participation subsidy exceeds the participation cost, their evolutionarily stable strategy will always be to participate in green transformation. Thirdly, increasing the price of pollution rights trading, the tax rate of environmental taxes, and local government subsidies can promote corporate green transformation, while increasing central government subsidies and the tax rate of environmental taxes will drive local governments to adopt strict regulatory measures. In addition, increasing subsidies to the public can also incentivize their active participation in green transformation.

6.2. Practical and managerial implications

Based on the research in this paper, several management implications can be drawn. Firstly, clear policies and measures need to be formulated to guide the evolutionary system towards the ideal equilibrium point and promote corporate green transformation. Secondly, economic incentives, such as subsidies from local governments and benefits from pollution rights trading, should be provided to reduce emission reduction costs and encourage enterprises to choose green transformation. Thirdly, environmental actions should be promoted through economic means, such as central government subsidies and environmental tax rates, to guide local governments to adopt strict regulatory measures. Fourthly, the participation of the public should be valued, and subsidies and incentives should be provided to encourage their active involvement in green transformation, forming social consensus and mobilizing forces. Lastly, policy parameters, such as increasing the price of pollution rights trading, the tax rate of environmental taxes, and local government subsidies, should be adjusted to promote corporate green transformation, and ensuring that central government subsidies and environmental tax revenue exceed the cost of strict regulation to drive local governments to adopt strict regulatory measures.

6.3. Limitations and future research

We conclude the paper by discussing some directions for future research. Firstly, although this paper has constructed a tripartite evolutionary game model involving the government, enterprises, and the public, there are still many factors that may influence the green transformation that have not been considered, such as technological innovation and sociocultural backgrounds. These factors deserve further exploration in the future. Secondly, this study is primarily based on theoretical analysis and numerical simulations. Future research should aim to validate the accuracy and generality of the model using empirical data. Thirdly, while this paper mainly focuses on the game relationships at the macro level, issues such as internal decision-making within enterprises and individual behavior choices among the public at the micro level also merit in-depth investigation. Finally, translating the policy recommendations of this paper into specific policy measures and implementation plans, as well as addressing issues related to monitoring and evaluation during policy execution, represent important directions for future research.

CRediT authorship contribution statement

Yanan Zhao: Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation. **Lili Zhang:** Software, Resources, Project administration, Methodology, Investigation, Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation. **Siyao Li:** Formal analysis, Conceptualization.

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.

Acknowledgments

This research was funded by the National Natural Science Foundation of China (NO. 72271038).

Data availability

No data was used for the research described in the article.

References

[1] Z. Cheng, Y. Wu, Can the issuance of green bonds promote corporate green transformation? J. Clean. Prod. 443 (2024) 141071.
[2] Z. Miao, G. Zhao, Configurational paths to the green transformation of Chinese manufacturing enterprises: a TOE framework based on the fsQCA and NCA approaches, Sci. Rep. 13 (1) (2023) 19181.
[3] C. Raghavendra, R. Mahesh, M.K. Khan, V. Dagar, S. Singh, R. Alvarado, Impact of carbon emissions, renewable and non-renewable energy consumption on inbound cross-border mergers and acquisition's investment inflow, Environ. Dev. Sustain. (2024).
[4] Y. Chen, X. Ma, X. Ma, M. Shen, J. Chen, Does green transformation trigger green premiums? Evidence from Chinese listed manufacturing firms, J. Clean. Prod. 407 (2023) 136858.
[5] J. Feng, Y. Wang, W. Xi, Does green technology transformation alleviate corporate financial constraints? Evidence from Chinese listed firms, Heliyon 10 (6) (2024) e27841.
[6] E.N. Udemba, V. Dagar, X. Peng, L. Dagher, Attaining environmental sustainability amidst the interacting forces of natural resource rent and foreign direct investment: is Norway any different? OPEC Energy Rev. 48 (1) (2024) 19–35.
[7] A.M. Rao, V. Dagar, K. Sohag, L. Dagher, T.I. Tanin, Good for the planet, good for the wallet: the ESG impact on financial performance in India, Finance Res. Lett. 56 (2023).
[8] S. Zhong, L. Peng, J. Li, G. Li, C. Ma, Digital finance and the two-dimensional logic of industrial green transformation: evidence from green transformation of efficiency and structure, J. Clean. Prod. 406 (2023) 137078.
[9] J. Du, X. Zhu, X. Li, E. Unal, P. Longhurst, Explaining the green development behavior of local governments for sustainable development: evidence from China, Behav. Sci. 13 (10) (2023).
[10] Y.Y. Nie, K. Wan, F. Wu, W.Y. Zou, S.Y. Chang, Local government competition, development zones and urban green innovation: an empirical study of Chinese cities, Appl. Econ. Lett. 29 (16) (2022) 1509–1514.
[11] F. Ye, Y.B. Quan, Y.X. He, X.F. Lin, The impact of government preferences and environmental regulations on green development of China's marine economy, Env. Impact Assess Rev. 87 (2021).
[12] C. Li, Z. Wang, L. Wang, Factors affecting firms' green technology innovation: an evolutionary game based on prospect theory, Env. Monit Assess 195 (1) (2022) 227.
[13] X. Li, J. Dai, X. Zhu, J. Li, J. He, Y. Huang, X. Liu, Q. Shen, Mechanism of attitude, subjective norms, and perceived behavioral control influence the green development behavior of construction enterprises, Humanit. Soc. Sci. Commun. 10 (1) (2023).
[14] R. Akhtar, S. Sultana, M.M. Masud, N. Jafrin, A. Al-Mamun, Consumers' environmental ethics, willingness, and green consumerism between lower and higher income groups, Resour. Conserv. Recycl. 168 (2021).
[15] A.K. Al-Swidi, M.A. Al-Hakimi, H.M. Gelaidan, S. Al-Temimi, How does consumer pressure affect green innovation of manufacturing SMEs in the presence of green human resource management and green values? A moderated mediation analysis, Bus. Ethics Environ. Responsib. 31 (4) (2022) 1157–1173.
[16] S.A. Hazaea, E.M. Al-Matari, K. Zedan, S.F.A. Khatib, J.Y. Zhu, H. Al Amosh, Green purchasing: past, present and future, Sustainability 14 (9) (2022).
[17] H.M. Chen, J.X. Wang, Y.J. Miao, Evolutionary game analysis on the selection of green and low carbon innovation between manufacturing enterprises, Alex. Eng. J. 60 (2) (2021) 2139–2147.
[18] J.J. Duan, Y.S. Wang, Y.B. Zhang, L.Y. Chen, Strategic interaction among stakeholders on low-carbon buildings: a tripartite evolutionary game based on prospect theory, Environ. Sci. Pollut. Res. (2024).
[19] L. Guo, Q. Zhang, J. Wu, E.D.R. Santibanez Gonzalez, An evolutionary game model of manufacturers and consumers' behavior strategies for green technology and government subsidy in supply chain platform, Comput. Ind. Eng. 189 (2024) 109918.
[20] P. Kumar, S. Gupta, V. Dagar, Sustainable energy development through non-residential rooftop solar photovoltaic adoption: empirical evidence from India, Sustain. Dev. 32 (1) (2024) 795–814.
[21] M. Li, X. Gao, Implementation of enterprises' green technology innovation under market-based environmental regulation: an evolutionary game approach, J. Env., Manage 308 (2022) 114570.
[22] L.Y. Yu, H. Xu, Z.Y. Zhang, Tripartite evolutionary game analysis of supply chain low-carbon transformation considering the coupling of carbon tax and subsidy regulations, Manag. Decis. Econ. 45 (2) (2024) 702–725.
[23] S.H. Guo, Tackling China's local environmental policy implementation gap: an evolutionary game analysis of China's environmental protection inspection system, J. Clean. Prod. 416 (2023).
[24] C.Y. Liu, W. Li, L. Chang, Q. Ji, How to govern greenwashing behaviors in green finance products: a tripartite evolutionary game approach, Financ. Innov. 10 (1) (2024).
[25] Z.Y. Sun, W.W. Zhang, Do government regulations prevent greenwashing? An evolutionary game analysis of heterogeneous enterprises, J. Clean. Prod. 231 (2019) 1489–1502.
[26] L. Wang, F. Pan, Y.J. Li, Evolutionary game strategies analysis of economic development and environmental protection between local governments under Central supervision mechanism in China, Sustainability 14 (19) (2022).
[27] R. Alvarado, B. Tillaguango, L. Cuesta, S. Pinzon, M.R. Alvarado-Lopez, C. Işık, V. Dagar, Biocapacity convergence clubs in Latin America: an analysis of their determining factors using quantile regressions, Environ. Sci. Pollut. Res. 29 (44) (2022) 66605–66621.
[28] L.L. Ding, Z.M. Guo, Y.M. Xue, Dump or recycle? Consumer's environmental awareness and express package disposal based on an evolutionary game model, Environ. Dev. Sustain. 25 (7) (2023) 6963–6986.
[29] X.X. Geng, L. Lv, Y.C. Wang, R. Sun, X.M. Wang, Evolutionary game research on green construction considering consumers' Preference under government supervision, Int. J. Env. Res. Public Health 19 (24) (2022).
[30] W. Qiao, X.B. Yin, Understanding the impact on energy transition of consumer behavior and enterprise decisions through evolutionary game analysis, Sustain. Prod. Consum. 28 (2021) 231–240.
[31] S. Kakran, A. Sidhu, P.K. Bajaj, V. Dagar, Novel evidence from APEC countries on stock market integration and volatility spillover: a Diebold and Yilmaz approach, Cogent Econ. Finance 11 (2) (2023) 2254560.
[32] Z. Chen, T. Wang, Y. Mao, Strategies of stakeholders to promote distributed photovoltaics in China: an evolutionary game study, Energy Rep. 8 (2022) 11039–11051.
[33] X.C. Fang, Y. Yang, W.C. Huang, The impact of green taxation on green low-carbon development in Yangtze River Delta region of China-based on mediating effect model and spatial Durbin model, Environ. Sci. Pollut. Res. 30 (47) (2023) 103674–103689.
[34] D. Huang, Green finance, environmental regulation, and regional economic growth: from the perspective of low-carbon technological progress, Environ. Sci. Pollut. Res. 29 (22) (2022) 33698–33712.
[35] Z. Liu, W.Z. Sun, Study on low-carbon technology investment strategies for high energy-consuming enterprises under the health Co-benefits of carbon emission reduction, Sustainability 15 (11) (2023).
[36] S.L. Qiu, Z.L. Wang, S. Liu, The policy outcomes of low-carbon city construction on urban green development: evidence from a quasi-natural experiment conducted in China, Sustain. Cities. Soc. 66 (2021).
[37] P. Feng, H.Y. Lu, W. Li, X.Y. Wang, Tax policies of low carbon in China: effectiveness evaluation, system design and prospects, Front. Environ. Sci. 10 (2022).
[38] Y. Sun, K. Wu, S. Liu, Y. Hong, Does environmental regulation affect analyst forecast bias? Evidence from China's low-carbon pilot policy, J. Env., Manage 353 (2024) 120134.
[39] X.K. Wei, W. Chen, M. Li, Y.A. Wang, Do environmental regulations promote low-carbon diffusion among different scales of enterprise? A complex network-based evolutionary game approach, Carbon. Manage 12 (6) (2021) 681–692.
[40] W.T. Gao, H. Zhang, J.F. Lu, T.J. Han, Research on green supply chain formation and government subsidy pricing strategy considering an online trading platform, Sustainability 15 (19) (2023).
[41] Z. Liu, W.Z. Sun, B. Hu, C.J. Han, P. Ieromonachou, Y.J. Zhao, J.Z. Zheng, Research on supply chain optimization considering consumer subsidy mechanism in the context of carbon neutrality, Energies 16 (7) (2023).
[42] Y.H. Zhang, T. Zhang, Complex dynamics of a low-carbon supply chain with government green subsidies and carbon cap-and-trade policies, Int. J. Bifurc. Chaos 32 (06) (2022).
[43] Y.Y. Zheng, J. Zhang, M.Y. Wang, P. Liu, T. Shu, Low-carbon manufacturing or not? Equilibrium decisions for capital-constrained news vendors with subsidy and carbon tax, Sustainability 15 (15) (2023).
[44] L. Dagher, A. Rao, D. Vishal, O. Shobande, Geopolitics, uncertainty, and cryptocurrency: a love triangle gone wrong, Appl. Finance Lett. 13 (2024) 48–62.
[45] C. Su, X.J. Liu, W.Y. Du, Green supply chain decisions considering consumers' Low-carbon awareness under different government subsidies, Sustainability 12 (6) (2020).
[46] Y. Tian, L. Zhao, M.H. Zhu, Dynamic game of the dual-channel supply chain under a carbon subsidy policy, Int. J. Bifurc. Chaos 32 (15) (2022).
[47] L. Xu, C.X. Wang, Z. Miao, J.H. Chen, Governmental subsidy policies and supply chain decisions with carbon emission limit and consumer's environmental awareness, Rairo-Oper. Res. 53 (5) (2019) 1675–1689.
[48] R. Long, S. Bao, M. Wu, H. Chen, Overall evaluation and regional differences of green transformation: analysis based on ?Government-enterprise-resident? Three-dimensional participants perspective, Env. Impact Assess. Rev. 96 (2022).
[49] X. Zhai, Y. An, Analyzing influencing factors of green transformation in China's manufacturing industry under environmental regulation: a structural equation model, J. Clean. Prod. (2020) 251.
[50] L. Yang, Y. Liu, H. Deng, Environmental governance, local government competition and industrial green transformation: evidence from China's sustainable development practice, Sustain. Dev. 31 (2) (2023) 1054–1068.
[51] M. Zeng, L. Zheng, Z. Huang, X. Cheng, H. Zeng, Does vertical supervision promote regional green transformation? evidence from central environmental protection inspection, J. Env., Manage 326 (Pt A) (2023), 116681-116681.

[52] R.Y.K. Chan, Y.H. Wong, T.K.P. Leung, Applying ethical concepts to the study of "green" consumer behavior: an analysis of Chinese consumers' intentions to bring their own shopping bags, J. Bus. Ethics 79 (4) (2008) 469–481.
[53] H. Huang, R. Long, H. Chen, K. Sun, Q. Sun, Q. Li, Why don't more people engage in green practices in China? A policy-oriented approach to promoting green transformation in five consumption areas, Env. Impact Assess Rev. 101 (2023).
[54] L.C. Zhen, J.W. Wen, Evolutionary game analysis of governments and polluting firms considering environmental tax regulation, Manage Rev. 29 (5) (2017) 226.
[55] L. Xu, Y. Ma, X. Wang, Study on environmental policy selection for green technology innovation based on evolutionary game: government behavior vs. Public participation, Chin. J. Manag. Sci. 30 (3) (2022) 30–42.
[56] A. Rustam, Y. Wang, H. Zameer, Environmental awareness, firm sustainability exposure and green consumption behaviors, J. Clean. Prod. 268 (2020) 122016.
[57] D. Friedman, Evolutionary games in economics, Econometrica (1991) 637–666.
[58] A.M. Lyapunov, The general problem of the stability of motion, Int. J. Control 55 (3) (1992) 531–534.