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Original Paper

Central environmental protection inspection and carbon emission reduction: A tripartite evolutionary game model from the perspective of carbon neutrality

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A R T I C L E I N F O

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A B S T R A C T

Since the carbon neutrality target was proposed, many countries have been facing severe challenges to carbon emission reduction sustainably. This study is conducted using a tripartite evolutionary game model to explore the impact of the central environmental protection inspection (CEPI) on driving carbon emission reduction, and to study what factors influence the strategic choices of each party and how they interact with each other. The research results suggest that local governments and manufacturing enterprises would choose strategies that are beneficial to carbon reduction when CEPI increases. When the initial willingness of all parties increases 20%, 50%–80%, the time spent for the whole system to achieve stability decreases from 100%, 60%–30%. The evolutionary result of "thorough inspection, regulation implementation, low-carbon management" is the best strategy for the tripartite evolutionary game. Moreover, the smaller the cost and the larger the benefit, the greater the likelihood of the three-party game stability strategy appears. This study has important guiding significance for other developing countries to promote carbon emission reduction by environmental policy.

1. Introduction

Ecological civilization construction is a millennium-long endeavor essential to the sustainability of the Chinese nation. Since 2012, the 18th CPC National Congress, China has regarded ecological civilization construction as a key component of the overall national strategy. Unprecedented efforts have been made to promote ecological civilization theory innovation, practical innovation, and institutional innovation. Ecological civilization construction represents a new direction and accomplishment in striving for the happiness of the people, revitalization for the nation, and harmony for the global. As a participant and contributor in building ecological civilization, China will join forces with all parties to address global environmental challenges and contribute Chinese strength to promote a shared future for human race. In the next step, China will continue to implement the national strategy for actively addressing climate change, accelerate the low-carbon transformation in key areas, and promote coordinated reduction of carbon emissions for enhanced efficiency.

To achieve the goal of the carbon peaking and carbon neutrality (CPCN) targets, China has conducted great efforts in the field of carbon reduction (Jiang et al., 2018). For example, some environmental policies can be effective in reducing carbon emissions (Zhang et al., 2023a), and establishing pilot zones for green finance innovation and reform is crucial to achieve the targets (Zhang et al., 2023b). China's carbon emission intensity in 2019 was 51.9% of that in 2005, which was about 48.1% lower. Although China's carbon emission intensity has dropped significantly in recent years, the total number of carbon emission continues to climb and remain at a high level, that is, the urgency, complexity, and long-term nature still exist. With the proposed carbon neutrality target, China has been facing severe challenges to carbon emission reduction

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sustainably, including institutional, economic and environmental challenges (Zhang et al., 2022a; Guilhot, 2022; Zhang et al., 2022b). China, as the largest carbon emitter globally, emitted approximately 10 billion tons of carbon in 2019, constituting 28.8% of the world's overall carbon emissions, which was twice and three times of the US and the EU, respectively (Wu and Li, 2022). Therefore, it is necessary to continuously push China's carbon emission reduction efforts with the help of policy measures and the broad participation of different parties.

Through the intervention of the highest authority, top-down mobilization, and the reorganization of multiple resources, the central environmental protection inspection (CEPI) has broken the original organizational structure and the conventional logic of power operation, which acts as a mobilization or corrective mechanism to address the administrative control dilemma of carbon emission reduction (Xiang and van Gevelt, 2020). As the key policy, the *Opinions on the Complete, Accurate and Comprehensive Implementation of the New Development Concept to Do a Good Job in CPCN* issued on September 22, 2021, emphasized that all regions should strengthen the implementation assessment of CPCN targets and incorporate them into the CEPI. Therefore, it has become urgent for China to achieve the CPCN targets by exploring the governance mechanism of carbon reduction driven by the CEPI and the competitive strategies among participants.

We review the relevant literature on three parts. The first part is the central government regulation on local governments. The regulation of the central government can effectively influence local governments' behavior, thus improving the management level and work efficiency, and preventing the abuse of power (Xiang and van Gevelt, 2020; Li et al., 2020; Wang et al., 2021b). Under China's existing governance system, local governments are faced with the twofold challenges of both environmental and economic benefits (Wang et al., 2021a; Young et al., 2015). It is indispensable that the central government make reasonable inspection and restraint to ensure local governments' enforcement and improve work efficiency (Zhang et al., 2017; Zhao and Percival, 2017). To a significant extent, the strategies of local governments are influenced by the regulations, incentives, and punishments imposed by the central government, as well as their own considerations of profits and losses (Li et al., 2019; Gao et al., 2019). Besides, the central government's regulation and rewards and punishments could increase the constraints on the local governments. Therefore, they tend to choose strategies that are beneficial to carbon reduction under the central government's regulation, including incentives and penalties they received, which further proves the necessity of central government regulation (Sun et al., 2021; Zhang et al., 2019).

The second part is local governments' regulation on manufacturing enterprises. The carbon emission behavior of manufacturing enterprises needs the correct guidance and reasonable restrictions of both the central and local governments, and their reward or punishment for manufacturing enterprises will greatly affect their strategic choices (Newton, 2018; Zhang et al., 2016; Zhang et al., 2019). Besides, costs or benefits of manufacturing enterprises and governments' regulation intensity could affect manufacturing enterprises' strategic choice, a direct subsidy will positively affect the implementation of carbon reduction (Bai et al., 2018; Zhao et al., 2016). Therefore, the strategy choice of manufacturing enterprises is largely influenced by local governments' reward and punishment mechanism. If local government allocate more cost subsidies to enterprises, it would accelerate the progress of enterprises towards low-carbon management (Fan et al., 2021). The local governments' way of guidance can influence the outcome of business behavior. Strict supervision and strong reward and punishment measures are needed to guide the carbon emission behavior of manufacturing enterprises (Qiao et al., 2022).

The third part is the three-player evolutionary game among the central, local governments and manufacturing businesses. In order to prevent the abuse of power and promote policy implementation, rules of the central government are of great importance to promote tripartite stability (Li and Wu, 2017; Ma et al., 2016; Zhang et al., 2019). Inspection of the central government can enhance the performance of policy execution, and prevent local governments and manufacturing businesses from acting alike, thus promoting the balance of interests of the three parties (Chu et al., 2021; Jiang et al., 2019).

The existing literature has been delved into the dual game of the central and local governments (Zhao and Percival, 2017; Li et al., 2020; Young et al., 2015; Sun et al., 2021), and local governments and manufacturing enterprises (Newton, 2018; Zhao et al., 2014; Bai et al., 2018; Qiao et al., 2022), and the three-player evolutionary game involving the central government, local governments, and manufacturing businesses (Li and Wu, 2017; Zhang et al., 2019; Jiang et al., 2019; Chu et al., 2021), which to a certain extent provides reference for this study. However, in the field of carbon emission reduction, few have been conducted by constructing tripartite evolutionary game models, especially integrating the costs as well as benefits of all players in the process of CEPI. Meanwhile, the study of energy issues in China has been a relatively hot topic, which made recommendations on Chinese energy efficiency and low-carbon strategies (Yang et al., 2021; Yang et al., 2020) and policy analysis (Jiang et al., 2010; Yu, 2010; Zhao et al., 2020; Guilhot, 2022).

Against this background, it is important to construct a comprehensive and integrated framework of CEPI in the purpose of promoting China's carbon reduction. However, the main challenge is how CEPI can promote carbon reduction, achieve the interests balance of the tripartite parties, and investigate how to reach stable in the game. Three questions deserve to be focused on in this study: (1) What is the impact logic of the central government, local governments, and manufacturing enterprises in the CEPI process? (2) How can we explore the incentive logic of the tripartite evolutionary game, and even identify a stabilization of the system? (3) How to investigate the effects of initial willingness, penalty intensity, and subsidy intensity in the analysis of evolutionary mechanism?

In this study, a three-player evolutionary game model is used to explore the effect of CEPI on driving carbon emission reduction, considering both incentives and punishments, costs of regulation, and effects of strategic choice, which causes the main gap between this study and current research. This study initially identifies the critical elements influencing the strategic choices of each party as well as to reveal mechanisms of the central government, local governments and manufacturing enterprises' interaction. This study aims at analyzing the logic of the three players in the process of carbon emission reduction, thus proposing some helpful policy recommendations.

This study contributes by introducing an evolutionary game model, integrating costs and benefits across all parties, and offering recommendations for China's energy efficiency and low-carbon strategies. These contributions fill important gaps in the current body of research and provide valuable insights for policymakers and stakeholders in the field of carbon reduction. The objective of this study is to reveal the game logic of the two-level governments and enterprises by incorporating a three-player evolutionary game model into the carbon reduction process promoted by the CEPI, and to analyze what factors influence the strategic choices of each party and how they interact with each other. From the perspective of the whole system and individual players, this study makes recommendations for the sustainable promotion of carbon emission reduction in China.

The innovations of this study are summarized from three aspects. First, as we know, this research initially studies how the CEPI drives carbon emission reduction in China, especially in the process of achieving the CPCN goal. Second, this study places the central government, local governments, and manufacturing enterprises under one analytical framework, so that the specific evolutionary path can be considered more reasonably and scientifically by dividing the governments into different levels. Third, by incorporating the notion of bounded rationality, this research utilizes an evolutionary game to explore the interaction mechanism among three parties, which better reflects the real-world scenario as they continuously evolve, interact, and mutually influence each other.

The remaining part of this study consists of the following five components: the second part explains the research hypotheses and parameters of each variable, the third part constructs and analyzes the game model of the three-player evolutionary game, the fourth part validates the numerical values by simulation, and the last part gives conclusions and some policy recommendations.

2. Research hypothesis and parameters setting

2.1. Research hypothesis

(1) Manufacturing enterprises take profit as their fundamental goal. They consider only economic benefits but not social and environmental benefits to decide management mode. Local governments are the medium between the central government and manufacturing businesses in centralization of China, so local governments are faced with dual influence by the central government and manufacturing enterprises. Government-business relations (GBR) is a kind of equilibrium formed between governments and businesses in the jurisdiction through some policies (e.g., subsidies, taxes, regulation). Local governments can intervene enterprises' production behavior through subsidies and regulations, while enterprises' behavior will also have an impact on governments' performance (e.g., economic growth, employment, ecological environment). Government can be further categorized into two levels: local governments and the central government. The central government makes the most macro and top-level decisions, focusing on the overall situation, while the local governments make regional decisions as well as high-level management and implementation, focusing on the balance between the top and the bottom. The Constitution of China provides for a unified framework for central-local relations, i.e., centralization, with sovereign authority held by a single state body, and with local governments acting in accordance with the central government. Simultaneously, the division of competencies between local and the central governments aims to empower local governments to take initiative and be enthusiastic while operating under the unified leadership of the central authorities. Therefore, local governments, as mediators of the top and the bottom players, are interdependent and interact with these two subjects.

Local governments receive rewards or punishments according to the efficiency of manufacturing enterprises and whether local governments regulating implementation. Besides, local governments receive fines by regulating manufacturing enterprises to conduct low-carbon management or subsidy to manufacturing enterprises. The central government pursues the unification of economic, environmental, and social benefits (Chu et al., 2021).

(2) The effect of manufacturing enterprises' management mode can be directly transmitted to the central government. The losses and gains of the top government can come from fines and rewards to local governments, social gains from manufacturing enterprises' low-carbon management, and social losses from manufacturing enterprises' high-carbon management. Local governments need to consider rewards or penalties from the central government and that to manufacturing enterprises. Based on hypothesis (1), local governments are the medium of the central government and manufacturing businesses. The top government pursues the unification of economic benefits, environmental results and social effects, and consider promoting carbon emission reduction as the direct goal.

This study has investigated the impact of carbon emission reduction by examining how profits and losses in manufacturing enterprises are directly fed back to the top government, while punishments from the local and central governments are indirectly fed back to local governments. The punishment for manufacturing enterprises comes from both local and the central governments. Only when the central government "thoroughly inspects" and local governments "regulate implementation" will manufacturing enterprises be punished accordingly. Local governments provide subsidies for low-carbon manufacturing enterprises (Zhao et al., 2012). If they choose not to regulate, manufacturing enterprises will not obtain subsidies.

(3) Regardless of whether the top government thoroughly conduct inspects, and the bottom governments regulate implementation or not, the central government is going to reward or punish local governments on the basis of final external effects caused by manufacturing enterprises (Sun et al., 2021). In summary, manufacturing enterprises are encouraged to conduct low-carbon management independently, as the top government rewards local governments for achieving positive social and environmental outcomes. This motivates local governments to shoulder their responsibilities and promote carbon emission reduction tasks.

2.2. Strategies adoption and parameters setting

2.2.1. Behavioral strategies of each party and their adoption probabilities

In the carbon emission reduction game model driven by CEPI, the three parties are selected as manufacturing enterprises, local governments and the central government, which are all limited rational.

The central government is initiator and the strongest promoter of the CEPI. Local governments and manufacturing enterprises have insufficient enforcement and environmental awareness under the original environmental protection policy. They suffered from data falsification, difficulty in defining responsibility for environmental violations, and inefficiency. The CEPI reflects the top government's determination to govern environment protection, not only to strengthen environmental protection supervision, but also to improve problems in environmental protection policy actions and awareness.

The central government makes the most macro and top-level decisions, focusing on the overall situation, while the local governments make regional decisions as well as high-level management and implementation, focusing on the balance between the top and the bottom. The Constitution of China provides for a unified framework for central-local relations, i.e., centralization, with sovereign authority held by a single state body, and with local governments acting in accordance with the central government. Meanwhile, the division of competencies between local and the central governments aims to empower local governments to take initiative and be enthusiastic while operating under the unified leadership of the top authorities. Local governments are supposed to execute the superior government's environmental protection policy, but the flexibility leads to the phenomenon that the policies always cannot be implemented properly. Simultaneously, the execution of local governments directly affects the carbon emission of enterprises. Therefore, local governments should be considered as one of the main players of the CEPI.

Manufacturing enterprises are the bottom implementers of the CEPI, and their carbon emission behavior has a direct impact on carbon emission reduction, making them another major object of the CEPI.

Enterprises aim at profitability. Based on the assumption of “rational people”, this study assumes that manufacturing enterprises only consider economic benefits, but not social and environmental benefits. Under China's centralized system, local governments are the intermediary between enterprises and the central government, and they face the dual influence of their supervisor government and manufacturing enterprises. They must consider the impact of manufacturing enterprises on local economy, ecological and environmental protection, as well as the central government's rewards and punishments for their own behavior. The central government, besides, pursues the harmonization of economic, environmental and social benefits.

The central government will inspect subordinate governments' execution of the carbon reduction policy occasionally. Its strategy set is “thorough inspection, not thorough inspection”. If local governments haven't fully implemented carbon reduction policy under thorough inspection, the central government will penalize them. It is assumed the central government chooses to “thorough inspection” is x ($0 \leq x \leq 1$), and the probability that it chooses to “not thorough inspection” is $1-x$.

The strategy set of local governments is: “regulate implementation, do not regulate implementation”. It is assumed that local governments choose to “regulate implementation” is y ($0 \leq y \leq 1$), when the probability that they choose to “do not regulate implementation” is $1-y$.

The manufacturing enterprises' strategy set is “low-carbon management, high-carbon management”. It is assumed that manufacturing enterprises choose to “low-carbon management” is z ($0 \leq z \leq 1$), when the probability they choose to “high-carbon management” is $1-z$.

2.2.2. Parameters setting of manufacturing enterprises

Low-carbon management refers to the production method in which manufacturing enterprises actively adopt new environmental protection technologies or carry out carbon emission reduction technology innovation, etc., changing from traditional high-carbon production to low-carbon production.

High carbon management means that manufacturing enterprises still operate with the original production method with high carbon emissions, without taking any measures to facilitate carbon reduction.

The cost of manufacturing enterprises' low-carbon management is C_1, and they would obtain a certain amount of subsidy S from local governments. The economic benefit of low-carbon management is R_1.

When manufacturing enterprises do not implement low-carbon management, their costs are C_2. The economic benefit of high-carbon management is R_2. High-carbon manufacturing enterprises will receive double punishment from both levels of government: the central inspection team inspects deep into the field and impose direct punishment, local governments regulate within the scope of responsibility, and manufacturing enterprises' losses are G_1 and G_2 respectively.

2.2.3. Parameters setting of local governments

The cost of local governments to regulate low-carbon management is C_3. “Regulation” refers to local governments investing certain amount of financial, human and material resources to regulate carbon emissions of manufacturing enterprises, including publicity, guidance, subsidies, promulgation of administrative regulations and so on.

The cost of local governments not regulating the low-carbon management of manufacturing enterprises is C_4. “Non-regulation” refers to local governments do not interfere with whether manufacturing enterprises conduct carbon emission reductions. $C_4 \neq 0$ because while local governments do not interfere with business practices, they still need to invest some cost in developing a government policy of non-interference in carbon reduction.

The central government will penalize local governments under thorough inspection if local governments do not regulate implementation, recorded as F_1. Under thorough inspection, if local governments regulate implementation, and manufacturing enterprises conduct low-carbon management, the positive external effect obtained is recorded as J. Local governments will be rewarded proportionally, if the reward coefficient is α, $0 < \alpha < 1$, the top government's incentive to bottom governments is αJ. Under thorough inspection, local governments are found to regulate implementation, but manufacturing enterprises do not conduct low-carbon management, resulting in a negative externality K, local governments will be penalized proportionally. Assuming the punishment coefficient is β, $0 < \beta < 1$, and the central government's punishment to local governments is βK.

Local governments' expenditure on subsidies for low carbon manufacturing enterprises is S.

2.2.4. Parameters setting of the central government

The cost of the central government's thorough inspection is C_5. Thorough inspection is manifested in measures such as going deep into the front line, stationing in manufacturing enterprises, and effectively accepting citizens' reports.

The cost of the central government's not thorough inspection is C_6. Incomplete inspections specifically include partial inspections, which are only partially completed, and no inspections, both of which are strategic choices that are the antithesis of thorough inspections. It is manifested in the possible problems of malfunction and formalism.

If the central government thoroughly inspects finding local governments do not regulate implementation, local governments will be punished and the fine will be recorded as F. If local governments are found to regulate implementation, they will neither be punished nor rewarded.

If the central government does not inspect thoroughly, local governments are tending to slacken their requirements for manufacturing enterprises, with the resulting potential negative externalities of L.

When manufacturing enterprises conduct low-carbon management, the central government obtains a positive external benefit J. Their incentive expenditure for local governments is αJ.

When manufacturing enterprises do not conduct low-carbon management, the central government obtains negative externalities K. The penalty to local governments is βK.

The parameters setting is shown in Table 1.

3. Evolutionary game model

Evolutionary game theory is a theory which was derived from game theory and evolutionism. Typical game theory emphasizes the necessity for players to act rationally, and the whole process of the game is not allowed to make mistakes, and every decision-making step remains rational. However, the problem is, in the real world, people cannot be completely rational, let alone rational at every decision-making stage. The combination of evolutionary theory and game theory produces the evolutionary game theory, which rejects the hypothesis of complete rational. The evolutionary game theory can not only offer successful explanations for

Table 1
Parameter setting and meaning.

Parameter	Parameter meaning
C_1	Cost of manufacturing enterprises implementing low-carbon management
C_2	Cost of manufacturing enterprises implementing high-carbon management
C_3	Cost of local governments regulating implementation
C_4	Cost of local governments not regulating implementation
C_5	Cost of central government inspecting thoroughly
C_6	Cost of central government not inspecting thoroughly
F	Penalties for local governments not regulating implementation under thorough inspection
L	Potential negative externalities for not inspecting thoroughly
J	Positive externalities gained by the central government for low-carbon management of manufacturing enterprises
K	Positive externalities gained by the central government for high-carbon management of manufacturing enterprises
αJ	Incentives from the central government to local governments for low-carbon management of manufacturing enterprises
βK	Incentives from the central government to local governments for high-carbon management of manufacturing enterprises
S	Subsidies from local governments for low-carbon manufacturing enterprises
G_1	The central government's penalties for high-carbon manufacturing enterprises
G_2	Local governments' penalties for high-carbon manufacturing enterprises
R_1	Economic benefits achieved by manufacturing enterprises' low-carbon management
R_2	Economic benefits achieved by manufacturing enterprises' high carbon management

phenomena in biological evolution, but also explain the management and economic problems in reality better than ordinary game theory.

Up till now, evolutionary game has been universally applied in many fields such as medical sciences (Sartakhti et al., 2017), physics (Park and Traulsen, 2017), sociology (Zhang et al., 2023c). The basic formation process of evolutionary game theory is shown in Fig. 1. In terms of environment research, Estalaki et al. (2015) explored the impact of reward and punishment systems on water governance through evolutionary game. Zhang et al. (2019) used it to study regional collaboration in governance of environment.

In this research, evolutionary game can well simulate how the three subjects of enterprises, local governments and the central government realize carbon emission reduction driven by the central environmental protection inspectors.

3.1. Construction of the evolutionary game model

Considering the above, eight different strategic combinations of the evolutionary game among local governments, the central government and manufacturing enterprises are constructed, as well as the payoff matrix under different combination modes (Table 2).

3.2. Analysis of evolutionary game model

3.2.1. Analysis of the tripartite replication dynamics

(1) Evolution of the dynamic game of the central government

Suppose the expected benefits of the central government's strategy of "thorough inspection" and "not thorough inspection" are E_{x1}、E_{x2} respectively, and the average expected return is E_x. Then there are:

Expected benefits of the central government's "thorough inspection" strategy:

$$E_{x1} = yz(-C_5+J-\alpha J)+y(1-z)(-C_5-K+\beta K+G_1)+(1-y)(1-z)(-C_5+F-K+\beta K+G_1)+z(1-y)(-C_5+F+J-\alpha J) \quad (1)$$

Expected benefits of the central government's "not thorough inspection" strategy:

$$E_{x2} = yz(-C_6-L+J-\alpha J)+y(1-z)(-C_6-L-K+\beta K)+(1-y)z(-C_6+J-\alpha J-L+F)+(1-y)(1-z)(-C_6-L-K+\beta K+F) \quad (2)$$

The central government's average expected return is:

$$E_x = xE_{x1} + (1-x)E_{x2} \quad (3)$$

The replication dynamic equation of the central government's "thorough inspection" strategy is:

$$\begin{aligned} F(x) = \frac{dx}{dt} &= x(E_{x1} - E_x) \\ &= x[E_{x1} - xE_{x1} - (1-x)E_{x2}] \\ &= x(1-x)(E_{x1} - E_{x2}) \\ &= x(1-x)(-C_5 + G_1 - G_1 z + C_6 + L) \end{aligned} \quad (4)$$

Based on the stability theorem of replication dynamic equation, x needs to satisfy the constraints of $F(x) = 0$ and $F'(x) < 0$.

From $F(x) = 0$, it follows that $x_1 = 0$, $x_2 = 1$, $z^* = \frac{-C_5+G_1+C_6+L}{G_1}$.

The asymptotic stability of the central government strategy is analyzed accordingly, that is, the effect of changes in z on the evolutionary stability of x (Jiang et al., 2020).

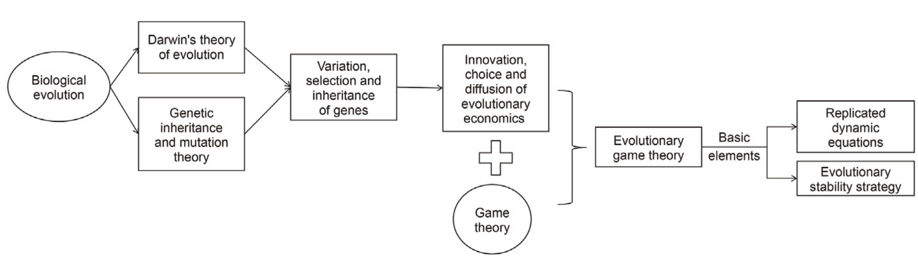


Fig. 1. The basic formation process of evolutionary game.

Table 2
Game payment matrix of the central government, local governments and manufacturing enterprises.

Strategy combinations	Central government's profit and loss	Local governments' profit and loss	Manufacturing enterprises' profit and loss
(1,1,1)	$--C_5+J-\alpha J$	$-C_3+\alpha J-S$	$-C_1+S+R_1$
(1,1,0)	$-C_5-K+\beta K+G_1$	$-C_3-\beta K+G_2$	$-C_2-G_1-G_2+R_2$
(1,0,1)	$-C_5+F+J-\alpha J$	$-C_4-F+\alpha J$	$-C_1+R_1$
(1,0,0)	$-C_5+F-K+\beta K+G_1$	$-C_4-F-\beta K$	$-C_2-G_1+R_2$
(0,1,1)	$-C_6-L+J-\alpha J$	$-C_3+\alpha J-S$	$-C_1+S+R_1$
(0,1,0)	$-C_6-L-K+\beta K$	$-C_3-\beta K-F+G_2$	$-C_2-G_2+R_2$
(0,0,1)	$-C_6+J-\alpha J-L+F$	$-C_4+\alpha J-F$	$-C_1+R_1$
(0,0,0)	$-C_6-L-K+\beta K+F$	$-C_4-\beta K-F$	$-C_2+R_2$

① When z=z*, $F(x)$ is equal to 0, and the system is always in a stable state. When the probability of manufacturing enterprises adopting the “low-carbon management” strategy is z*, the central government's strategic choice remains unchanged.
② When $z > z$*, $x_1 = 0$ is the only evolutionary stabilization strategy, when the probability of manufacturing enterprises adopting the “low-carbon management” strategy is increasing, the central government evolves from “thorough inspection” to “not thorough inspection".
③ When $z < z$*, $x_2 = 1$ is the only evolutionary stabilization strategy, when the probability of manufacturing enterprises adopting the “high-carbon management” strategy is increasing, the central government evolves from “not thorough inspection” to “thorough inspection".

(2) Evolution of the dynamic game of local governments

Suppose the expected benefits of local governments' strategy of “regulating implementation” and “not regulating implementation” are E_{y1}, E_{y2} respectively, and the average expected benefit is E_y. Then there are:

Expected benefits of local governments “regulate implementation":

$$E_{y1} = xz(-C_3+\alpha J-S)+x(1-z)(-C_3-\beta K+G_2)+(1-x)z(-C_3+\alpha J-S)+(1-x)(1-z)(-C_3-\beta K-F+G_2) \tag{5}$$

Expected benefits of local governments “do not regulate implementation":

$$E_{y2} = xz(-C_4-F+\alpha J)+x(1-z)(-C_4-F-\beta K)+(1-x)z(-C_4+\alpha J-F)+(1-x)(1-z)(-C_4-\beta K-F) \tag{6}$$

The local governments' average expected return is:

$$E_y = yE_{y1}+(1-y)E_{y2} \tag{7}$$

The replication dynamic equation of local governments' “regulating implementation” is:

$$\begin{aligned} F(y) &= \frac{dy}{dt} = y(E_{y1}-E_y) \\ &= y[E_{y1}-yE_{y1}-(1-y)E_{y2}] \\ &= y(1-y)(E_{y1}-E_{y2}) \\ &= y(1-y)(-Sz+Fz-C_3+G_2+Fx-G_2z-Fxz+C_4) \end{aligned} \tag{8}$$

First, analyze the impact of changes in x on the evolutionary stability of y:

Based on the stability theorem of replication dynamic equation, from $F(y)$=0, it follows that, $y_1=0$, $y_2=1$, $x^*=\frac{z(S-F+G_2)+C_3-G_2-C_4}{(1-z)F}$.

① When x=x*, $F(y)$ is equal to 0, and the system is always in a stable state. When the probability of the central government adopting the strategy of “thorough inspection” is x*, the strategy choice of the local governments remains unchanged.
② When $x > x$*, $y_2 = 1$ is the only evolutionary stabilization strategy, when the probability of the central government choosing the strategy of “thorough inspection” is increasing, the local governments will change from “not regulating implementation” to “regulating implementation".
③ When $x < x$*, $y_1 = 0$ is the only evolutionary stabilization strategy, when the probability of the central government choosing the strategy of “not thorough inspection” is increasing, the local governments will change from “regulating implementation” to “not regulating implementation".

Next, analyze the impact of the change of z on the evolutionary stability of y. Based on the stability theorem of the replication dynamic equation, from $F(y)$=0, it follows that, $y_1=0$, $y_2=1$, $z^*=\frac{C_3-G_2-C_4-Fx}{F-S-G_2-Fx}$.

① When z=z*, $F(y)$ is equal to 0, and the system is always in a stable state. That is, when the probability of manufacturing enterprises adopting the “low-carbon management” strategy is z*, the strategy choice of local governments remains unchanged.
② When $z > z$*, $y_2 = 1$ is the only evolutionary stabilization strategy, when the probability of manufacturing enterprises adopting “low-carbon management” is increasing, the local

governments will change from “not regulating implementation” to “regulating implementation".

③ When $z < z^*$, $y_1 = 0$ is the only evolutionary stabilization strategy, when the probability of manufacturing enterprises adopting “high-carbon management” is increasing, the local governments will change from “regulating implementation” to “not regulating implementation".

(3) Evolution of the dynamic game of manufacturing enterprises

Suppose the expected benefits of manufacturing enterprises' strategy of “low-carbon management” and “high-carbon management” are E_{z1}、E_{z2} respectively, and the average expected benefit is E_z. Then there are:

Expected benefits of manufacturing enterprises choosing the “low carbon management” strategy:

$$E_{z1} = xy(-C_1+S+R_1)+x(1-y)(-C_1+R_1)+(1-x)y(-C_1+S+R_1) +(1-x)(1-y)(-C_1+R_1) \tag{9}$$

Expected benefits of manufacturing enterprises choosing the “high carbon management” strategy:

$$E_{z2} = xy(-C_2-G_1-G_2+R_2)+x(1-y)(-C_2-G_1+R_2)+ (1-x)y(-C_2-G_2+R_2)+(1-x)(1-y)(-C_2+R_2) \tag{10}$$

The average expected return of manufacturing enterprises is:

$$E_z = zE_{z1} + (1-z)E_{z2} \tag{11}$$

The replication dynamic equation of manufacturing enterprises' strategy of “low-carbon management” is:

$$\begin{aligned} F(z) &= \frac{dz}{dt} = z(E_{z1} - E_z) \\ &= z[E_{z1} - zE_{z1} - (1-z)E_{z2}] \\ &= z(1-z)(E_{z1} - E_{z2}) \\ &= z(1-z)(Sy - C_1 + R_1 + G_1 x + G_2 y + C_2 - R_2) \end{aligned} \tag{12}$$

First, analyze the impact of changes in y on the evolutionary stability of z:

According to the replication dynamic equation stability theorem, from $F(z)=0$, it follows that, $z_1 = 0,\ z_2 = 1,\ y^* = \frac{C_1-R_1-G_1x-C_2+R_2}{S+G_2}$.

① When $y=y^*$, $F(z)$ is equal to 0, and the system is always in a stable state, when the probability of local governments adopting the strategy of “regulating implementation” is y^*, the enterprise's strategy choice remains unchanged.

② When $y > y^*$, $z_2 = 1$ is the only evolutionary stabilization strategy, when the probability of local governments adopting the strategy of “regulating implementation” is increasing, manufacturing enterprises will change from “high-carbon management” to “low-carbon management".

③ When $y < y^*$, $z_1 = 0$ is the only evolutionary stabilization strategy, when the probability of local governments adopting the strategy of “not regulating implementation” is increasing, manufacturing enterprises will change from “low-carbon management” to “high-carbon management".

Next, analyze the impact of the change of x on the evolutionary stability of z. Based on the stability theorem of the replication dynamic equation, from $F(z)=0$, it follows that, $z_1 = 0,\ z_2 = 1,\ x^* = \frac{C_1+R_2-C-_2G_2y-R_1-Sy}{G_1}$.

① When $x=x^*$, $F(z)$ is equal to 0, and the system is always in a stable state, when the probability of the central government adopting the “thorough inspection” strategy is x^*, the strategic choice of the enterprise remains unchanged.

② When $x > x^*$, $z_2 = 1$ is the only evolutionary stabilization strategy, when the probability of the central government adopting the strategy of “thorough inspection” is increasing, enterprises evolves from “high-carbon management” to “low-carbon management".

③ When $x < x^*$, $z_1 = 0$ is the only evolutionary stabilization strategy, when the probability of the central government adopting the strategy of “not thorough inspection” is increasing, enterprises evolves from “low-carbon management” to “high-carbon management".

From the above replication dynamic analysis, we can see that to the central government, its strategy is mainly influenced by the strategies of manufacturing enterprises. When manufacturing enterprises decide to conduct “low carbon management”, the top government will tend to “not inspect thoroughly”, and vice versa. When the manufacturing enterprises' carbon reduction situation deteriorates, the central government will promptly inspect and correct the deviation. It indicates that the central government plays an overall coordinating and regulating role, and does a good top-level design. When the overall situation is good enough, the central government can save resources and does not “thoroughly inspect".

Local governments' strategic choices are influenced by both manufacturing enterprises and the top government. The stronger the central government's supervision, the more the local governments will “regulate implementation”. When the central government's inspection decreases, bottom governments will be lax to “not regulate implementation”, which indicates that the top government largely influences local governments' decision as the “superior”. In addition, when manufacturing enterprises tend to choose “low carbon management”, local governments choose to “regulate implementation”. When manufacturing enterprises tend to choose “high carbon management”, bottom governments tend to “do not regulate implementation”. This indicates that local governments and manufacturing enterprises tend to act towards the same direction. With manufacturing enterprises choosing “low carbon management” and local governments “regulate implementation”, and carbon emission reduction will achieve good results. With manufacturing enterprises choosing “high carbon management”, local governments “do not regulate implementation”, the carbon emission reduction deteriorates. This indicates that the strategies taken by manufacturing enterprises and local governments for carbon emission reduction converge to a certain extent. It is possible that manufacturing enterprises and local governments will form alliances, resulting in rent-seeking corruption, etc., so thorough supervision by the central government is necessary.

Manufacturing enterprises' strategic choices are impacted by both the two-level governments. When local governments “regulate implementation”, manufacturing enterprises tend to choose” low-carbon management”, and vice versa. The central government's “thorough inspection” will encourage the “low-carbon management” of manufacturing enterprises. This suggests that both two level governments need to regulate and supervise the management models of manufacturing enterprises to achieve carbon reduction targets.

With all players are bounded rational, it is hard to achieve optimal strategy. The starting strategy of the three players will change in evolution. The impact logic is shown in Fig. 2.

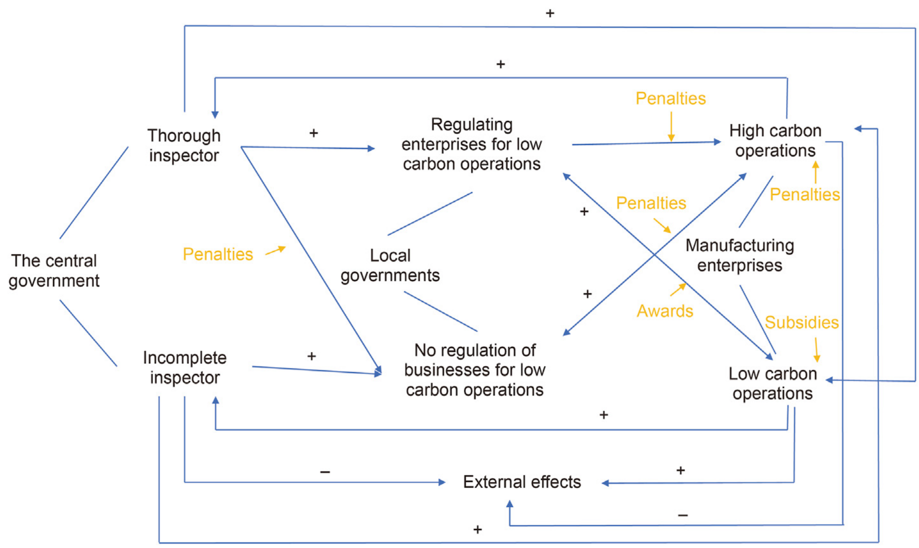


Fig. 2. Impact logic of the strategy choice of tripartite participants.

Table 3
Eigenvalues at each equilibrium state.

Equilibrium point	Eigenvalue		
	λ_1	λ_2	λ_3
(0,0,0)	$-C_5+G_1+C_6+L$	$-C_3+G_2+C_4$	$-C_1+R_1+C_2-R_2$
(0,0,1)	$-C_5+C_6+L$	$-S+F-C_3+C_4$	$C_1-R_1-C_2+R_2$
(0,1,1)	$-C_5+C_6+L$	$S-F+C_3+C_4$	$-S+C_1-R_1-G_2-C_2+R_2$
(1,0,0)	$C_5-G_1-C_6-L$	$-C_3+G_2+C_4+F$	$-C_1+R_1+C_2-R_2+G_1$
(1,1,0)	$C_5+C_6+L-G_1$	$C_3-G_2+C_4+F$	$S-C_1+R_1+G_1+G_2+C_2-R_2$
(1,1,1)	C_5-C_6-L	C_3-C_4+S-F	$C_1-C_2-G_1-G_2-R_1+R_2-S$
(1,0,1)	C_5-C_6-L	$-S+F-C_3+C_4$	$C_1-R_1-G_1-C_2+R_2$
(0,1,0)	$-C_5+G_1+C_6+L$	$C_3-G_2+C_4$	$S-C_1+R_1+G_2+C_2-R_2$

This study aims to propose an ideal low-carbon operation model that the central government thoroughly inspects, local governments regulate, and the manufacturing businesses conduct low-carbon management, that is, (1, 1, 1) is the optimal stable point expected.

3.2.2. *Evolutionary stability strategy analysis of three-party game*

By Lyapunov's system stability theory, the stable state of evolutionary system is determined by the eigenvalues of the Jacobian matrix. When the system is tending to stable, the matrix eigenvalues exhibit negativity. When the system is stable, all the eigenvalues are negative or equal to zero. And there are innumerable roots when the eigenvalues are equal to zero. Calculated by the three-party replication dynamic equation, the Jacobian matrix is:

$$\boldsymbol{J}=\begin{pmatrix}(1-2x)(-C_5+G_1-G_1z+C_6+L & x(1-x)(-C_5+G_1-G_1z+C_6+L & x(1-x)(-C_5+C_6+L\\ y(1-y)(-Sz+Fz-C_3+G_2+F-G_2z-Fz+C_4 & (1-2y)(-Sz+Fz-C_3+G_2+Fx-G_2z-Fxz+C_4 & y(1-y)(-S+F-C_3+C_4\\ z(1-z)(Sy-C_1+R_1+G_1+G_2y+C_2-R_2 & z(1-z)(S-C_1+R_1+G_1x+G_2+C_2-R_2 & (1-2z)(Sy-C_1+R_1+G_1x+G_2y+C_2-R_2\end{pmatrix}$$

Table 3 displays the eigenvalues corresponding to each equilibrium point state.

First, a (0,1,1) model without government involvement always has a negative effect to the strategic choices of local governments and enterprises, which prolongs the time taken for the whole system to achieve stabilization.

Second, the CEPI highlights the part played by the top government of supervising and encouraging the construction of ecology civilization. Taking the central government's proactive strategy into account reflects the need to implement this policy. As we said in this study: The CEPI addresses the administrative control dilemma of carbon emission reduction through top-down mobilization and resource reorganization, breaking conventional power structures (Xiang and van Gevelt, 2020).

If the ideal model is (0,1,1), then the significance of how the CEPI, the topic of this study, drives carbon emission reduction is absent. The ideal low-carbon operation model of (1,1,1) reflects the irreplaceable importance and central role of environmental protection inspection departments, especially the central level, in the comprehensive environmental regulatory system of China.

The three players are stabilized when the top government adopts "thorough inspection", bottom governments adopt "regulate implementation" and manufacturing enterprises adopt "low-carbon management". At this point, the characteristic values are:

$$\begin{cases}\lambda_1=C_5-C_6-L\\ \lambda_2=C_3-C_4+S-F\\ \lambda_3=C_1-C_2-G_1-G_2-R_1+R_2-S\end{cases}\tag{13}$$

The stability conditions are:

$$\begin{cases}C_5-C_6-L<0\\ C_3-C_4+S-F<0\\ C_1-C_2-G_1-G_2-R_1+R_2-S<0\end{cases}\tag{14}$$

The conditions should satisfy that the cost of low-carbon

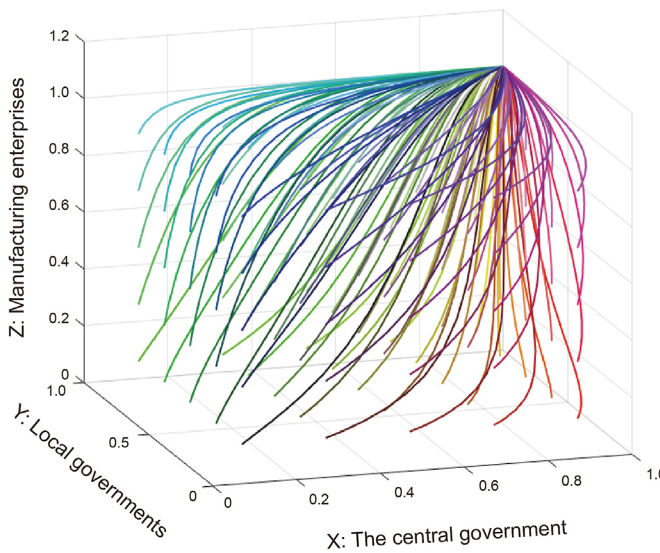


Fig. 3. Game strategy evolution diagram of three parties.

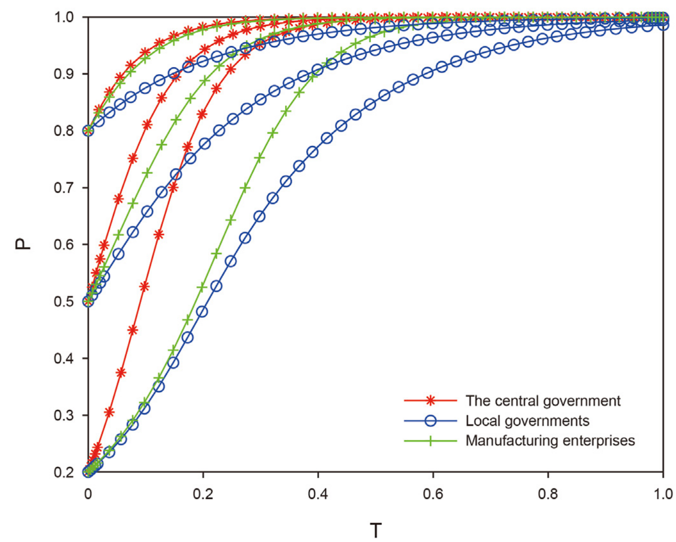


Fig. 4. Evolution results of simultaneous changes in participation willingness in *x*, *y*, and *z*.

management C_1 for manufacturing enterprises, C_3 for local governments regulating implementation, and C_5 for the thorough inspection by the central government are smaller than the cost of high-carbon management C_2 for manufacturing enterprises, C_4 for local governments not regulating implementation, and C_6 for not thorough inspection by the central government, respectively. The economic benefit R_2 obtained by high-carbon manufacturing enterprises is less than the economic benefit R_1 obtained by low-carbon manufacturing enterprises. Under the thorough inspection, the penalty F for local governments not regulating implementation is greater than the subsidy S that low-carbon manufacturing enterprises receive from local governments. That is, the smaller C_1, C_3, C_5, the larger R_1, F, the larger C_2, C_4, C_6, and the smaller R_2, S (S can be not small, but the strength of the fine must be greater than the strength of the subsidy), the more active all parties will fulfill their respective responsibilities to promote carbon reduction targets.

4. Numerical experiments and simulations

To validate the evolving path and stable state of the tripartite game, this study uses theoretical analysis and MATLAB simulations. The parameters are assigned numerical values based on replication dynamic equations and related constraints (Chu et al., 2021; Jiang et al., 2020; Zhang et al., 2019). The parameters of the game model should meet the economic assumptions and empirical judgments. The principle is to change the specific parameter but not the simulation results.

This study assumes parameters as: $C_1 = 1$, $C_2 = 2$, $C_3 = 2$, $C_4 = 4$, $C_5 = 3$, $C_6 = 6$, $F = 7$, $S = 4$, $L = 10$, $R_1 = 8$, $R_2 = 5$, $G_1 = 3$, $G_2 = 2$.

The evolving path of the three-player evolutionary game is shown in Fig. 3.

The evolving equilibrium state of the system is (1,1,1). At this point, the central government choose to inspect thoroughly, local governments choose to regulate, and manufacturing enterprises conduct low-carbon management.

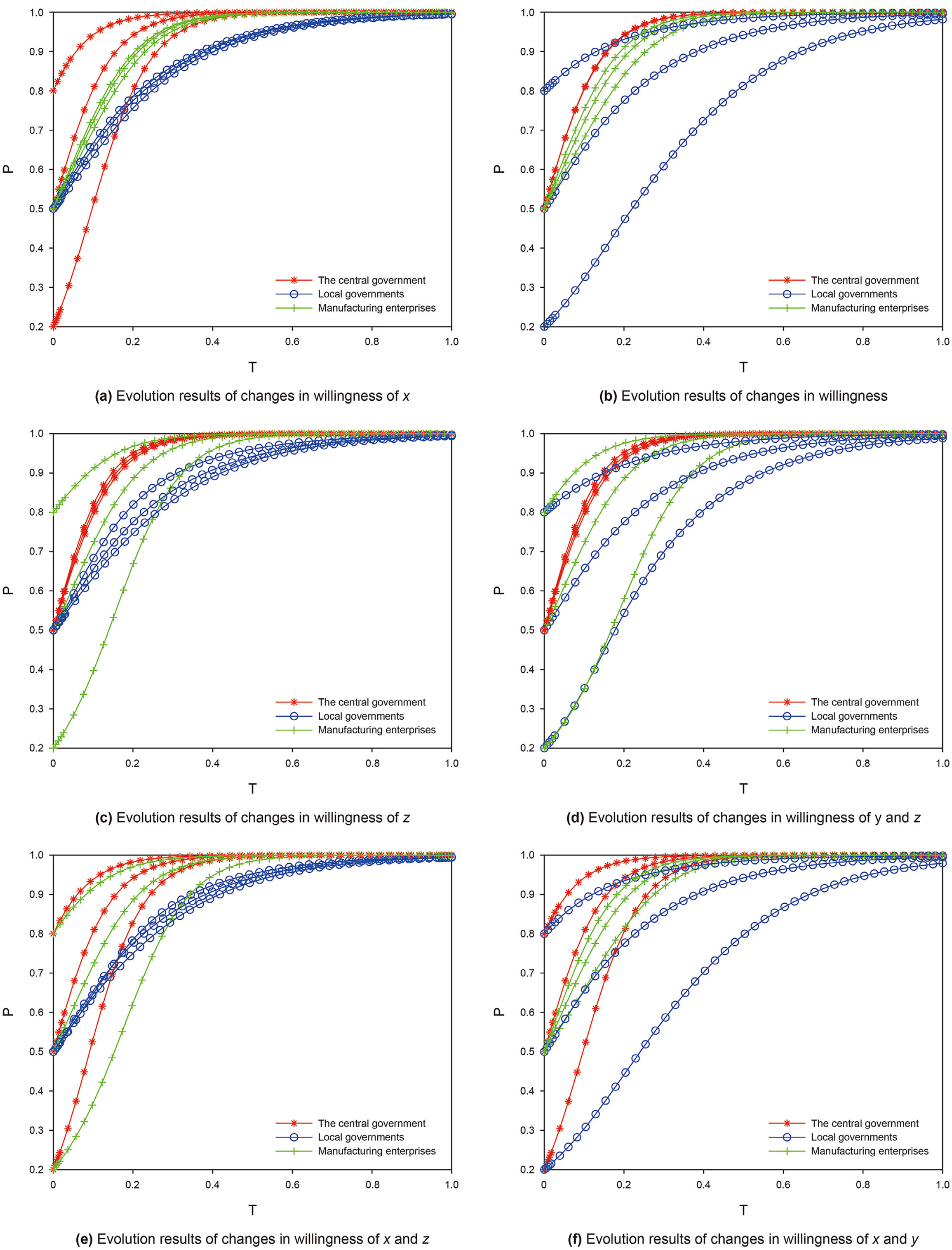
In summary, to make all parties adopt strategies that are conducive to carbon reduction, it is important to lessen the cost and increase the benefit of corresponding measures. Besides, the fines to manufacturing enterprises must be greater than the subsidies.

The carbon emission reduction mechanism under CEPI, with the participation of bottom governments and the execution of manufacturing businesses, is a prolonged dynamic game and cooperation process. In this three-player evolutionary game, local governments play a key role as intermediaries between the “top” and “bottom”, and the major factors impacting the evolution are analyzed accordingly. The impact of the yop government on bottom governments is mainly demonstrated in the penalties F, which is for local governments' not regulating implementation. The influence of the manufacturing enterprises on local governments is mainly reflected in the subsidies of local governments for low-carbon manufacturing enterprises S and the penalties of the local government for high-carbon manufacturing enterprises G_2. In this study, the evolution path of each party under different parameter values is obtained by analyzing initial willingness and assigning the three key parameters respectively.

4.1. Impact of initial participation willingness on the evolution of carbon reduction mechanisms

4.1.1. Simultaneous changes in the initial participation willingness of tripartite participants

Fig. 4 shows the simulation of the evolution of the carbon emission reduction mechanism by changing the initial participate intentions of the three players, with other parameters held constant. Given the assumption that the primary participate intention of businesses, local governments, and the central government are the same, that is, $x=y=z$, which increases from 0.2 to 0.5 to 0.8, respectively. The lower the three parties' initial willingness to participate, for the system, the longer it needs to evolve to cooperative governance. The local governments' willingness grows the slowest, while the central government's intention to participate grows the fastest. This also confirms the replication dynamic analysis above: as the intermediary of the supervisor government and manufacturing enterprises, local governments' strategy choice is influenced by multiple factors, so the growth is the slowest. As the “top-level designer”, the top government's increasing willingness to participate will lead to increasing inclination of local governments and manufacturing enterprises. Therefore, it has the most rapid growth.



(a) Evolution results of changes in willingness of *x*

(b) Evolution results of changes in willingness

(c) Evolution results of changes in willingness of *z*

(d) Evolution results of changes in willingness of y and *z*

(e) Evolution results of changes in willingness of *x* and *z*

(f) Evolution results of changes in willingness of *x* and *y*

Fig. 5. Evolution results of separate changes in participation willingness of *x*, *y*, and *z*.

4.1.2. Changes in the initial willingness of the central government to participate

Fig. 5(a) shows an imitation of the impact when the central government changes its intention to engage in the evolution, keeping other parameters constant. Given the assumption that the starting willingness of local governments and manufacturing businesses are the same, that is, $y=z=0.5$ (in a medium state), the primary participation inclination of the central government x increases from 0.2 to 0.5 to 0.8. When the central government change its starting intention, the willingness of enterprises and local governments will also change to a certain extent. If the top government's initial participation intention is low, the growth of bottom governments' and manufacturing enterprises' participation willingness will slow down accordingly, making the system take longer to reach a steady state.

4.1.3. Changes in the initial willingness of local governments to participate

Fig. 5(b) shows an imitation of the impact when the local governments change their starting participate intentions in the evolution of the carbon reduction mechanism, keeping other parameters constant. Given the assumption the starting participation intentions of the top government and manufacturing enterprises are equal, that is, $x=z=0.5$ (in a medium state), the initial participation inclination of local governments y grows from 0.2 to 0.5 to 0.8. When local governments change their starting intentions, the willingness of the enterprises and central government will also change to some extent. When the starting participation willingness of bottom governments is not high, the growth of local governments' and manufacturing enterprises' participation willingness slows down accordingly, making it longer to eventually reach a steady state. Meanwhile, manufacturing enterprises are more influenced by the shift in the initial intentions of local governments to participate compared to the top government. It also confirms that the central government is little affected by the primary participation intention of local governments as the "top designer" and "superior" of local governments.

4.1.4. Changes in the initial willingness of manufacturing enterprises to participate

Fig. 5(c) has shown the emulation of the impact when manufacturing enterprises change their starting intentions in the evolution, keeping other parameters constant. Given the assumption that the starting participation intentions of the two-level governments are the same, that is, $x=y=0.5$ (in a medium state), the initial participation inclination of manufacturing businesses grows from 0.2 to 0.5 to 0.8. When manufacturing enterprises change their starting intentions, the willingness of both top and bottom governments will also change to some extent. When the starting intention of manufacturing businesses to participate is low, the growth of the top government's willingness and bottom governments' willingness slow down accordingly, making the system take longer to reach stable eventually. What is more, the impact of the change on the starting participate willingness of manufacturing enterprises on local governments is greater than that on the central government, the change in the starting intention of manufacturing enterprises slows down the participation willingness of bottom governments greater than that of the top government. In addition, comparing Fig. 5(b) with Fig. 5(c), it can be found that when the initial change in the willingness of the same magnitude (from 0.2 to 0.5 to 0.8 in steps of 0.3), the impact of manufacturing enterprises on the top government's intention to participate is greater than the impact of bottom governments on the top government's intention to engage in. This confirms our analysis above: the central government's strategy is mainly influenced by manufacturing

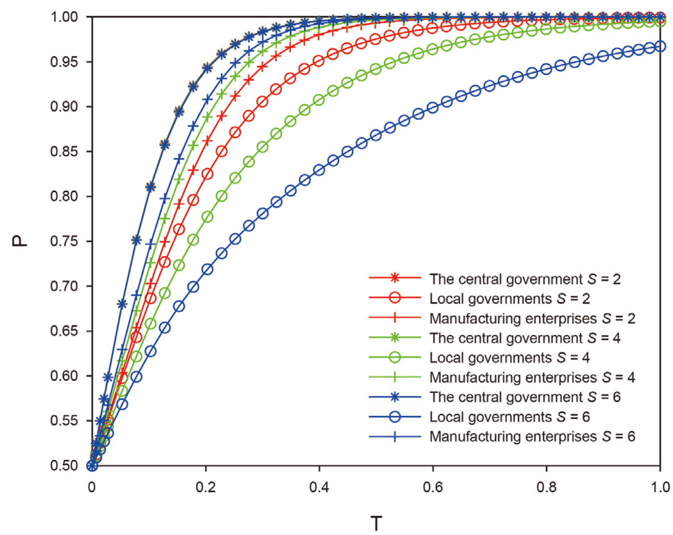


Fig. 6. Evolutionary results of changes of S.

enterprises. It is also consistent with the previous feedback logic that "the gains and losses from low-carbon management are fed back directly to the top government and indirectly to bottom governments".

4.1.5. Simultaneous changes in the initial willingness of local governments and manufacturing enterprises

Fig. 5(d) shows an emulation of the effect of the change when local governments change their starting intentions in the evolution, keeping other parameters constant. Given the assumption that the starting participation intention of the central government $x=0.5$ (in the medium), the starting participation intention of local governments and manufacturing businesses grows from 0.2 to 0.5 to 0.8. When the starting participation intention of local governments and manufacturing businesses is low, the participation intention of the central government decelerates accordingly, which makes the system take longer to reach a steady state.

4.1.6. Simultaneous changes in the initial willingness of the central government and manufacturing enterprises

Fig. 5(e) shows an emulation of the effect of the change when the central government and manufacturing businesses change their starting intentions in the evolution, keeping other parameters constant. Given the assumption that the starting participation intention of the local government $x=0.5$ (in the medium), the starting participation intention of central government and manufacturing enterprises grows from 0.2 to 0.5 to 0.8. When the starting participation intention of the top government and manufacturing businesses is low, the participation willingness of local governments slows down accordingly, which makes the system take longer to reach a steady state.

4.1.7. Simultaneous changes in the initial willingness of the central government and local governments

Fig. 5(f) shows an emulation of the effect of the change when the top government and bottom governments change their starting intentions in the evolution while keeping the other parameters constant. Given the assumption that the starting intention of manufacturing enterprises $x=0.5$ (in the medium), the starting intention to participate of the top government and bottom governments grows from 0.2 to 0.5 to 0.8. When the starting intention of the two-level governments is not high, the intention of manufacturing enterprises also slows down accordingly, which

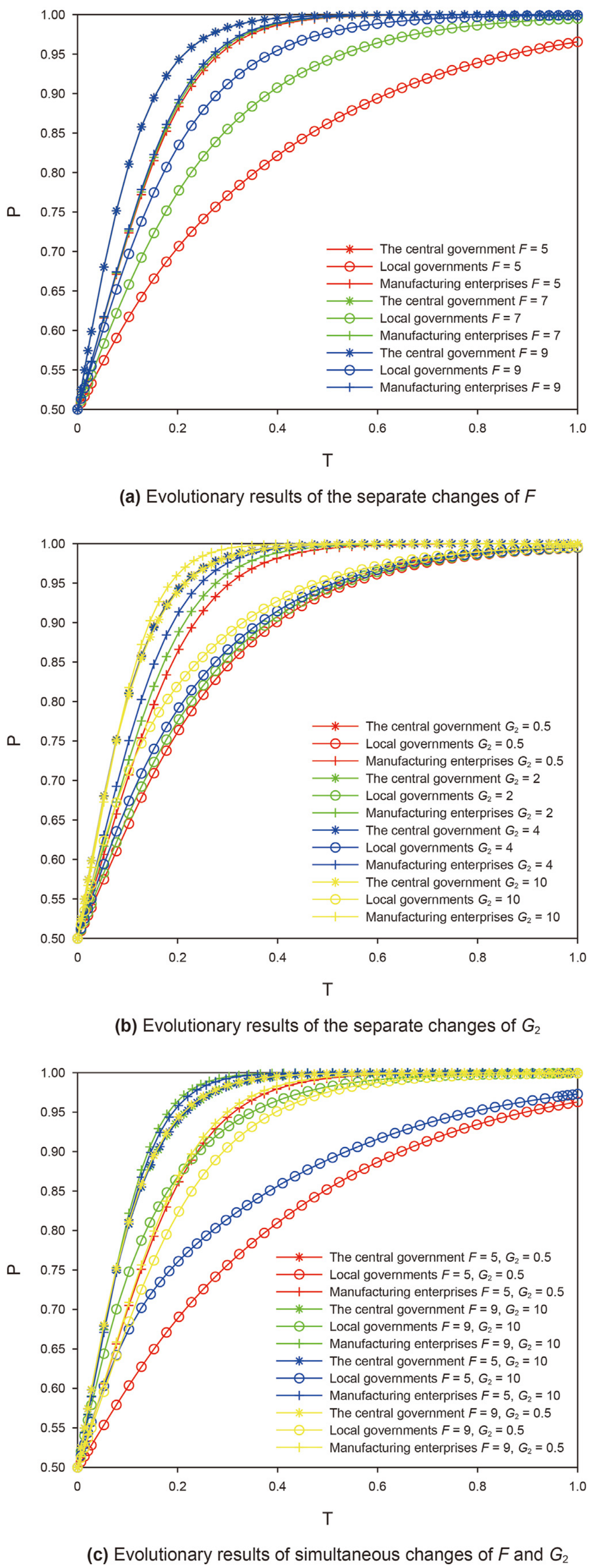


Fig. 7. Evolutionary results of changes of F or G_2.

makes the system take longer to finally reach a stable state. Comparing Fig. 5(d)–(f), with the change of the two parties affecting the third party, the impact on the participation willingness of the top government is less than that of bottom governments and manufacturing enterprises. This proves again that the central government, as the “top designer”, has a relatively stable willingness.

In summary, the eventual evolutionary equilibrium point is (1,1,1) regardless of how the initial state of the three parties changes as long as the constraints are satisfied. However, the three parties will influence and restrict each other, and the reduction of any party's initial willingness to participate will take a longer time for the entire system to achieve its final stability (Liu et al., 2015). Each party is affected differently. As the “top-level designer”, the growth in the willingness to participate of the top government will lead to an increase in the willingness of both manufacturing enterprises and local governments. The participation intention of the top government grows most rapidly and is the least affected. However, it is relatively more affected by the willingness of manufacturing enterprises. As the intermediary, the increase of the local governments' intention to engage in is affected by multiple factors, so the growth is the slowest.

4.2. Impact of subsidy intensity on the evolutionary mechanism of carbon emission reduction

Fig. 6 shows the emulation of impact of the variation in subsidies of local governments to low-carbon manufacturing enterprises on the evolution with other parameters held constant. When the subsidies gradually increase, the growth of local governments' participation willingness gradually slows down and manufacturing enterprises' willingness to conduct low-carbon management gradually increases, while the central government's participation willingness does not change significantly. This indicates that manufacturing enterprises are more inclined to conduct low-carbon management when they receive more subsidies. While local governments, as the financial supporters of subsidies, will reduce their willingness to participate due to the increase in fiscal expenditures. The central government is not very engaged in this process, so the willingness to participate does not changed significantly. Thus, the central government should give appropriate financial support to local governments to motivate their participation on the premise of ensuring its own willingness to participate (Zhao et al., 2012).

4.3. Impact of penalty intensity on the evolutionary mechanism of carbon emission reduction

The penalty intensity here includes two parts: first, the central government's penalty F for local governments' not regulating implementation under thorough inspection. Second, the local governments' penalty G_2 for high-carbon manufacturing enterprises.

4.3.1. Under thorough inspection, penalties F that the central government imposes on local governments for not regulating implementation changes separately

Fig. 7(a) shows demonstrating the effect of the shift in penalty intensity F on the evolution under thorough inspection with other parameters held constant. The penalty intensity F has no obvious impact on the top government and manufacturing enterprises, while bottom governments are greatly impacted by it. As the penalty intensity F grows, the intention of local governments to involve in increases and the time taken to achieve the final steady state decreases. Thus, the top government is supposed to impose a high level of penalty intensity for local governments' not regulating implementation with strict and top-level punishments.

4.3.2. Separate changes in G_2 of local governments' penalties for high-carbon manufacturing enterprises

Fig. 7(b) shows the emulation of the influence of changes in the local governments' punishment G_2 to high-carbon manufacturing enterprises on the evolution = with other parameters held unchanged. The penalty intensity G_2 has no obvious impact on the central government, while it significantly impacts to manufacturing enterprises and local governments. Increasing the penalty intensity G_2 results in an increase in the intention of local governments and manufacturing businesses to engage in. It also shortens the time to achieve the final stability. For being the penalized party and the punishing party respectively, manufacturing enterprises and local governments are in a zero-sum game, where one party damaged the other benefits. Thus, the local government should also maintain a high level of punishment for high-carbon manufacturing enterprises with strict and top-level penalties (Jiang et al., 2020; Cai and Kock, 2009).

4.3.3. Simultaneous changes in central government's penalties F for local governments and local governments' penalties G_2 for high carbon manufacturing enterprises

Fig. 7(c) shows an emulation of the effect of simultaneous changes in the central government's penalties F for local governments not regulating implementation under thorough inspection, and local governments' penalties G_2 for high-carbon manufacturing enterprises on the evolution, with the other parameters constant. Regardless of the combination of F and G_2, the central government's intention to participate is maintained at a relatively stable high level. When both F and G_2 remain a high level, the willingness of manufacturing enterprises and local governments to participate are also higher (Cai and Kock, 2009). While analyzing which one of F and G_2 has a stronger impact on the intention of local governments, when F increases from 5 to 9 (G_2 unchanged), the growth in local governments' participation intention (from the red line to the black line) is greater than the increase in local governments' participation willingness (from the red line to the blue line) when G_2 increases from 0.5 to 10 (F unchanged). Thus, the top government's penalty F for bottom governments' not regulating implementation is more influential under thorough inspection, which fully proves the importance of thorough inspection by the central government (Ji et al., 2015).

5. Conclusions and policy recommendations

It is inevitable to promote carbon emission reduction continuously to achieve CPCN targets. Manufacturing enterprises, local governments, and the central government need to form collaboration for promoting carbon reduction as the main participants of the tripartite governance. This research employs an evolutionary game to examine the internal logic of CEPI in promoting carbon emission reduction from the angle of the tripartite interests, analyzes the factors and interrelationships that affect the strategy choices of each party, and thus explores the evolutionary path and stable strategies. Except for the three players mentioned in the paper, others such as the media, the public, and the intermediary finances are also involved in the real world. Although including them will make the game scenario richer, the complexity of the game will skyrocket, and the solution will be too complicated, leading to the tendency of discussing the subject's strategy choices only by the simple control variable method. This approach has lost the kernel of the evolutionary game and is a kind of downgrading in the traditional model, which does not help the results well enough. Therefore, they are not considered in this study.

Combining theoretical research and numerical simulation, we can reach the following conclusion. (1) It is necessary to lower the cost and increase the benefits of implementing corresponding measures, and the fines imposed on manufacturing enterprises must be greater than the subsidies. The increase in penalty will lead to increases in the involvement willingness of local governments and manufacturing enterprises. (2) The central government plays a coordinating role as the “top-level designer”, whose participation willingness maintains at a high and stable level. However, the central government's strategic choice is mainly influenced by manufacturing enterprises. (3) When any party's participation willingness decreases, the whole system will take longer to reach the final stability. Among them, local governments are considered to be the key to the tripartite evolutionary game. (4) There exists a feedback mechanism that the tripartite participants influence each other. For the central government, when manufacturing enterprises tend to conduct low carbon management, the central government tends to “not inspect thoroughly”. For the local government, it tends to “regulate implementation” when the top government's inspection increases, and bottom governments tend to “regulate execution” when the manufacturing enterprises tend to conduct low-carbon management. For manufacturing enterprises, when bottom governments choose “regulate implementation” and the top government adopts “thorough inspection”, they would conduct “low-carbon management".

According to the research conclusions above, the following policy recommendations are proposed.

- All participants should strive to reduce their costs of implementing measures through institutional reforms, technological upgrades, and updating of specific measures. The fines for manufacturing enterprises must be stronger than the incentives.
- Under thorough inspection, the central government should appropriately offer financial support and subsidies to local governments to avoid excessive fiscal deficits. Both two-level governments need to regulate and supervise the management modes of manufacturing enterprises for achieving the carbon emission reduction goal.
- Local governments have crucial roles in the tripartite evolutionary game. To enhance their participation willingness, it is important to provide them with necessary resources, support, and enforcement capabilities. By empowering local governments, they can effectively regulate the implementation of carbon reduction measures and contribute to the stability and progress of the overall system.
- Punishment stringency should all be proper but not superficial. Penalties from both the two-level governments should be maintained at a high level with strict and top penalties.
- Thorough inspection from the central government is crucial. The central government is advised to implement a dynamic inspection system and carry out rounds of inspections with the quality of thorough inspections ensured.
- Recognizing the interdependence among the tripartite participants, it is essential to establish feedback mechanisms. When manufacturing enterprises tend to adopt low-carbon management, the central government should respond by conducting fewer inspections, motivating enterprises to continue their efforts. Similarly, when the central government increases inspection efforts, local governments should enhance their regulation implementation, while manufacturing enterprises should increase their focus on low-carbon management. These feedback mechanisms can ensure a dynamic and mutually reinforcing system.

Future researches can be carried out from the following aspects. First, the reason why local government is the slowest growth of the three main participants can be demonstrated through another method, such as the case study. Second, further research can take the public as one of the subjects to explore the impact mechanism of their behavior choices on the promotion of carbon emission reduction.

Data availability

The data used in this study is available upon request via the corresponding author.

CRediT authorship contribution statement

Zhen-Hua Zhang: Conceptualization, Methodology, Writing – original draft. **Dan Ling:** Data curation, Formal analysis. **Qin-Xin Yang:** Investigation, Software. **Yan-Chao Feng:** Funding acquisition, Supervision, Writing – review & editing. **Jing Xiu:** Validation, Visualization.

Declaration of competing interest

No conflict of interest exits in the submission of this manuscript, and the manuscript is approved by all authors for publication.

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