Engaging Stakeholders in Collaborative Control of Air Pollution: A Tripartite Evolutionary Game of Enterprises, Public and Government

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Abstract

In the current context of air pollution control, inconsistent interest demands from various stakeholders hinder efficient cooperative governance. This study developed a tripartite evolutionary game model to examine the decision-making mechanism of enterprises, the public, and the governments involved in China's air pollution control process. Using theoretical and simulation analysis, the study identifies critical factors of stakeholders' strategies and propose possible evolution paths for achieving collaborative air pollution control. The results showed that collaborative governance among the three stakeholders is the optimal path for air pollution control in China, which evolves through four stages: government regulation, enterprises' pollution control, public participation, and government withdrawal. Currently, China is currently in a transitional period from public participation to government withdrawal and should focus on introducing subsidy policies to encourage green technology innovation among enterprises, strengthen environmental information disclosure, and establish and improve public participation mechanisms. In the future, China should prioritize the construction of public participation channels, incentivize green technology innovation, and focus on synergistic effect of carbon emission reduction among enterprises. This will help achieve the possible government withdrawal stage where joint governance of the public and enterprises can effectively control air pollution, allowing the government to shift focus to other important environmental issues such as carbon emission reduction.

Keywords

Environmental regulation; Public participation; Pollution control; Tripartite evolutionary game; Air pollution

1. Introduction

Air pollution has caused a significant burden during China's rapid economic growth (Matus et al., 2012; Wang, C. et al., 2022), with 631,230 premature deaths attributed to $PM_{2.5}$ exposure in 129 cities in 2015 (Zhu et al., 2019). To reduce the health burden caused by air pollution, China's air pollution prevention and control policies have also been constantly changing, which has gone through three main stages from early policies, through the national total control policies, to "declaration of war against pollution" (Jin et al., 2016). However, conventional top-down planning and vertical accountability are insufficient for addressing the worsening air quality, and diverse governance approaches including more flexible market-based policies and bottom-up policies are recommended to confront the long-term challenges in nationwide attainment of air quality standards (Wang, 2021).

There have been many studies in different areas exploring air pollution control policies in China. Zheng et al. (2015) investigated the effeteness of provincial energy saving and emission reduction policies on local air pollution control, suggesting the positive effect of provincial energy saving regulations and two environmental standards. Wang et al. (2021) evaluated the effect of the Air Pollution Prevention and Control Action Plan using a Geographical Detector was used to quantify the impact of natural and socioeconomic factors on the $PM_{2.5}$. Hu et al. (2019) used a multiregion multisector

Computable General Equilibrium model to quantify the impacts of the Environmental Protection Tax Law policy on modulating air pollutants emissions. But these studies usually address emissions side of the issue and overlook the public goods attribute of the atmospheric environment, which has strong mobility that allows pollution and carbon dioxide to diffuse widely, involving multiple stakeholders such as emitters, regulators, and the affected public.

Stakeholders have diverse environmental agendas and political interests, resulting in different environmental concerns (Lam et al., 2019). Conflicting interests among stakeholders such as the national government, local governments, and enterprises often negatively affect the implementation of environmental policies (Shen and Lisa Ahlers, 2018; Sheng et al., 2020). China's current air pollution control is still dominated by the government (Tu et al., 2019; Zhang et al., 2019). Local governments prioritize plan-based policies because of authoritarian environmentalism in China, with greater focus on achieving specific goals, but may neglect other environmental challenges (Bao and Liu, 2022; Li, X. et al., 2019). While the government remains a central actor in processes of environmental governance, the roles and capabilities of both governmental and non-governmental actors have changed over time(Bulkeley and Mol, 2003). That is, the potential of enterprises and the public has not been fully developed, and stakeholders have not been effectively coordinated to participate in the process of air pollution control in China (Duan et al., 2020). Compared with the single government-led or market-led models, the collaborative governance model has the potential to achieve better governance outcomes, with medium transaction costs, medium management costs and efficient resource allocation. (Meng et al., 2021). Therefore, collaborative air pollution control should be promoted to achieve more efficient air pollution control by coordinating all stakeholders.

Despite the potential benefits of collaborative governance in air pollution control, various obstacles such as information gaps, limited capacity, lack of cooperation channels, and conflicts of interest can make coordination challenging. Nevertheless, in recent years, stakeholders in China have exhibited similar perceptions of environmental pollution at the national scale, with air pollution being of most concern (Liu et al., 2022), suggesting common interests and potential for cooperative governance. Given this context, the challenge can be framed as a multi-period public goods game dilemma involving multiple stakeholders with different interests and governance costs, as well as their interactions. Evolutionary game can be employed to address this challenge.

There are many studies have focused on environmental governance in China from the perspective of evolutionary games. Wang et al. (2011) and Fan et al. (2021) used the evolutionary game model to analysis the relationship between governments and polluting enterprises. Sun et al. (2021) and Gao et al. (2019) focus on the government itself, respectively discussing the game between the central government and local governments, as well as the upstream and downstream governments of rivers when dealing with environmental issues. Scholars have also paid attention to the three-party game in environmental governance. For example, Xu et al. (2018) discussed the game equilibrium and dynamic evolution of the government, environmental service companies, and pollutant discharge companies. Jiang et al. (2019) used the three-party evolutionary game to reveal the strategic adjustment of environmental supervision under China's fiscal decentralization. Chen et al. (2019) analyzed the tripartite relationship among the government, enterprises, and the public in environmental governance, and conducted an empirical analysis using panel data from 30 provinces in China. Despite exemplified in documents such as Agenda 21 and the initiatives of the World Bank that there is an emerging consensus that the public need to be more involved in the processes of environmental decision making (Bulkeley and Mol, 2003). These evolutionary game studies mainly considered stakeholders such as the central government, local governments, polluting companies, and environmental service companies, but paid less attention to public participation.

Arnstein (1969) proposed that public participation is a form of civic power and developed a "Ladder of Citizen Participation" which includes eight levels of participation. As a stakeholder in air pollution issues, the public has the right to participate in air pollution control. Recent studies have also revealed that proposals made by members of the Chinese People's Political Consultative Conference (CPPCC) have a more significant impact on the living environment than complaint letters (Zhang et al., 2019). This enlightens us that although evolutionary games are suitable for studying cooperative governance issues, the model parameters in current research are not comprehensive enough. When the subject of the public is included in the evolutionary game model, more detailed settings must be made to consider the impact of the form of participation. Additionally, the impact of government decentralization (Lin and Xu, 2022) and corporate innovation (Zhao and Sun, 2016) should be taken into account when studying the internal mechanisms of stakeholders. Here, we developed a tripartite evolutionary game model to examine the decision-making mechanism of enterprises, the public, and the governments involved in China's air pollution control process, expecting to identify its evolution scenarios and key factors under different evolution paths.

This paper is organized as follows. Section 2 presents a tripartite game model among enterprises, government and the public in the process of air pollution control. We introduced the model hypothesis, rationale for parameters and examines the evolutionary stable strategies of these stakeholders in collaborative air pollution control in China, by analyzing the asymptotic stability of the equilibrium points. Section 3 presents the evolutionary stable strategies and evolution paths under different scenarios. We analyzed the role of each stakeholder in each stage under the most feasible and reasonable scenario, and illustrated the influence of parameters on the stages. Section 4 presents our conclusions.

2. Material and methods

2.1 Model hypotheses

In this study, we assume that stakeholders in the air pollution control process include enterprises, the publics, and the government (Figure 1). There are interactions between them as well as some internal mechanisms that will affect the tripartite strategy, all of which will be used as parameters of the evolutionary game model. We introduce the criteria and reasons for selecting these game model parameters of each stakeholder in the following.

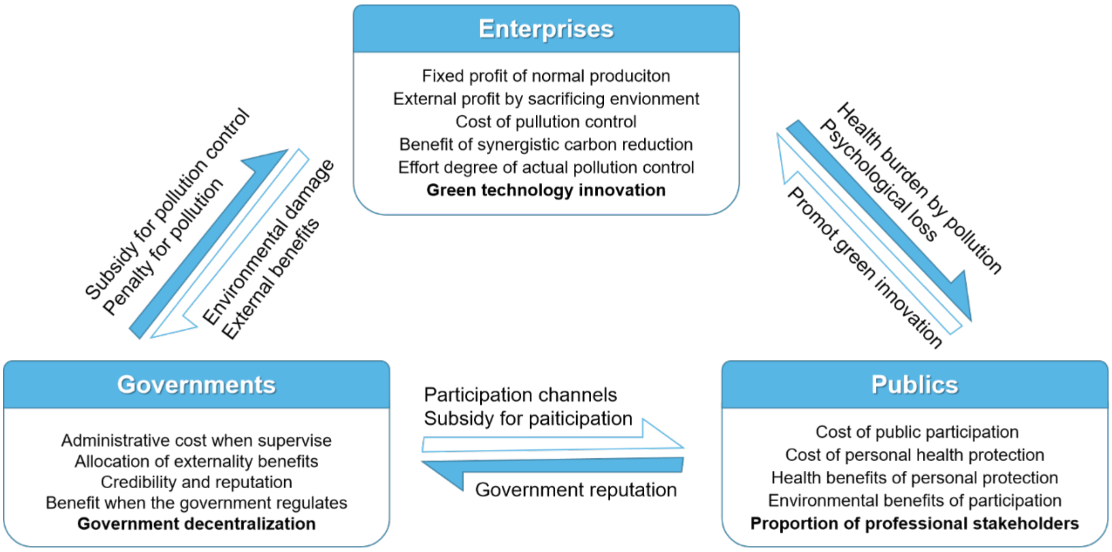

Figure 1. The relationship between the three stakeholders in collaborative control of air pollution in China. The arrow represents the interaction between stakeholders, and the rounded rectangle represents the internal characteristics of each stakeholder.

In this model, we assume that the strategies of enterprises are mainly driven by economic interests, and the Environmental, Social, and Governance (ESG) is omitted from the purpose of enterprises. Enterprises will calculate the cost-benefit of different decisions and choose the way to maximize the benefits. Hence, we aim to identify the following primary factors that influence strategies of enterprises on collaborative air pollution control. (1) Economic externality benefits. By prioritizing economic interests over an ESG strategy that internalizes the environmental externalities of companies(Tan and Zhu, 2022), enterprises may exacerbate air pollution at the expense of environmental quality to generate external benefits and boost profits. (2) Pollution control costs. When the enterprises completely control pollution, it is the sum of the cost of technology development, pollution control equipment purchases, and labor costs. (3) Government supervision. In response to the air pollution, the Chinese government has implemented several nationwide pollution standards and control measures over the past three decades (Zeng et al., 2019). The government offers subsidies to pollution control enterprises and impose penalties on those that fail to control pollution. (4) Enterprises green technology innovation ability. The "weak" version of the hypothesis posits that environmental regulation will stimulate environmental innovations but cannot bring about cost-saving innovation, which has also been confirmed in China (Jaffe and Palmer, 1997; Zhao and Sun, 2016). Therefore, our model assumes that the stronger the innovation capability, the lower the actual pollution control investment of the enterprise, but it cannot completely save the pollution control investment. (5) Synergistic emission reduction benefits. As study has found that the implementation of air pollutant emission targets will have a greater synergistic effect on CO_2 emission reduction (Li, H. et al., 2019), we assume that the corresponding carbon emission reduction benefits will be transformed into corporate profits through the carbon trading market.

Heightened public awareness of environmental degradation and increasing anxieties over health and property values drive people to participate in environmental decisions (Li et al., 2012). Thus, the parameters affecting public participation in our model mainly include (1) Health impact. The public's strategy between public participation and personal protection depends on the adverse health effects of air pollution. We assume that individuals will evaluate the costs and benefits associated with each option to determine their optimal strategy. (2) Costs and benefits of personal protection. When the public chooses personal protection, it includes the total cost and benefit of purchasing protective equipment and personal medical expenses. (3) Costs and benefits of public participation. Complex participation channels result in higher costs for the public, including time spent collecting information, reporting environmental concerns, and lodging complaints. The benefits of public participation include improved environmental quality, reduced health loss, and government subsidies for participants, as supported by evidence from previous studies. (4) Proportion of professional stakeholders. Referring to the ladder of citizen participation and the varieties of participation (Arnstein, 1969; Fung, 2006), our model simplifies the public into two categories: professional public and non-professional public. As mentioned in introduction that proposals made by members of the CPPCC have a more significant impact on the living environment than complaint letters (Zhang et al., 2019). We assume that when the proportion of the professional public is higher, the channel effectiveness of public participation is higher, and the actual environmental benefits obtained are higher.

Here we assume that the interests pursued by the government are the improvement of environmental quality and the reduction of public health burden. Although a study suggests a conflict of interest between the central and local governments regarding environmental regulation, rent-seeking behavior and promoting employment (Sheng et al., 2020). In this model, we regard the local governments as the stakeholder while central governments as regulatory authorities, and the main parameters affecting strategy of local governments are set as follows: (1) Administrative cost. The total cost input when the government chooses to regulate strictly, including human resources input, environmental protection supervision, information disclosure, etc. (2) Government reputation. A higher reputation can attract more new customers or companies to the local area to improve government performance(Andreassen, 1994), which can also be used for air pollution control. We assume that the governments' strategy on air pollution control will influence public opinion and contribute to enhancing the governments' reputation as a benefit of these efforts. (3) Policy costs and benefits. When the government chooses to regulate, the penalties for polluting enterprises and the subsidies for pollution control enterprises and public participation are the governments' benefits and costs, respectively(Fan et al., 2021; Zeng et al., 2019). (4) Environmental decentralization. China's environmental decentralization has significantly intensified the pollution emissions of enterprises, and the higher the degree of environmental decentralization, the better the reduction in $PM_{2.5}$ emissions (Lin and Xu, 2022; Xu et al., 2021). The environmental decentralization coefficient is added to the model. The higher the value, the more the local government pursues economic benefits, and the more they ignore environmental benefits.

In addition to setting model parameters concerning the above discussion, the model we will build next also follows these assumptions:

(1) The governments, enterprises, and the publics are all participants of bounded rationality, and none of them can reach the optimal strategy at the beginning of the game.

(2) The stakeholders in each population (enterprises/publics/governments) will continue to learn and adapt to changes in the environment, constantly optimize their own strategies during the game, and evolve towards the direction of the maximum average profit of the population.

(3) Each stakeholder has two possible strategies to cooperate (C) or defect (D). Specifically, enterprises have two pollution control strategies [control pollution (C), do not control pollution at all (D)], the publics have two behavioral strategies [public participation (C), personal protection (D)], and the government has two supervision strategy [regulation (C), non-regulation (D)].

When the evolutionary stable state of the game model is corporate pollution control, public participation, and government regulation, then our desired goal of collaborative control of air pollution will be achieved.

2.2 Tripartite evolutionary game model

Based on the above discussion, the parameters of the evolutionary game model are shown in Table 1, which could reflect the relationship between the three stakeholders as fully as possible. As discussed in the parameter (4) of each stakeholder in Section 2.1, we consider the parameters of corporate innovation capability (γ), the ratio of professionals to the public (ζ), and the coefficient of government decentralization (κ) as factors that show the internal mechanism of each stakeholder's decision-making.

Table 1. Description of major parameters

Parameters	**Description**	**References**
P_A	Fixed profit during normal production of the enterprises. ($P_A > 0$)	
P_e	The external profit obtained by sacrificing environmental quality when enterprises do not control pollution at all. ($0 < P_e < P_A$)	Tan and Zhu (2022)
C_A	The total cost of the enterprises for complete pollution control. ($C_A > 0$)	Fan et al. (2021)
e_A	Coefficient of effort degree of enterprises actually participating in pollution control. ($0 \leq e_A < 1$)	Jiang et al. (2019)
R_c	The maximum synergistic benefit of air pollution emission reduction on carbon emission when enterprises completely control air pollution emissions. ($0 < R_c < P_A$)	Li, H. et al. (2019)
α	Coefficient of subsidies given by the governments when enterprises control pollution. ($0 \leq \alpha < 1$)	Fan et al. (2021); Zeng et al. (2019)
β	The coefficient of governments fine when enterprises do not carry out pollution control. ($0 \leq \beta < 1$)	Fan et al. (2021); Zeng et al. (2019)
γ	The coefficient of the enterprises' green technology innovation capability. ($0 < \gamma < 1$)	Jaffe and Palmer (1997); Zhao and Sun (2016)
C_H	The loss of public health when enterprises do not control pollution. ($C_H < 0$)	Zhu et al. (2019)
C_{B1}	The total cost of public participation. ($C_{B1} > 0$)	
δ	The coefficient of the complexity of participation channels. ($0 < \delta < 1$)	Shen and Lisa Ahlers (2018)
C_{B0}	The cost of choosing personal health protection without public participation ($C_{B0} > 0$)	
P_{B0}	Health benefits of personal protection. ($P_{B0} > 0$)	
ε	Coefficient of subsidizing public participation when governments regulate. ($0 \leq \varepsilon < 1$)	
R_p	The environmental benefits of public participation include environmental improvements and reduced health losses. ($R_p > 0$)	
ζ	Proportion of professional stakeholders among public groups. ($0 < \zeta < 1$)	Arnstein (1969); Fung (2006); Zhang et al. (2019)
η	The coefficient of public participation on promoting green innovation of enterprises can increase the fixed profits of pollution control enterprises. ($\eta > 0$)	Zhao, L. et al. (2022)
θ	The coefficient on the strengthening of governments reputation gains or losses when public participation. ($\theta > 0$)	
λ	The coefficient of psychological loss when the public participates but the enterprises fail to control pollution. ($\lambda > 0$)	
C_{G1}	The total administrative cost when the governments strictly supervise. ($C_{G1} > 0$)	Bao and Liu (2022)
C_E	Environmental damage when enterprises do not control pollution at all, and is counted as a loss to the governments. ($C_E > 0$)	Jiang et al. (2019)
gov	The governments allocation coefficient of externality benefits. ($0 < gov < 1$)	
G_0	The loss of governments credibility and reputation when the governments do not regulate whether or not the public participates. ($G_0 > 0$)	Andreassen (1994)
G_1	The total benefit when the government regulates. ($0 < G_1 < G_0$)	
κ	Coefficient of government decentralization. ($0 < \kappa < 1$)	Lin and Xu (2022)

Note: for those parameters without references are our assumptions.

The payoffs for each subject under different combinations of strategies are calculated based on the research assumptions and model parameters.

For example, when all stakeholders chose to defect (D), meaning the enterprises do not control pollution, the public does not participate, and the governments do not regulate. (1) The payment of the enterprises is the fixed profit of normal production (P_A) plus the enterprises share of external profit ($P_e(1-gov)$). Thus, the expression of enterprises' payoff is given by $P_A + P_e(1-gov)$. (2) Similarly, the public's payoff is determined by the loss of public health (C_H) plus the benefit of personal protection (P_{B0}) minus the cost of personal protection (C_{B0}), i.e., $C_H + P_{B0} - C_{B0}$. (3) As for the governments, κ is the environmental decentralization coefficient. As mentioned in Section 2.1, we assume that the higher the degree of environmental decentralization, the more the government will pursue the external benefits obtained by sacrificing the environment, and underestimate the benefits brought about by improving the environment. In this case, its payoff includes reputation loss ($-G_0$), the governments' share of external income ($P_e\ gov$), and the environmental damage ($-C_E$). Hence, the governments' payoff expression becomes $-G_0 - \kappa P_e gov + C_E(1-\kappa)$.

When all stakeholders choose to cooperate (C), that is, when the enterprises control pollution, the public participates, and the governments regulate. (1) Different from the situation of no pollution control, even if the enterprises choose to control pollution, they may not completely control pollution. We assume that there is a coefficient the actual effort degree of enterprises pollution control (e_A). In addition, considering the coefficient of technological innovation capability (γ) can reduce its pollution control cost. The enterprises' payment consists of government subsidy (α) on the total income of enterprise, which is fixed profit of normal production (P_A) plus the enterprises share of external profit ($P_e(1-gov)$), the synergistic benefit of air pollution emission reduction (R_C), the role of public participation in promoting enterprises fixed profits ($\eta\, P_A$), and the cost of pollution control (C_A). Thus, the expression of enterprises' payoff is given by $e_A R_c + \eta P_A + (\alpha+1)\big(P_A + P_e(1-e_A)(1-gov)\big) - e_A C_A(1-\gamma)$. (2) As described in the model hypotheses in Section 2.1, we added two parameters, the proportion of professional public (ζ) and complexity of participation channels (δ). Similarly, the public's payoff is determined by the loss of public health (C_H), the benefit of public participation (R_p), the cost of public participation (C_{B1}), government's subsidy for public participation (ε), i.e., $\zeta R_p + C_H(1-e_A) - \delta C_{B1}(1-\varepsilon)$. (3) The government's payoff includes the total benefits of regulation (G_1) strengthened by the public participation (θ), administrative cost of regulation (C_{G1}), the subsidies for corporate pollution control (α) and public participation (ε), the government's share of external income ($P_e\, gov$), and the environmental damage ($-C_E$). Hence, the government's payoff expression becomes $G_1(\theta+1) - C_{G1} - \alpha\big(P_A + P_e(1-e_A)(1-gov)\big) - \delta\varepsilon C_{B1} - C_E(1-e_A)(1-\kappa) + \kappa P_e gov(1-e_A)$.

In the same way, the payoff of each stakeholder under other six combinations of strategies can be obtained (Table 2).

Table 2. Payoff matrix

Strategies	Payoffs

Enter-prises	Publics	Gover-nments	Enterprises	Publics	Governments
C	C	C	$e_A R_c + \eta P_A$ $+(\alpha+1)\big(P_A + P_e(1-e_A)(1-gov)\big)$ $-e_A C_A(1-\gamma)$	$\zeta R_p + C_H(1-e_A)$ $-\delta C_{B1}(1-\varepsilon)$	$G_1(\theta+1) - C_{G1}$ $-\alpha\big(P_A + P_e(1-e_A)(1-gov)\big)$ $-\delta\varepsilon C_{B1} - C_E(1-e_A)(1-\kappa)$ $+\kappa P_e gov(1-e_A)$
D	C	C	$P_A + P_e(1-gov)$ $-\beta\big(P_A + P_e(1-e_A)(1-gov)\big)$	$\zeta R_p + C_H(\lambda+1)$ $-\delta C_{B1}(1-\varepsilon)$	$G_1(\theta+1) - C_{G1}$ $+\beta\big(P_A + P_e(1-e_A)(1-gov)\big)$ $-\delta\varepsilon C_{B1} - C_E(1-\kappa) + \kappa P_e gov$
C	D	C	$e_A R_c$ $+(\alpha+1)\big(P_A + P_e(1-e_A)(1-gov)\big)$ $-e_A C_A(1-\gamma)$	$C_H(1-e_A) + P_{B0}$ $-C_{B0}$	$G_1 - C_{G1}$ $-\alpha\big(P_A + P_e(1-e_A)(1-gov)\big)$ $-C_E(1-e_A)(1-\kappa)$ $+\kappa P_e gov(1-e_A)$
D	D	C	$P_A + P_e(1-gov)$ $-\beta\big(P_A + P_e(1-e_A)(1-gov)\big)$	$C_H + P_{B0} - C_{B0}$	$G_1 - C_{G1} + C_E(\kappa-1)$ $+\beta\big(P_A + P_e(1-e_A)(1-gov)\big)$ $+\kappa P_e gov$
C	C	D	$e_A R_c + P_A(\eta+1)$ $+P_e(1-e_A)(1-gov) - e_A C_A(1-\gamma)$	$C_H(1-e_A) + \zeta R_p$ $-\delta C_{B1}$	$-G_0(\theta+1) - C_E(1-e_A)(1-\kappa)$ $+\kappa P_e gov(1-e_A)$
D	C	D	$P_A + P_e(1-gov)$	$C_H(\lambda+1) + \zeta R_p$ $-\delta C_{B1}$	$-G_0(\theta+1) - C_E(1-\kappa)$ $+\kappa P_e gov$
C	D	D	$e_A R_c + P_A$ $+P_e(1-e_A)(1-gov) - e_A C_A(1-\gamma)$	$C_H(1-e_A) + P_{B0}$ $-C_{B0}$	$-G_0 - C_E(e_A-1)$ $(\kappa-1) - \kappa P_e gov(e_A-1)$
D	D	D	$P_A + P_e(1-gov)$	$C_H + P_{B0} - C_{B0}$	$-G_0 + \kappa P_e gov - C_E(1-\kappa)$

Assuming that the probabilities of the three stakeholders adopting the cooperative strategy are x, y, z, respectively, then the probabilities of the three stakeholders choosing the defection strategy are $(1-x), (1-y), (1-z)$. We used the E_{A1} and E_{A2} to represent the expected payoffs of the enterprises for choosing control pollution (C) and not control pollution (D), respectively. $\bar{E}_A$ represents the average expected payoffs of the enterprises.

$$\begin{cases} E_{A1} = ENT._{CCC}\, yz + ENT._{CCD}\, y(1-z) + ENT._{CDC}\, (1-y)z + ENT._{CDD}\, (1-y)(1-z) \\ E_{A2} = ENT._{DCC}\, yz + ENT._{DCD}\, y(1-z) + ENT._{DDC}\, (1-y)z + ENT._{DDD}\, (1-y)(1-z) \\ \bar{E}_A = E_{A1}x + E_{A2}(1-x) \end{cases} \tag{1}$$

As shown in Table 1, $ENT._{CCC} = e_A R_c + \eta P_A + (\alpha+1)\big(P_A + P_e(1-e_A)(1-gov)\big) - e_A C_A(1-\gamma)$, $ENT._{DCC} = P_A + P_e(1-gov) - \beta\big(P_A + P_e(1-e_A)(1-gov)\big)$, $ENT._{CDC} = e_A R_c + (\alpha+1)\big(P_A + P_e(1-e_A)(1-gov)\big) - e_A C_A(1-\gamma)$, $ENT._{DDC} = P_A + P_e(1-gov) - \beta\big(P_A + P_e(1-e_A)(1-gov)\big)$, $ENT._{CCD} = e_A R_c + P_A(\eta+1) + P_e(1-e_A)(1-gov) - e_A C_A(1-\gamma)$, $ENT._{DCD} = P_A + P_e(1-gov)$,

$ENT._{CDD} = e_A R_c + P_A + P_e(1-e_A)(1-gov) - e_A C_A(1-\gamma), ENT._{DDD} = P_A + P_e(1-gov).$

Similarly, we can get E_{B1}, E_{B2}, and $\bar{E}_B$ for public, and E_{C1}, E_{C2}, and $\bar{E}_C$ for governments. Then, according to the formulation of replication dynamics for evolutionary games (Hofbauer and Sigmund, 1998), the replicator equation of enterprises adopting the control pollution strategy can be formulated in the following way:

$$FX = \frac{dx}{dt} = x(E_{A1} - \bar{E}_A) = x(1-x)\big((\alpha+\beta)(P_A + P_e(1-e_A)(1-gov))z + \eta P_A y - e_A P_e(1-gov) + e_A(R_c - (1-\gamma)C_A)\big) \quad (2)$$

We can also get the replicator equation of public adopting the participation strategy:

$$FY = \frac{dy}{dt} = y(E_{B1} - \bar{E}_B) = y(1-y)\big(\delta\varepsilon C_{B1}\, z - \lambda C_H\, x + C_{B0} - P_{B0} - \delta C_{B1} + \lambda C_H + \zeta R_p\big) \quad (3)$$

And the replicator equation of governments adopting the regulation strategy:

$$FZ = \frac{dz}{dt} = z(E_{C1} - \bar{E}_C) = z(1-z)\big(-(\alpha+\beta)(P_A + P_e(1-e_A)(1-gov))x - (\delta\varepsilon C_{B1} - (G_1+G_0)\theta)y + \beta\big(P_A + P_e(1-e_A)(1-gov)\big) - C_{G1} + G_0 + G_1\big) \quad (4)$$

Then, the three-dimensional dynamic system is constructed as follows:

$$\begin{cases} FX = \frac{dx}{dt} = x(E_{A1} - \bar{E}_A) = x(1-x)(A_1 z + A_2 y - A_3 + A_4) \\ FY = \frac{dy}{dt} = y(E_{B1} - \bar{E}_B) = y(1-y)(A_5 z - A_6 x + A_7) \\ FZ = \frac{dz}{dt} = z(E_{C1} - \bar{E}_C) = z(1-z)(-A_1 x - A_8 y + A_9 + A_{10}) \end{cases} \quad (5)$$

Where $A_1 = (\alpha+\beta)(P_A + P_e(1-e_A)(1-gov))$, $A_2 = \eta P_A$, $A_3 = e_A P_e(1-gov)$, $A_4 = e_A(R_c - (1-\gamma)C_A)$, $A_5 = \delta\varepsilon C_{B1}$, $A_6 = \lambda C_H$, $A_7 = C_{B0} - P_{B0} - \delta C_{B1} + \lambda C_H + \zeta R_p$, $A_8 = (\delta\varepsilon C_{B1} - (G_1+G_0)\theta)$, $A_9 = \beta\big(P_A + P_e(1-e_A)(1-gov)\big)$, $A_{10} = -C_{G1} + G_0 + G_1$.

When $\frac{dFX}{dt} = 0$, $\frac{dFY}{dt} = 0$, $\frac{dFZ}{dt} = 0$, we can get the eight pure strategic equilibrium points of three-dimensional dynamic systems: A(0, 0, 0), B(1, 0, 0), C(0, 1, 0), D(0, 0, 1), E(1, 1, 0), F(1, 0, 1), G(0, 1, 1), H(1, 1, 1). These pure strategic equilibrium points constitute the boundaries of the solution domain of the tripartite evolutionary game. The area enclosed by these boundaries (Ω) is the equilibrium solution domain of the tripartite evolutionary game:

$$\Omega = \{(x, y, z) | 0 < \mathrm{x} < 1; 0 < \mathrm{y} < 1; 0 < \mathrm{z} < 1\} \tag{6}$$

There are also six equilibrium points where a single population adopts a pure strategy, and they are $S_1(1, \frac{-A_1+A_9+A_{10}}{A_8}, \frac{A_6-A_7}{A_5})$, $S_2(\frac{-A_8+A_9+A_{10}}{A_1}, 1, \frac{A_3-A_2-A_4}{A_1})$, $S_3(\frac{A_5+A_7}{A_6}, \frac{A_3-A_1-A_4}{A_2}, 1)$, $S_4(0, \frac{A_9+A_{10}}{A_8}, -\frac{A_7}{A_5})$, $S_5(\frac{A_9+A_{10}}{A_1}, 1, \frac{A_3-A_4}{A_1})$, $S_6(\frac{A_7}{A_6}, \frac{A_3-A_4}{A_2}, 0)$. The conditions for the existence of S_1 are $0 < \frac{-A_1+A_9+A_{10}}{A_8} < 1$, $0 < \frac{A_6-A_7}{A_5} < 1$. Similarly, the conditions for other five points can also be obtained.

Moreover, the system may also have a mixed strategy equilibrium point $M(x^*, y^*, z^*)$ that satisfies Equation (7)

$$\begin{cases} x^*(1-x^*)(A_1 z^* + A_2 y^* - A_3 + A_4) = 0 \\ y^*(1-y^*)(A_5 z^* - A_6 x^* + A_7) = 0 \\ z^*(1-z^*)(-A_1 x^* - A_8 y^* + A_9 + A_{10}) = 0 \end{cases} \tag{7}$$

However, $M(x^*, y^*, z^*)$ should be discarded when $M \notin \Omega$.

According to Friedman (1991), the evolutionary stable state (ESS) points of the tripartite replication system can be judged by the Jacobian matrix local asymptotic stability analysis method. The Jacobian matrix of the tripartite evolutionary game is as follows:

$$J = \begin{cases} (1-2x)(A_1 z + A_2 y - A_3 + A_4) & x(1-x)A_2 & x(1-x)A_1 \\ -y(1-y)A_6 & (1-2y)(A_5 z - A_6 x + A_7) & y(1-y)A_5 \\ -z(1-z)A_1 x & -z(1-z)A_8 & (2z-1)(A_1 x + A_8 y - A_9 - A_{10}) \end{cases} \quad (8)$$

Evolutionarily stable strategies must be pure strategies if a condition of information asymmetry holds in the dynamic replication system of the multi-party evolutionary game when, and only when, it is a pure-strategy Nash equilibrium (Ritzberger and Weibull, 1995; Selten, 1988). That is to say, it is only necessary to test the asymptotic stability of the eight pure strategy equilibrium points in the tripartite game.

For example, the Jacobian matrix of the tripartite evolutionary game at the pure strategic equilibrium point A (0, 0, 0) is the following:

$$J_A = \begin{cases} -A_3 + A_4 & 0 & 0 \\ 0 & A_7 & 0 \\ 0 & 0 & A_9 + A_{10} \end{cases} \quad (9)$$

The eigenvalues of matrix J_A are $\lambda_{A1} = -A_3 + A_4$, $\lambda_{A2} = A_7$, $\lambda_{A3} = A_9 + A_{10}$, respectively.

By substituting all the eight pure strategy equilibrium points into Equation (8) and computing the corresponding Jacobian matrix. We can get the resulting eigenvalues of them (Table 3).

Table 3. Equilibrium points of the system and their eigenvalues.

Equilibrium point	**Eigenvalues** λ_1	λ_2	λ_3
A (0,0,0)	$e_A(R_c - P_e(1-gov) -C_A(1-\gamma))$	$P_{B0} - C_{B0} - C_{B1}\delta + C_H\lambda + R_p\zeta$	$G_0 - C_{G1} + G_1 +\beta(P_A + P_e(1-e_A)(1-gov))$
B (1,0,0)	$-P_{B0} + C_{B0} - C_{B1}\delta + R_p\zeta$	$G_0 - C_{G1} + G_1 -\alpha(P_A + P_e(1-e_A)(1-gov))$	$-e_A(R_c - C_A(1-\gamma) - P_e(1-gov))$
C (0,1,0)	$(G_0 + G_1)(\theta + 1) - C_{G1} +\beta(P_A + P_e(1-e_A)(1 - gov)) - C_{B1}\delta\varepsilon$	$C_{B1}\delta + P_{B0} - C_{B0} - C_H\lambda - R_p$	$e_A R_c + \eta P_A - P_e(1-gov) + P_e(1-e_A)(1-gov) -e_A C_A(1-\gamma$

D (0,0,1)	$-P_{B0}+C_{B0}+R_p\zeta+\lambda C_H$ $-C_{B1}\delta(1-\varepsilon)$	$R_c e_A$ $+(\alpha+\beta)\begin{pmatrix}P_A+P_e(1-e_A)\\(1-gov)\end{pmatrix}$ $+P_e e_A(gov-1)+C_A e_A(\gamma-1)$	$C_{G1}-G_0-G_1$ $-\beta(P_A+P_e(1-e_A)(1-gov))$
E (1,1,0)	$\delta C_{B1}+P_{B0}-C_{B0}-\zeta R_p$	$G_0(\theta+1)-C_{G1}+G_1(\theta+1)$ $-\alpha\left(P_A+P_e(1-e_A)(1-gov)\right)$ $-C_{B1}\delta\varepsilon$	$-R_c e_A-\eta P_A+P_e(1-gov)$ $-P_e(1-e_A)(1-gov)$ $-e_A C_A(\gamma-1)$
F (1,0,1)	$-P_{B0}+C_{B0}+R_p\zeta$ $-C_{B1}\delta(1-\varepsilon)$	$C_{G1}-G_0-G_0$ $+\alpha(P_A+P_e(1-e_A)(1-gov))$	$-R_c e_A-P_e(gov-1)$ $-(\alpha+\beta)\begin{pmatrix}P_A+P_e(1-e_A)\\(1-gov)\end{pmatrix}$ $-P_e(1-e_A)(1-gov)$ $+C_A e_A(1-\gamma)$
G (0,1,1)	$C_H+P_{B0}-C_{B0}-R_p\zeta$ $-C_H(\lambda+1)+C_{B1}\delta(1-\varepsilon)$	$C_{G1}-(G_0+G_1)(\theta+1)$ $-\beta\left(P_A+P_e(1-e_A)(1-gov)\right)$ $+C_{B1}\delta\varepsilon$	$R_c e_A+\eta P_A-P_e(1-gov)$ $+(\alpha+\beta)\begin{pmatrix}P_A+P_e(1-e_A)\\(1-gov)\end{pmatrix}$ $+P_e(1-e_A)(1-gov)$ $-C_A e_A(1-\gamma)$
H (1,1,1)	$P_{B0}-C_{B0}-R_p\zeta$ $-C_{B1}\delta(\varepsilon-1)$	$C_{G1}-(G_0+G_1)(\theta+1)+$ $\alpha\left(P_A+P_e(1-e_A)(1-gov)\right)$ $+C_{B1}\delta\varepsilon$	$-R_c e_A-\eta P_A+P_e(1-gov)$ $-(\alpha+\beta)\begin{pmatrix}P_A+P_e(1-e_A)\\(1-gov)\end{pmatrix}$ $-P_e(1-e_A)(1-gov)$ $+C_A e_A(1-\gamma$

3. Results and discussion

3.1 Evolutionary path analysis

According to Lyapunov (1992), the equilibrium point is asymptotically stable only when all eigenvalues are negative. That is, when $\lambda_1<0, \lambda_2<0$, and $\lambda_3<0$ are satisfied at the same time, the corresponding equilibrium point is the ESS.

For example, under the condition that the initial state point A (0,0,0) is an asymptotically stable equilibrium point, that is, when $\lambda_{A1}<0, \lambda_{A2}<0, \lambda_{A3}<0$ has been satisfied, enterprises do not control pollution, the public does not participate, and the governments do not regulate. In the same way, $\lambda_{B1}<0, \lambda_{B2}<0, \lambda_{B3}<0$ is satisfied when point B (0,0,1) is an asymptotically stable equilibrium point. The difference from point A (0,0,0) is that the government strategy has become regulation. In other words, from path A-B, in order for the government to choose regulation, it must meet the stability conditions of point A (and the initial order of the parameters in Table

1), and satisfy the stability conditions of point B. Then, comparing expressions of $\lambda_{A1}, \lambda_{A2}, \lambda_{A3}, \lambda_{B1}, \lambda_{B2}, \lambda_{B3}$, it can be found that the condition of A-B is $R_C - C_A(1-\gamma) > P_e(1-gov)$ (this is the condition 4 shown in Figure 2), meaning that the net profit of control pollution is great than the external profit of not controlling pollution. By analogy, we can get other conditions for cooperation, and construct the tripartite evolutionary path cube (Figure 2).

In initial state A (0,0,0), given that the externality benefit of corporate pollution abatement is greater than the total benefit after pollution abatement, which is due to low income of carbon emission reduction, high cost of pollution control technology and poor innovation ability of green technology, the stable strategy of the enterprises is not to control pollution. Starting from the initial state, to reach the ESS of corporate pollution control, we identified the following four different scenarios:

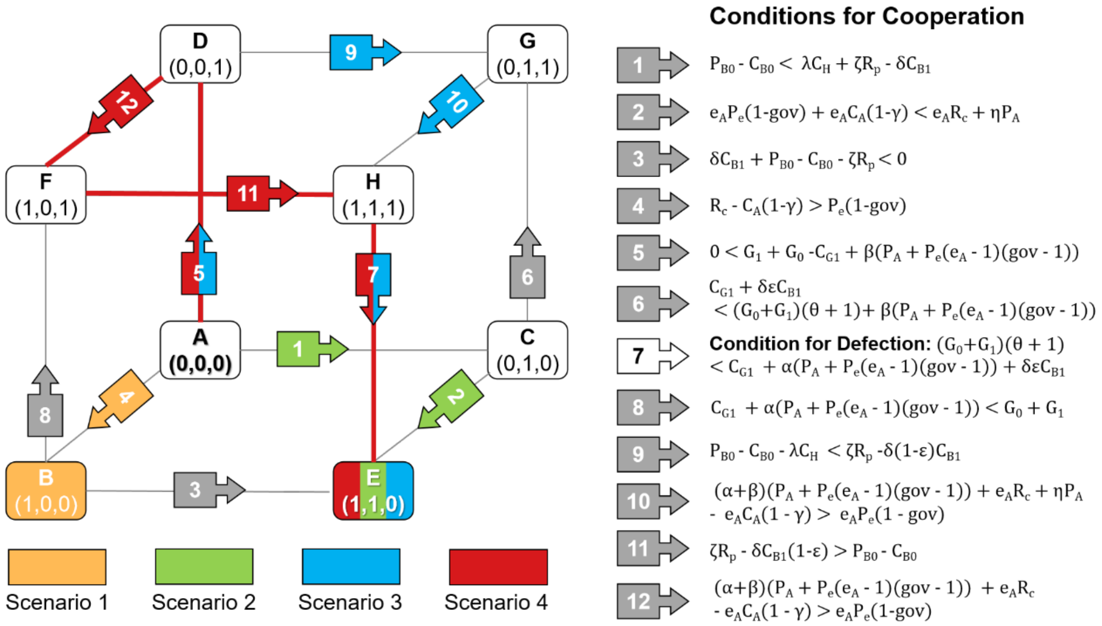

Figure 2. Three-player evolution path cube. The eight vertices on the left correspond to eight pure strategy equilibrium points, and the lines between each point correspond to the conditions of cooperation

(number 7 is the condition for defection). The specific conditional expressions are listed on the right. The identified paths under the four scenarios are represented by orange, green, blue, and red lines, respectively.

Scenario 1. The evolution path is A-B. The practical significance of condition 4 is that when the benefits of synergistic emission reduction minus the actual cost of pollution control are greater than the external benefits obtained by companies without pollution control, which requires green technology innovation. This should have been the most perfect path whereby enterprises could accomplish air pollution control even without government regulation or public participation. But the fact is that technological innovation is a long-term dynamic process, and it needs two steps of innovation and adoption to achieve pollution reduction or other goals, which requires time and cost(Jaffe et al., 2005). So far, there seems to be no such technological innovation that can definitely bring net profits and make polluting enterprises voluntarily take the initiative to control pollution, so this scenario is unrealistic.

Scenario 2. The evolution path is A-C-E. After conditions 1 and 2 are met successively, the ideal state of air pollution control can be achieved in a stable state where only public participation is required to cooperate with air pollution control, and the government does not need to supervise. The practical significance of this path is that the total income of public participation is greater than the total income from personal protection, and the total income of air pollution control is greater than the total income from non-pollution control. Similar to scenario 1, meeting condition 2 in stage 2 (C-E) of this scenario requires a well-established carbon trading market and enterprises with strong green technology innovation capabilities, which does not conform to the cognition of the gradual development of technology as mentioned in scenario 1. Furthermore, public consultation mechanisms in China always need to be facilitated and steered by local authorities, on which they are also highly dependent (Shen and Lisa Ahlers, 2018) indicating that it is challenging for the public to participate spontaneously in environmental governance under China's national circumstances. Although the China Air Pollution Map Application has a certain effect on inhibiting industrial pollution emissions, but its marginal effect will diminish over time, which shows that only the joint participation of government policies, the public, and enterprises can effectively control air pollutant emissions (Li, L. et al., 2018). Consequently, this path appears impractical.

Scenario 3. The evolution path is A-D-G-H-E. When conditions 5, 9, 10, and 11 are met successively, the system will gradually evolve from the initial state to E (1,1,0). That is to say, when the profit of the three stakeholders choosing the cooperation strategy is greater than the defection, the system will gradually evolve to H (1,1,1). In the final stage (H-E), the effect of government regulation is reduced and the government chooses to defect. The ideal state E (1,1,0) that only requires the participation of the public and enterprises to control pollution can be achieved. From the expressions of conditions 10 and 12, it can be seen that the two conditions are almost the same, except for the inclusion of the promotion coefficient of public participation in enterprises benefits (η) in condition 10. While it is true that public participation constraint plays an important role in promoting enterprises green technological innovation(Zhao, L. et al., 2022), we believe that the benefits derived from this participation are relatively insignificant when compared to the advantages of implementing green technological innovation itself. That is to say, the resistance faced by the evolution from D to F and G to H is nearly the same. When the government breaks the predicament, that is, when the system evolves to D (0,0,1), it can directly evolve to F (1,0,1) to encourage enterprises to participate in pollution control as soon as possible to achieve the primary purpose of pollution control, instead of promoting public participation. Consequently, Scenario 3 is practical but not reasonable enough.

Scenario 4. The evolution path is A-D-F-H-E. The only difference from Scenario 3 is that after government regulation, priority is given to promoting corporate pollution control instead of promoting public participation, which is more in line with the primary purpose of pollution control. Therefore, this scenario shows the most feasible and reasonable evolution path, suggesting that the cooperative governance of the three is the optimal solution to China's air pollution process. We will conduct a simulation analysis for each stage of this scenario in the next section.

3.2 Simulation analysis

The initial stage of each scenario is the same. Enterprises choose not to control pollution due to high external benefits, high treatment costs, and low carbon emission reduction benefits from coordinated emission reductions. The environmental health damage is still within the acceptable range of the public, the obstacles to public participation channels are substantial, the cost of public participation is too high, and the proportion of the professional public is low, making the public more inclined to personal protection. The governments choose not to regulate because of the high administrative costs of regulation, the low reputation loss of non-regulation, and the fact that government revenue also partially depends on enterprises' share of external profits.

The simulation parameters we set first need to meet the basic parameter relationship of the game model in Table 1, and also meet the condition that point A (0,0,0) is an asymptotically stable point ($\lambda_{A1} < 0, \lambda_{A2} < 0, \lambda_{A3} < 0$).

$$P_A = 40,\ P_e = 20,\ C_A = 35, e_A = 0.1, R_C = 10, \alpha = 0, \beta = 0, \gamma = 0.1$$

$$C_H = -30, C_{B1} = 30, \delta = 0.8, P_{B0} = 10,\ C_{B0} = 28, \epsilon = 0, R_p = 25, \zeta = 0.2, \eta = 0.1, \theta = 0.1, \lambda = 0.1$$

$$C_{G1} = 25,\ C_E = 30, gov = 0.5, G_0 = 10, G_1 = 5, \kappa = 0.8$$

In this case, as shown in Figure 3a, regardless of the proportion of the three stakeholders choosing to cooperate initially, the evolutionary stable state of the system in each scenario is the state A (0,0,0) in which all three stakeholders defect.

3.2.1 Evolutionary stages of Scenario 4

In Section 3.1, we identified Scenario 4 as the most practical path. As far as China's air pollution control process is concerned, the initial state of evolution corresponds to the early barbaric development state. During this period, enterprises were more likely to prioritize obtaining higher external benefits by directly discharging pollutants, at the expense of environmental quality. These practices were enabled, in part, by the defects in the legal system for the prevention and control of air pollution (PCAP) during the preceding phase, when the Chinese government first recognized the importance of environmental protection, beyond political considerations (Feng and Liao, 2016). Unfortunately, the general public had a low awareness of air pollution risks and no awareness of participation. Furthermore, the high degree of environmental decentralization in the initial state means that local government officials blindly pursue economic growth to get promoted, vigorously introduce high energy-consuming and heavy polluting enterprises but do not remediate polluting enterprises, and ignore environmental quality and choose not to regulate.

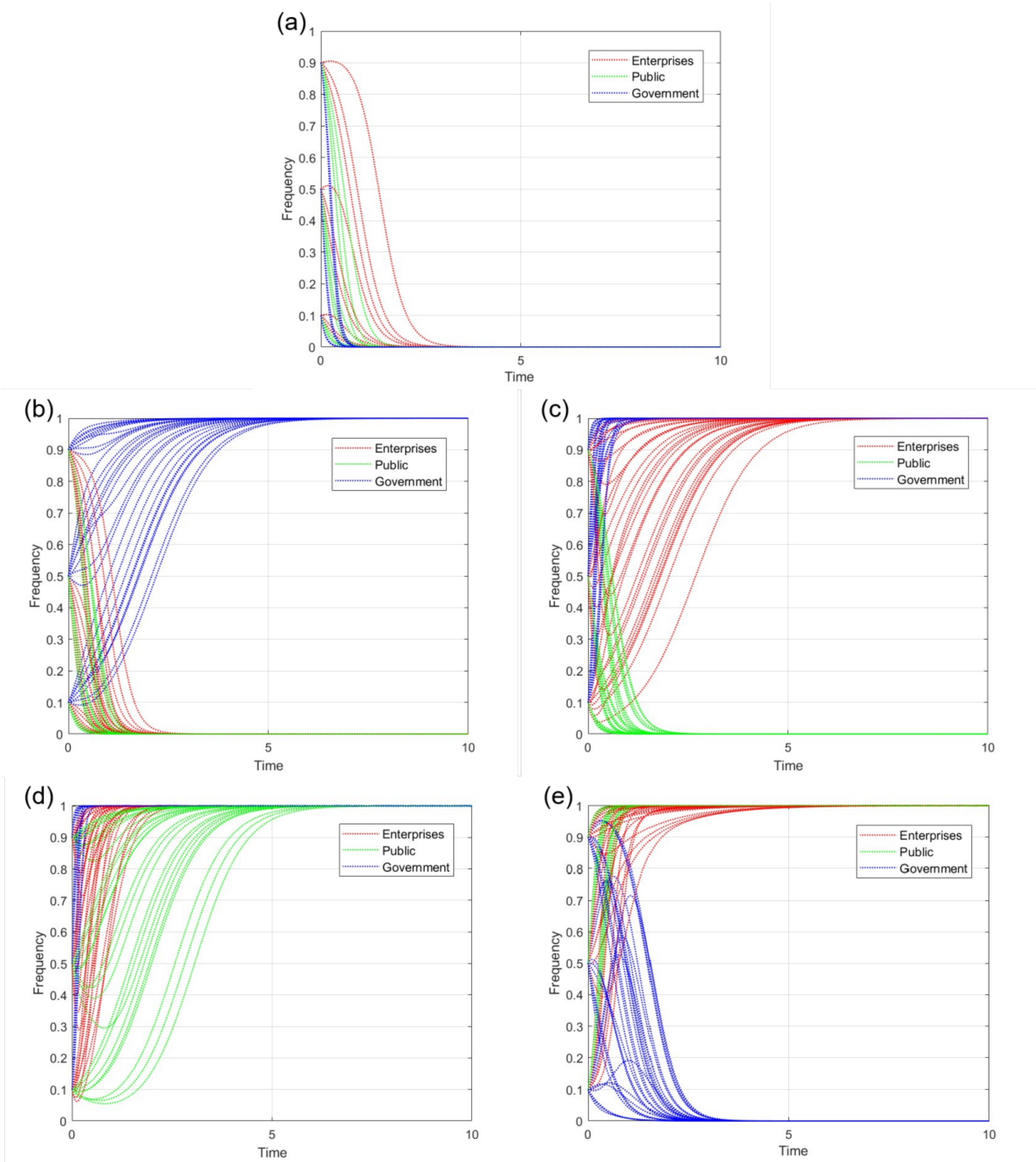

Figure 3. The evolution paths of the different stages of scenario 4. (a) The initial stage for all scenarios; (b) Stage 1 evolution towards sink D (0, 0, 1); (c) Stage 2 evolution towards sink F (1, 0, 1); (d) Stage 3 evolution towards sink H (1, 1, 1); (e) Stage 4 evolution towards sink E (1, 1, 0).

Since then, with economic development, pollution has intensified, and its negative impact on environmental governance and public health has gradually emerged. An inventory of air pollutant emissions in Asia in the year 2000 shows that emissions in China dominate the signature of pollutant concentrations in Asia (Streets et al., 2003).

Besides, news reports on environmental pollution in China have gone through two hot periods, the mid-to-late 1980s and the mid-to-late 1990s, indicating that the public's environmental awareness is constantly increasing (Zhang et al., 2021). Society has begun to pay attention to air pollution, and reputation pressure has been passed on to the government, forcing it to start controlling environmental pollution. In this case, the corresponding model parameters change as follows: $G_0 = 19, \beta = 0.05, e_A = 0.2$, and the other parameters remain unchanged. As shown in Figure 3b, the evolution of the three-party game reaches stage 1, and the government begins to supervise, which roughly corresponds to the period between the 1980s and 2000s in China.

After the government began to regulate, it took measures such as penalties for pollution and subsidies for treatment technology to encourage enterprises to control pollution (Figure 3c). In reality, the Chinese government has begun to control the total amount of air pollutants and regional joint prevention and control, and the prevention and control of acid rain and sulfur dioxide pollution has been included in the "Tenth Five-Year Plan" and "Twelfth Five-Year Plan." For the prevention and control of critical industries and enterprises, several air pollutant emission standards have been revised successively, and coordinated control of various pollutants has been carried out (Wang et al., 2019). The corresponding model parameters change as follows: $e_A = 0.4, R_c = 15, \alpha = 0.06, \beta = 0.2, G_1 = 10$. This stage roughly corresponds to the period between the 2000s and 2010s in China.

Since then, an essential stage of environmental governance has come. In the context of government regulation and corporate pollution control, to allow the public, a stakeholder, to participate in air pollution control, the government has begun to build channels for public participation, strengthen the intensity of information disclosure, carry out publicity and education, and subsidize public participants (Figure 3d). In reality, air pollution is getting worse and has endangered public health(Huang et al., 2023), research shows that ambient $PM_{2.5}$ pollution led to 631,230 premature deaths in 129 cities in 2015 (Zhu et al., 2019). In 2010, the former Ministry of Environmental Protection opened the "12369" environmental reporting hotline, and in 2015 opened the new media method of WeChat environmental reporting, making it easier to report pollution and allowing the public to participate in air pollution control to safeguard their vital interests (Wang et al., 2019). At the same time, the carbon market is also developing, corporate pollution control and coordinated emission reductions have begun to have positive benefits, and actual pollution control efforts have also increased. These responses are as follows in the model parameters: $\delta = 0.6, \varepsilon = 0.1, \zeta = 0.3$ $e_A = 0.6, R_c = 20, G_0 = 25, G_1 = 15$. This stage roughly corresponds to the period from 2010s to the present in China.

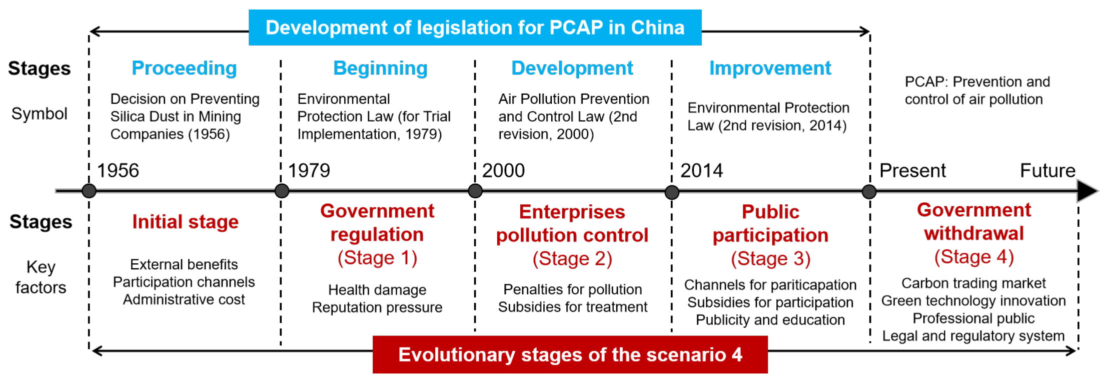

Figure 4. Comparison of different stages of PCAP and evolutionary stages of Scenario 4.

The legal system for PCAP in China can also be divided into four stages: pioneering, start-up, development, and improvement (Feng and Liao, 2016), and the corresponding relationship with the evolution path of the scenario 4 is shown in Figure 3. Combined with the above analysis, we believe that China is currently in the transition period from stage 3 to stage 4, and should focus on promoting coordinated emission reduction and tapping the potential of the carbon emission reduction market. And pay more attention to the role of the public, establish and improve public participation channels, and strengthen environmental information disclosure and environmental protection publicity and education to promote public participation.

We also believe that the system should be able to evolve to the optimal stage 4, as shown in Figure 3e and Figure 4. At this time, governmental supervision may not be necessary to ensure the control of air pollution, as reliance on public participation and corporate pollution control can suffice. The practical significance of this stage is that during later stage of economic development, high-polluting enterprises have been eliminated, resulting in reduced external benefits for enterprises. Therefore, enterprises must continuously innovate green technology to reduce the cost of pollution control technology. At the same time, the carbon trading market is already highly developed, and synergistic emission reduction from collaborative air pollution control offers greater benefits than external benefits, making pollution control a natural choice.

In addition, the public has access to sufficient environmental information through channels gradually established by the government in the early stages. Furthermore, a high proportion of professional public, including members of the CPPCC, are actively engaged in promoting corporate pollution control. These individuals can provide valuable proposals through the CPPCC to improve the living environment, beyond simply submitting complaint letters (Zhang et al., 2019). Based on the above situation, continued government supervision would only result in unnecessary administrative costs. Instead, once an established environmental laws and regulations system is in place (i.e., to reach later stage of "Improvement" of PCAP in Figure 4), government supervision can be withdrawn, and an ideal joint governance situation between enterprises and the public can be achieved. We believe that this will not only effectively control air pollution but also allow the government to shift its focus to other important issues, optimizing the allocation of its resources. The corresponding model parameters change as follows: $P_e = 10, e_A = 0.7, R_c = 30, \gamma = 0.3, \alpha = 0, \delta = 0.5, \varepsilon = 0, \zeta = 0.2, G_0 = 15, G_1 = 5.$

3.2.2 Key parameter simulation analysis

Going back to the unreasonable Scenario 1, we have focused on the impact of the two parameters of enterprises innovation capability (γ) and collaborative emission reduction benefits (R_c) on the evolution state of the system through simulation analysis. It can be seen that in the initial state, upgrading innovative technologies cannot effectively promote corporate pollution control (Figure 5a), while developing a carbon trading market cannot effectively promote corporate pollution control (Figure 5b).

Despite the difficulties to achieve from the initial state, it reflects the importance of carbon emission reduction policies.

Combined with the previous discussion on Scenario 4, we can see that the benefits of synergistic carbon emission reductions at each stage have played a positive role in the evolution of the system towards the final state. The Chinese government has established ambitious goal to reach its carbon peak by 2030 and achieve carbon neutrality by 2060(Wang, P. et al., 2022), despite facing numerous challenges (Zhao, X. et al., 2022). Thus, reducing carbon emissions will be a critical undertaking for China to address climate change in the future(Pu et al., 2022; Wang et al., 2023). Recent study has made it clear that CO_2 emission reduction activities will significantly promote $PM_{2.5}$ emission reduction (Dong et al., 2019). This discovery has inspired us that while formulating carbon emission reduction policies, attention should be paid to the co-design with air pollution control policies. Such an approach would enable the simultaneous achievement of the objectives of carbon and pollution emission reduction with minimal investments.

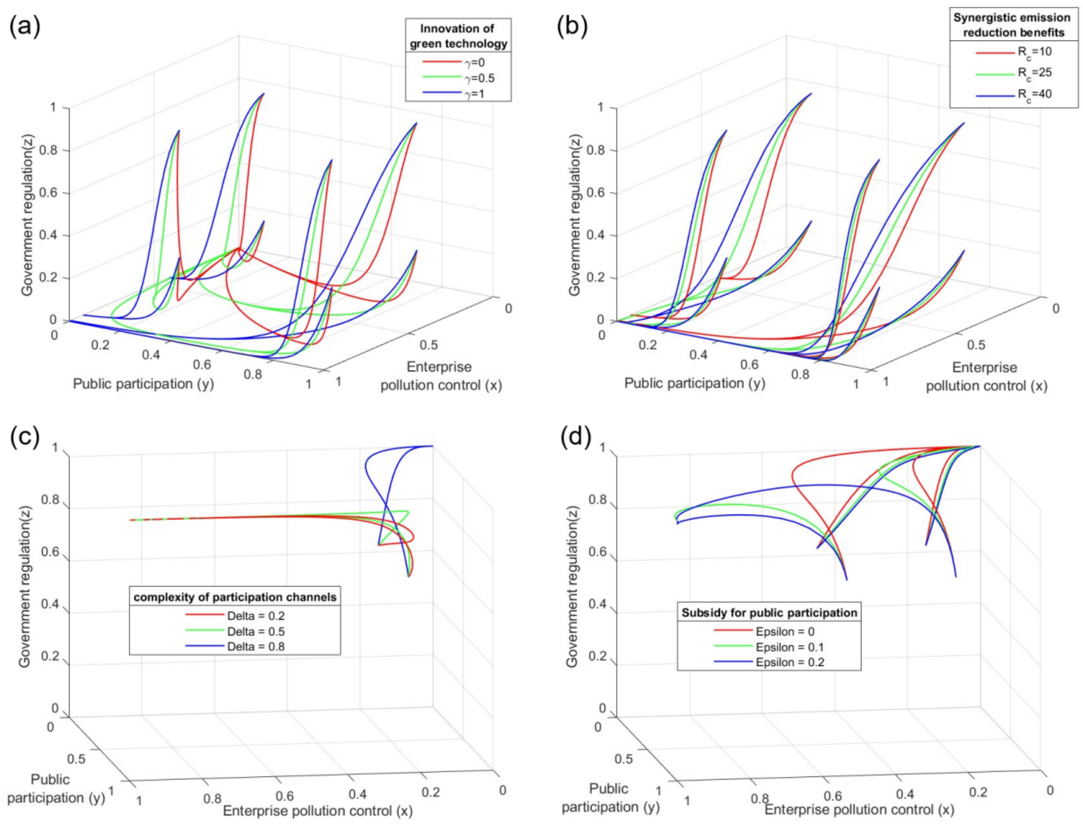

Figure 5. Evolutionary path diagram when a certain parameter changes. (a) Changes in capabilities of green technology innovation. (b) Changes in the benefits of synergistic emission reductions. (c) Changes in the complexity of participation channels. (d) Changes in the subsidy coefficient for public participation.

Going back to Stage 1 of Scenario 3, we find that when the government starts to regulate, if we increase subsidies for public participation or establish public participation channels, we can still evolve to H (1,1,1) (Figure 5c & 5d). Although this depends on the proportion of the three stakeholders choosing to cooperate, especially when the probability of government regulation is at a high level, it still reflects the great potential of public participation.

In the process of managing the environment in reality, it is not only necessary to assess the stage of development that the reality is in, but also to select the variables that have the greatest impact on the evolutionary stable state based on the cooperation probability of the three stakeholders, and to formulate targeted strategies to ensure that the ideal state is reached faster. It can be seen that public participation has great potential to promote corporate pollution control, but this requires the government to disclose enough environmental information and establish communication channels to promote public participation. As the public's awareness of environmental degradation grows, government should build a meaningful institutional framework to engage the public participation and get their voices heard (Li et al., 2012).

Different environmental policy tools may have diverse governance effects due to differences in their implementers and mechanisms. Referring to our results, we emphasize that in addition to government-led command-and-control policies, it is also necessary to explore economic stimulus and persuasion-based policies led by enterprises and the public, so as to promote pollution control through market means and public power.

3.2.3 External validity

Our conclusion is consistent with Tu et al. (2019) research that although the government plays a major role in environmental governance, the way to better deal with environmental challenges is the joint efforts of the government, the public and enterprises. Moreover, In addition, some scholars have applied the coupling coordination model and found that although the level of environmental collaborative governance is not high, the degrees of government-corporation-public collaborative governance generally keep increase (Duan et al., 2020), which also confirms our judgment on the current evolution stage of air pollution control. That is, China is still in the stage of tripartite cooperation in air pollution control. In addition to this, we have additionally identified that there may be a phase of government withdrawal in the future, reflecting our additional contribution.

Since our tripartite evolution model is tailor-made for China and cannot be directly copied to other countries and regions, it is necessary to reconsider the inclusion of stakeholders and parameters according to local conditions. The United States and Canada, Germany and France, China and Japan are respectively in the green technology network cooperation centers of the Americas, Europe and Asia, and the determinants of their technology cooperation are different (Li et al., 2021). This will affect the initial value of the green technology innovation capability of enterprises, and countries with extremely advanced green technology are expected to even achieve corporate environmental autonomy (corresponding to Scenario 1 of this study). China's environmental non-governmental organizations (ENGOs) are playing an increasingly important role in environmental governance, while the role of ENGOs has long been recognized by foreign scholars (Li, G. et al., 2018). For countries with a more developed environmental public participation level, their participation channels, professional public proportions, and the in promoting enterprise pollution control may be better, and those countries are expected to reach the stage of collaborative governance between the public and enterprises envisioned in this study earlier.

Affected by various factors, even to deal with the same environmental challenges, each region may have different kinds of stakeholders, evolution paths and evolution stages, resulting in the need for environmental strategies tailored to local conditions.

4. Conclusion

In the current context of air pollution control, inconsistent interest demands from various stakeholders hinder efficient cooperative governance. This situation constitutes a multi-period public goods game dilemma involving multiple stakeholders with different interests and governance costs, as well as their interactions. This study uses a tripartite evolutionary game method to examine the decision-making mechanism of various stakeholders in China's air pollution control process. We attempt to explore the evolution scenarios of cooperative governance with compatible interests from the internal mechanism and mutual influence of their decision-making, finding that the collaborative governance among the three stakeholders is the optimal path for China's air pollution control.

In the tripartite collaborative air pollution control in China, government regulation, enterprises' pollution control, public participation, and government withdrawal constitute four stages, and the government plays an important role in the first three stages. China is in a transitional period from public participation to government withdrawal, and the following countermeasures should be taken to promote cooperative governance. First, introduce science and technology subsidy policies to encourage polluting enterprises to carry out green technology innovation. Second, strengthen environmental information disclosure, publicity, and education to enhance public awareness of participation in environmental governance. Third, establish and improve the system and mechanism of public participation to ensure the smoothness of public participation channels.

In the future, public participation should be emphasized, and the degree of public participation should be enhanced through participation mechanism construction and environmental information disclosure. This will stimulate the potential of public participation to improve the environment and reach the "degree of citizen power" (Arnstein, 1969). Additionally, to incentivize and reward green technology innovation among enterprises, it is recommended to introduce science and technology subsidy policies. Furthermore, it is important to follow the China's carbon neutral policy and pay close attention to the synergistic effect of carbon emission reduction policies on air pollution reduction. This will promote enterprises to actively reduce pollution and carbon emissions. As a result, the joint governance of the public and enterprises can effectively control air pollution, allowing the government to shift its focus to other important issues.

Compared with the current research on air pollution control, the marginal contributions of this study are: (1) It demonstrated how to simulate the game process among multiple stakeholders involved in China's air pollution control process through a tripartite evolutionary game model. (2) The study employs theoretical analysis and simulation analysis to propose possible evolution paths and recommendations for achieving collaborative air pollution control. (3) The incorporation of additional parameters into the game model, including enterprise innovation, professional public, and government decentralization, that provide a more comprehensive understanding of the game relationships and offer more practical information for promoting collaborative governance policies.

However, this research has some limitations. First, our game model only considers the collaborative governance among enterprises, the public, and the government, and does not account for the coordination among various departments and regions. Second, we only explored the general issue of air pollution control without involving specific air pollutants. Third, while our model incorporates parameters reflecting economic stimulus and persuasive policies, it does not analyze the impact of the simultaneous effect of multiple policy instruments. Fourth, due to the lack of sufficient real data in the simulation to set the model parameters, we cannot draw more practical conclusions. Finally, the parameters of our evolutionary game model are tailored to China's national conditions. When adapting our evolutionary game model to other countries or regions, several parameters should be used, taking into account cultural and political differences.

CRediT author statement

Jiaming Wang: Software, Formal analysis, Writing - Original Draft, Visualization.

Ling Jia: Writing - Review & Editing. **Pan He**: Writing - Review & Editing. **Peng Wang:** Conceptualization, Methodology, Supervision, Writing - Review & Editing. **Lei Huang:** Funding acquisition.

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.

Research data

The code for the evolutionary game model in this study is available at https://github.com/Carl723000/A-Tripartite-Evolutionary-Game-of-Enterprises-Public-and-Government

Acknowledgement

This work was supported by the Key Research and Development Program of Jiangsu Province (BE2022841); and the National Key Research and Development Project (2020YFC1807502).

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