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Research article

Strategic dynamics of local governments in regional collaborative governance: An evolutionary game theory analysis of haze pollution response in the Fen-Wei Plain, China

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ABSTRACT

Regional collaborative governance has become a key strategy for environmental protection, especially in reducing transboundary pollution transfer. This study, set against the backdrop of environmental governance in China's Fen-Wei Plain, employs evolutionary game theory to deeply analyze the strategic choices of local governments in managing haze pollution. We developed a model incorporating 14 key variables to systematically explore the emission reduction strategies of local governments under various policy environments. Through numerical simulations, we not only validate the effectiveness of the model but also focuses on how incentives and punishments from the central government influence the stability of local governments adopting a "strict enforcement" strategy. We find that appropriate incentives from the central government can significantly enhance the tendency of local governments to choose a "strict enforcement" strategy for emission reduction. Under certain conditions, whether adopting "strict enforcement" or "superficial enforcement," both can lead to an Evolutionarily Stable Strategy (ESS). Moreover, the intensity of rewards and penalties from the central government and the benefits of collaborative governance by local governments are key factors determining the stability of strategies. Our findings underscore the importance of establishing performance-oriented incentive mechanisms, refining reward and punishment measures, and focusing on sustainable and adaptable governance strategies. The strategic recommendations provided by this study offer important guidance for balancing incentives and punishments, thereby stimulating local government enthusiasm for governance, which supports high-quality environmental protection and sustainable development goals.

1. Introduction

Environmental challenges, particularly deteriorating air quality and the pervasive issue of haze, have emerged as pressing global concerns, affecting health and social aspects, especially in rapidly industrializing countries [1–3]. In addressing this global issue, learning from international experiences offers valuable insights. For example, the United States faced similar air quality crises in the

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1950s and 1960s [4], which led to the enactment of the Clean Air Act in 1970, establishing national air quality standards and a regulatory framework. In recent years, countries in Europe and North America have achieved further reductions in air pollution by imposing stricter vehicle emission standards, encouraging the adoption of electric vehicles, and establishing low-emission zones.

As one of the most significant developing countries, China has faced its own air quality challenges in the 21st century [5]. Particularly in the Beijing-Tianjin-Hebei region, an economic area comprising multiple cities in Beijing, Tianjin, and Hebei province, haze pollution has been a collective concern [6]. The haze management in this region exemplifies the importance of regional collaborative governance. Measures implemented in the Beijing-Tianjin-Hebei area include industrial pollution control, energy structure optimization, unified vehicle emission standards, and cross-regional pollution monitoring and information sharing [7,8]. These initiatives have not only improved the air quality in the region but also offered valuable experiences for other parts of China. Compared to the approaches of European and American countries, China's unique aspect of regional collaborative governance for environmental issues lies in its hierarchical policy-making and implementation structure [9,10]. The central government is responsible for formulating key policies and objectives, while local governments tailor these to local realities [11,12].

Regional collaborative governance has been proven to be an effective method for addressing environmental issues that span traditional political and geographical boundaries. Some research indicate that this governance model has not only significantly improved air quality but also spurred economic growth and enhanced product quality [13–17]. These studies underscore the emission reduction efficacy of collaborative governance for atmospheric pollution across various cities and regions, demonstrating its multiple benefits.

China's Fen-Wei Plain, depicted in Fig. 1, exhibits unique aspects in region collaborative governance. Firstly, compared to other major urban clusters like the Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta, this region displays significant differences in the sources, types, and management strategies of air pollution. Haze pollution in the Fen-Wei Plain primarily stems from agricultural activities [18], coal combustion [19,20], and industrial emissions, presenting a stark contrast to other regions. Secondly, the unique geographical location and industrial structure of this region pose distinct challenges in formulating regional environmental collaborative governance strategies. Thirdly, the effectiveness of regional collaborative governance is particularly evident in the Fen-Wei Plain. Research by Xiao et al. [21] highlights the regional characteristics of haze pollution in the Fen-Wei Plain, as well as the

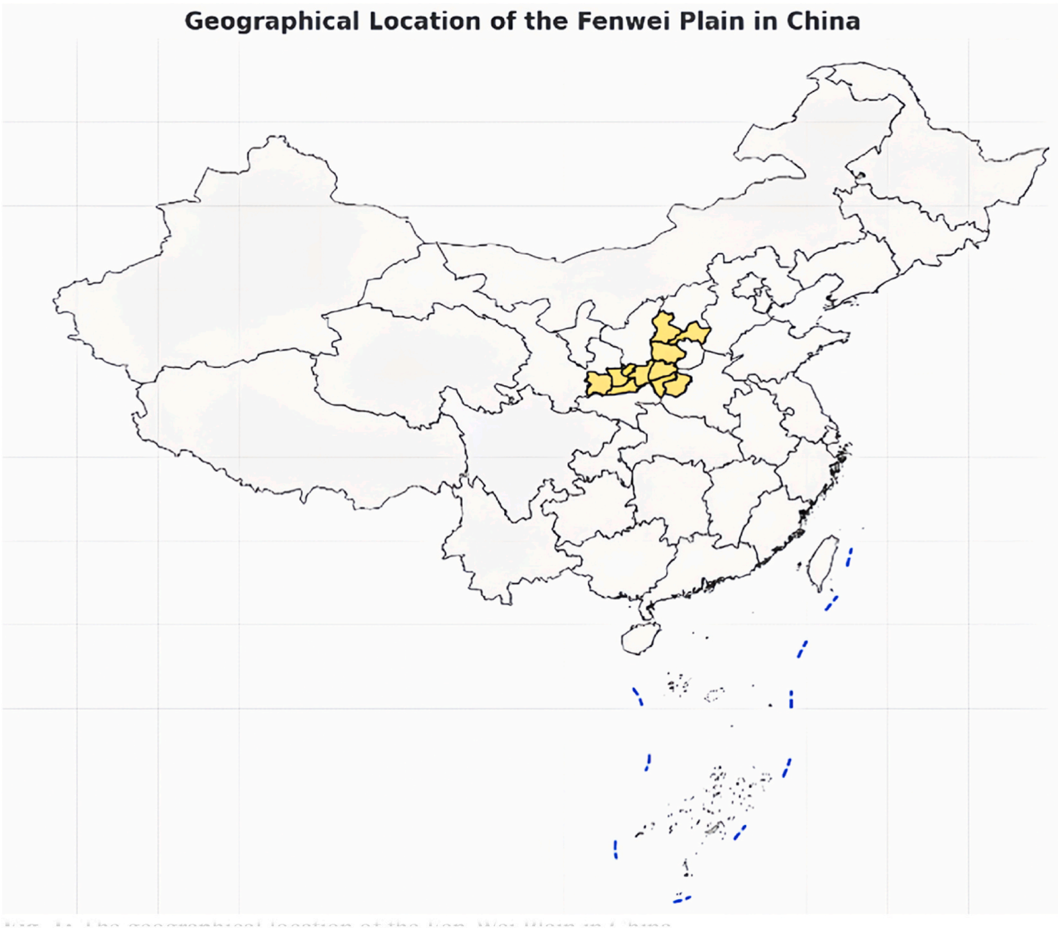

Fig. 1. The geographical location of the Fen-Wei Plain in China.

transmission and spatial correlation of air pollution among cities. Additionally, Dai et al. [22] assessed the effectiveness of the Fen-Wei Plain's three-year action plan, finding significant improvements in regional air quality.

While these studies largely confirm the necessity of collaborative governance for haze pollution in the Fen-Wei Plain, there remains room for further research on the specific mechanisms and pathways of collaborative governance. Current research mainly predominantly on the source analysis and impact assessment of haze in the Fen-Wei Plain, providing compelling evidence on the dynamics of regional air pollution and its influencing factors [18,19,21,23–25]. However, these studies often lack a deep understanding of the complexities involved in implementing actual policies, particularly concerning the motivations and decision-making processes of local governments. Moreover, effective collaborative governance strategies must comprehensively consider social, economic, and political factors to ensure long-term sustainability and broad social acceptance. To more comprehensively reveal the differences between these studies and to provide more precise strategic directions, Appendix Table A1 details the distinctions between previous research and this study in key aspects, including geographical focus, methodologies used, and main findings.

Therefore, this study introduces an evolutionary game model to address the following two questions. First, what are the key factors enabling local governments in the Fen-Wei Plain to establish a lasting cooperation mechanism for haze pollution collaborative governance? Second, how does the central government, as a pivotal constraining factor, influence the collaborative governance of local governments in the Fen-Wei Plain?

By answering these questions, this study makes three contributions. First, this research applies an evolutionary game model to analyze the behavioral motivations and strategic choices of local governments in the Fen-Wei Plain area for environmental governance. This provides a new perspective for developing effective regional collaborative governance mechanisms. Secondly, it explores the role of the central government as a key constraint in local government collaboration, clarifying the interactive mechanisms between central and local governments in implementing environmental policies and highlighting the dynamic interactions in policy execution. Thirdly, by integrating theoretical analysis and numerical simulation results, this study offers targeted policy recommendations to enhance the effectiveness of environmental governance. These recommendations include establishing performance-oriented collaborative governance incentive mechanisms, improving reward and punishment systems, and emphasizing the sustainability and adaptability of governance strategies.

The structure of this paper is as follows: the second part is a literature review; the third part discusses the policy background; the fourth part introduces the theoretical model; the fifth part presents policy simulation analysis based on the theoretical model; the sixth part is a discussion; and the final part concludes and provides policy implications.

2. Literature review

2.1. Regional governance

Regional collaborative governance emphasizes cross-boundary cooperation and interaction among multiple stakeholders [26]. It plays a crucial role in addressing transboundary environmental issues, especially those involving multiple administrative regions or countries. Through collaborative cooperation, parties can share resources, information, and technology to develop and implement effective environmental policies jointly [27].

In the field of environmental governance, regional collaborative governance is extensively applied to the control of air and water pollution. For instance, in managing the water quality of transboundary rivers, cooperation among various water-related areas is crucial for the sustainable utilization of water resources [28]. Air pollution issues particularly necessitate regional collaborative governance, as the spread of air pollutants is not confined by administrative boundaries. Effective regional collaborative governance can reduce the emission of air pollutants and improve air quality [29]. In China, regional environmental issues are particularly pronounced due to rapid industrialization and urbanization. Especially in regions such as Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta, intergovernmental collaborative cooperation is crucial for controlling and reducing regional air and water pollution [11,30–33]. The Chinese government has begun implementing a series of regional collaborative governance measures, such as the unifying cross-regional pollutant emission standards and establishing a regional environmental quality monitoring network [34].The effectiveness of regional collaborative governance in addressing haze pollution issues is particularly evident. Initially, the study by Wu et al. [35] evaluates the effectiveness of the "2 + 26 cities" air pollution joint control policy in the Beijing-Tianjin-Hebei region, proposing a comprehensive assessment model. This research not only quantifies the policy effects but also underscores the importance of collaborative governance in large urban agglomerations. Concurrently, the study by Meng et al. [36] delves into the governance mechanisms and approaches of joint air pollution control in the Beijing-Tianjin-Hebei region, revealing the application of effective collaborative governance strategies in complex urban environmental management. Subsequently, the research by Yu et al. [37] shifts focus to the Yangtze River Delta region, assessing the effectiveness of air pollution control collaborative governance policies there and analyzing their coordination mechanisms. By examining the unique environmental issues and governance strategies of the Yangtze River Delta region, the study further confirms the importance of regional collaboration in the implementation of environmental policies. These studies collectively demonstrate the key role of regional collaborative governance in effectively addressing regional environmental issues in China, especially in large urban clusters like Beijing-Tianjin-Hebei and the Yangtze River Delta. They underscore the need for the collective efforts of multiple stakeholders and effective policy mechanisms to address and mitigate environmental challenges such as haze.

2.2. Evolutionary game theory

Evolutionary game theory, originally developed in biology in 1973, aims to explain the evolution of organisms through strategic interactions within the process of natural selection [38]. This theory later expanded into economics and social sciences to analyze how individuals adjust their strategies based on feedback from repeated interactions, aiming for an Evolutionarily Stable Strategy (ESS). In the context of environmental governance, specifically in collaborative governance of haze pollution, it provides a framework for understanding and analyzing strategic interactions among various stakeholders, such as different cities or regional governments. These entities must consider not only their own interests and costs but also the actions of other participants and the collective environmental goals.

In recent years, the application of evolutionary game theory to environmental policy and governance has garnered widespread attention in academia and significantly influenced policy-making. This paper highlights two key categories of literature that focus on using evolutionary game theory to tackle specific environmental challenges, aligning closely with our research direction. Some researchers have employed evolutionary game models to analyze the resolution of interest conflicts and the establishment of cooperation mechanisms among various stakeholders in environmental governance [39–42]. For example, Sheng et al. [39] examined the interest conflicts among national governments, local governments, and corporations, emphasizing the need to formulate environmental regulatory policies that balance incentives and oversight to mitigate conflicts and encourage cooperation. Wang et al. [42] investigated the role of public participation in fostering cooperation between local governments and businesses in emission reduction. These studies illustrate how regional governments are formed and how the strategies of actors in environmental governance relate to improvements in environmental quality.

Another stream of research has focused on analyzing the pivotal role of the central government in environmental governance [33,43,44]. For instance, Zhang & Li [44] emphasized the importance of higher-level governments in penalizing non-cooperative ones. Wu et al. [33] discovered that by increasing environmental taxes, the central government can motivate industrial enterprises to adopt green transformation practices and encourage all levels of government to intensify supervision and enforcement of environmental regulations. These studies highlight the central government's role in regional environmental governance.

The literature review indicates that evolutionary game theory has attracted significant academic interest in the formulation of effective environmental policies, particularly regarding the interactions among actors in regional environmental governance and the central government's critical role. However, current studies still need to explore further how collaborative benefits, punishment mechanisms, and reward compensation strategies influence the strategic choices of local governments.

3. Policy background

Air pollution is a pressing global challenge, with particularly acute conditions in China's Fen-Wei Plain due to its distinct industrial and geographical features. The management of air quality in the Fen-Wei Plain is not only a critical component of China's efforts to control air pollution but also a significant example of global environmental governance.

The Chinese government initiated its response with the "Air Pollution Prevention and Control Action Plan" covering 2013 to 2017, followed by the "Three-Year Action Plan to Win the Battle for Blue Skies" from 2018 to 2020. These initiatives played key roles in combating haze pollution. Notably, during these periods, the government designated different priority regions. From 2013 to 2017, the Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta regions were identified as priority areas for haze control. In contrast,

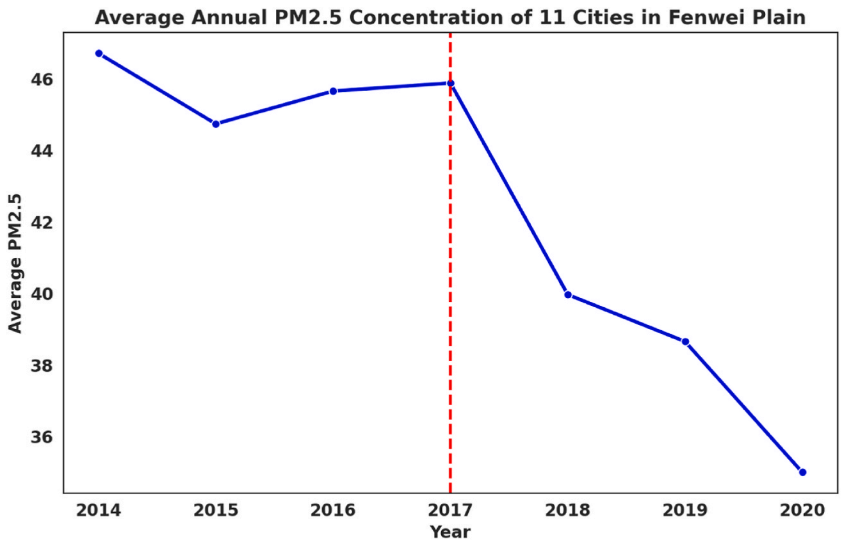

Fig. 2. Trend of annual average PM2.5 concentrations in 11 cities of the fen-wei plain.

from 2018 to 2020, the focus shifted to the Fen-Wei Plain. Although air quality in the Fen-Wei Plain did not significantly improve between 2013 and 2017 (Fig. 2), the implementation of the “Three-Year Initiatives” in 2018 led to a significant reduction in PM2.5 levels in the Fen-Wei Plain, underscoring the effectiveness of these policy measures (Fig. 3).

4. Theoretical model

4.1. Problem description and model assumptions

When addressing haze pollution management in the Fen-Wei Plain, local governments must take into account the environmental dynamics and geographical characteristics of the region. The distinct geographical layout of the Fen-Wei Plain, characterized by valleys and plains, significantly influences air movement and pollutant dispersion. This configuration can result in atmospheric pollution spillover to cities located downstream of prevailing winds from upstream cities. Such uneven spatial distribution of air pollution necessitates collaborative efforts among local governments in developing and implementing environmental policies.

In China’s political system, the central government plays a pivotal role in guiding and supervising local governance. While the central government does not intervene directly in the specific decision-making process at the local level, it establishes the framework and objectives for local environmental governance by formulating national environmental policies, standards, and regulations, and by monitoring and evaluating the performance of local governments. This management model is designed to ensure that local governments adhere to national environmental policies while also tailoring their governance strategies to their unique characteristics.

The evolutionary game model focuses on the dynamic evolutionary process of participant groups, analyzing how the current state is achieved, including selection and mutation processes, with group-selected behaviors exhibiting certain inertia. In China, there is one central government, but many local governments, comprising 333 prefectural-level administrative regions, including 293 cities, 7 regions, 30 autonomous prefectures, and 3 leagues. This structure implies that the central government plays a unique role in the evolutionary game, primarily influencing the behavior patterns of local governments through policy setting, standardization, and supervisory mechanisms, rather than acting as one among many participants. This paper delves deeper into how central government policies influence local government decisions, particularly how local governments interact within the central government’s policy framework to adjust strategies and achieve policy equilibrium at different levels. Through this approach, we can more accurately understand the complexity of regional collaborative governance and the interaction mechanisms between local governments, while overcoming the theoretical and practical limitations of considering the central government as a direct participant in the game.

To gain a deeper understanding of the behavior patterns of local governments in the Fen-Wei Plain regarding haze management, this study proposes the following Research Assumptions:

Research Assumption 1: Local governments, when deciding on environmental governance strategies, will consider the policy framework of the central government, the spillover effect of atmospheric pollution between regions, and interactions with neighboring cities.

Research Assumption 2: Collaborative governance strategies may yield regional synergistic benefits but may also lead to uneven benefits and free-riding behavior among different cities.

Research Assumption 3: The reward and punishment mechanisms of the central government significantly influence the choice of environmental governance strategies by local governments.

Research Assumption 4: The decision-making of local governments will be based on their assessment of the long-term environmental benefits and costs of cooperation versus independent action.

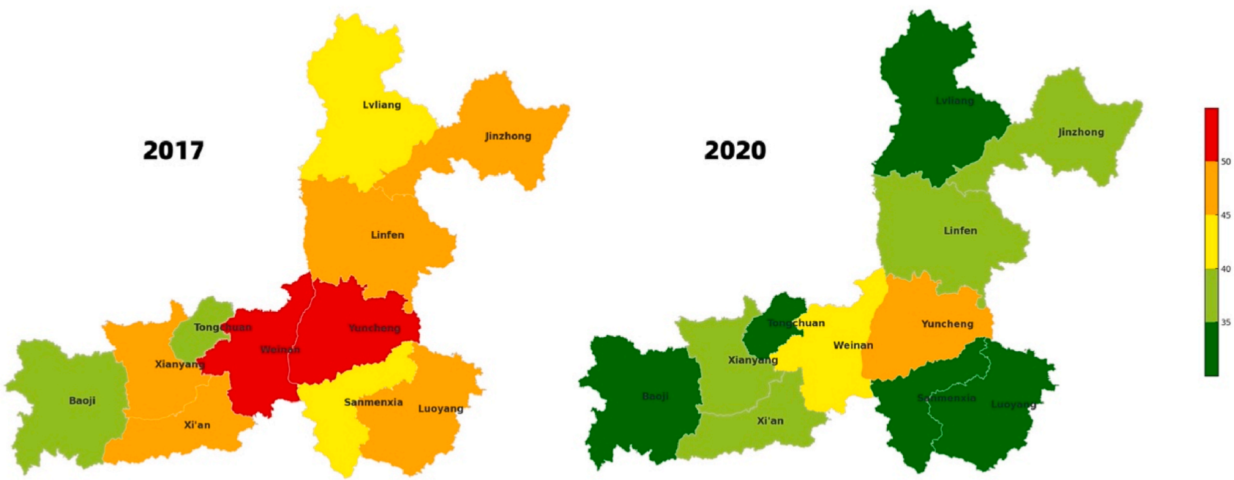

Fig. 3. Distribution map of annual average PM2.5 concentrations in 11 cities of the fen-wei plain, 2017 and 2020.

4.2. Parameters setting

In the regional cooperative governance game framework of the Fen-Wei Plain, local governments A and B, as principal players, face the decision between two distinct emission reduction strategies: “Strict Enforcement” or “Superficial Enforcement.” In this model, we establish the following parameters to describe and analyze the strategic choices of the two local governments:When local governments opt for the “Strict Enforcement” strategy, they will secure environmental benefits R_1 and R_2 for their respective regions, potentially gaining additional synergistic environmental benefits R from collaborative emission reduction efforts. Conversely, should they adopt the “Superficial Enforcement” strategy, their regional environmental benefits will reduce to zero. Furthermore, due to the breakdown in cooperation, neither government will receive the synergistic environmental benefit R.Furthermore, the governance costs for local governments implementing the “Strict Enforcement” strategy are C_1 and C_2, respectively, while the cost for adopting “Superficial Enforcement” is zero. Adopting the “Strict Enforcement” strategy incurs short-term economic losses, L_1 and L_2, respectively, whereas the “Superficial Enforcement” strategy does not lead to economic losses. However, “Superficial Enforcement” results in additional environmental damages, P_1 and P_2.

Considering the central government’s role in encouraging local governments to collaborate in haze pollution reduction, this study posits the following hypotheses: If both local governments “Strict Enforcement,” the central government will reward them with W_i. For local governments adopting the “Superficial Enforcement” strategy, a penalty F_i be imposed by the central government. If one local government “Strict Enforcement” while the other adopts “Superficial Enforcement,” the central government will levy a higher penalty $KF_i(K > 1)$ on the government that opts for “Superficial Enforcement,” while compensating the government that “Strict Enforcement” with G_i. The specific definitions of these variables are presented in Table 1.

4.3. Model construction and stability analysis

Based on the above assumptions, the game payoff matrix for the two local governments can be obtained.

$$U_{11} = y(R_1 + R - C_1 - L_1 + b_2(R_2 + R) + W_1) + (1 - y)(R_1 - C_1 - L_1 - b_2P_2 + G_1) \tag{1}$$

The expected benefit for Local Government 1 when adopting “Superficial Enforcement” is as follow:

$$U_{12} = y(- P_1 + b_2R_2 - KF_1) + (1 - y)(- P_1 - b_2P_2 - F_1) \tag{2}$$

Therefore, the average benefit for Local Government 1 is calculated:

$$U_1 = xU_{11} + (1 - x)U_{12} \tag{3}$$

Similarly, the expected benefit for Local Government 2 when adopting “Strict Enforcement” is as follow:

$$U_{21} = x(R_2 + R - C_2 - L_2 + b_1(R_1 + R) + W_2) + (1 - x)(R_2 - C_2 - L_2 - b_1P_1 + G_2) \tag{4}$$

The expected benefit for Local Government 2 when adopting “Superficial Enforcement” is as follow:

$$U_{22} = x(- P_2 + b_1R_1 - KF_2) + (1 - x)(- P_2 - b_1P_1 - F_2) \tag{5}$$

Therefore, the average benefit for Local Government 2 is calculated:

$$U_2 = yU_{21} + (1 - y)U_{22} \tag{6}$$

Table 1
Parameters setting.

Parameters	Definitions	Value range
x	The probability of local government 1 choosing the “Strict Enforcement” strategy	$0 < x < 1$
y	The probability of local government 2 choosing the “Strict Enforcement” strategy	$0 < y < 1$
R_1, R_2	The environmental benefits for local governments 1 and 2 when implementing “Strict Enforcement”	$R_1 > 0$; $R_2 > 0$
R	The synergistic environmental benefits (available to both) when both local governments 1 and 2 “Strict Enforcement”	$R > 0$
C_1, C_2	The governance costs for local governments 1 and 2 when implementing “Strict Enforcement”	$C_1 > 0$; $C_2 > 0$
L_1, L_2	The short-term economic losses for local governments 1 and 2 due to implementing “Strict Enforcement”	$L_1 > 0$; $L_2 > 0$
P_1, P_2	The governance costs for local governments 1 and 2 when implementing “Superficial Enforcement”	$P_1 > 0$; $P_2 > 0$
W_1, W_2	Rewards provided by the central government to local governments 1 and 2, respectively, for implementing the “Strict Enforcement” strategy.	$W_1 > 0$; $W_2 > 0$
F_1, F_2	Penalties imposed by the central government on local governments 1 and 2, respectively, for adopting the “Superficial Enforcement” strategy.	$F_1 > 0$; $F_2 > 0$
K	The increased penalty coefficient from the central government for a government that implements “Superficial Enforcement” unilaterally	$K > 0$
G_1, G_2	Ecological compensation awarded by the central government to local governments 1 and 2, respectively, for their adherence to the “Strict Enforcement” strategy.	$G_1 > 0$; $G_2 > 0$
b_1, b_2	Atmospheric spill-over coefficients, where b_1 represents the air pollution spread from local government 1 to 2, and b_2 from 2 to 1.	$b_1 > 0$; $b_2 > 0$

Table 2
The game payoff matrix of the two local governments.

		Local Government 1	
		Strict Enforcement	Superficial Enforcement
Local Government 2	Strict Enforcement	$R_1+R-C_1-L_1+b_2(R_2+R)+W_1$ $R_2+R-C_2-L_2+b_1(R_1+R)+W_2$	$-P_1+b_2R_2-KF_1$ $R_2-C_2-L_2-b_1P_1+G_2$
	Superficial Enforcement	$R_1-C_1-L_1-b_2P_2+G_1$ $-P_2+b_1R_1-KF_2$	$-P_1-b_2P_2-F_1$ $-P_2-b_1P_1-F_2$

The expected benefit for Local Government 1 when adopting "Strict Enforcement" is as follow.

The replicator dynamic equations for Local Government 1 and Local Government 2 are presented:

$$\begin{aligned} F(x) &= \frac{dx}{dt} \\ &= x(U_{11}-U_1) \\ &= x(1-x)(U_{11}-U_{12}) \\ &= x(1-x)[(R_1-C_1-L_1+G_1+P_1+F_1)+y(R+b_2R+W_1+KF_1-G_1-F_1)] \end{aligned} \tag{7}$$

$$\begin{aligned} F(x) &= \frac{dy}{dt} \\ &= y(U_{21}-U_2) \\ &= y(1-y)(U_{21}-U_{22}) \\ &= y(1-y)[(R_2-C_2-L_2+G_2+P_2+F_2)+y(R+b_1R+W_2+KF_2-G_2-F_2)] \end{aligned} \tag{8}$$

Letting $F(x) = F(y) = 0$, five equilibrium points are obtained.
Which are (0,0)、(1,0)、(0,1)、(1,1)和(x^*,y^*)。

$$y^* = \frac{R_1-C_1-L_1+G_1+P_1+F_1}{G_1+F_1-R-b_2R-W_1-KF_1} \tag{9}$$

$$x^* = \frac{R_2-C_2-L_2+G_2+P_2+F_2}{G_2+F_2-R-b_1R-W_2-KF_2} \tag{10}$$

From the above replication dynamics equation, the Jacobian matrix is derived:

$$J = \begin{pmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} \end{pmatrix}$$

$$\frac{\partial F(x)}{\partial x} = (1-2x)(R_1-C_1-L_1+G_1+P_1+F_1)+y(R+b_2R+W_1+KF_1-G_1-F_1) \tag{11}$$

$$\frac{\partial F(x)}{\partial y} = x(1-x)(R+b_2R+W_1+KF_1-G_1-F_1) \tag{12}$$

$$\frac{\partial F(y)}{\partial x} = y(1-y)(R+b_1R+W_2+KF_2-G_2-F_2) \tag{13}$$

$$\frac{\partial F(y)}{\partial y} = (1-2y)(R_2-C_2-L_2+G_2+P_2+F_2)+x(R+b_1R+W_2+KF_2-G_2-F_2) \tag{14}$$

According to the principles of evolutionary game theory, all initial and evolved points are only meaningful within the two-dimensional space defined as $\{(x,y)|0 \le x \le 1, 0 \le y \le 1\}$.

$$0 < x^* < 1, 0 < y^* < 1 \tag{15}$$

This results in four mathematical constraint scenarios: $0 < x^* < 1$ and $0 < y^* < 1$, leading to four possible combinations: ①+③, ①+④, ②+③ and ②+④.

① $G_1 - KF_1 > R + b_2R + W_1 - F_1$;
② $G_1 - KF_1 < R + b_2R + W_1 - F_1$;
③ $G_2 - KF_2 > R + b_1R + W_2 - F_2$;
④ $G_2 - KF_2 < R + b_1R + W_2 - F_2$。

Analyzing the point (0,0)

$$J = \begin{pmatrix} R_1 - C_1 - L_1 + G_1 + P_1 + F_1 & 0 \\ 0 & R_2 - C_2 - L_2 + G_2 + P_2 + F_2 \end{pmatrix}$$

$$det(J) = (R_1 - C_1 - L_1 + G_1 + P_1 + F_1)(R_2 - C_2 - L_2 + G_2 + P_2 + F_2) \tag{16}$$

$$tr(J) = (R_1 - C_1 - L_1 + G_1 + P_1 + F_1) + (R_2 - C_2 - L_2 + G_2 + P_2 + F_2) \tag{17}$$

Situation ①+③, $det(J) > 0, tr(J) > 0$, unstable point
Situation ①+④, $det(J) < 0, tr(J) \sim$,indeterminate point
Situation ②+③, $det(J) < 0, tr(J) \sim$,indeterminate point
Situation ②+④, $det(J) > 0, tr(J) < 0$,ESS
Analyzing the point (1,0)

$$J = \begin{pmatrix} -(R_1 - C_1 - L_1 + G_1 + P_1 + F_1) & 0 \\ 0 & R_2 - C_2 - L_2 + P_2 + R + b_1R + W_2 + KF_2 \end{pmatrix}$$

$$det(J) = -(R_1 - C_1 - L_1 + G_1 + P_1 + F_1)(R_2 - C_2 - L_2 + P_2 + R + b_1R + W_2 + KF_2) \tag{18}$$

$$tr(J) = -(R_1 - C_1 - L_1 + G_1 + P_1 + F_1) + (R_2 - C_2 - L_2 + P_2 + R + b_1R + W_2 + KF_2) \tag{19}$$

Situation ①+③, $det(J) > 0, tr(J) < 0$, ESS
Situation ①+④, $det(J) < 0, tr(J) \sim$,indeterminate point
Situation ②+③, $det(J) < 0, tr(J) \sim$,indeterminate point
Situation ②+④, $det(J) > 0, tr(J) > 0$, unstable point
Analyzing the point (0,1)

$$J = \begin{pmatrix} R_1 - C_1 - L_1 + P_1 + R + b_2R + W_1 + KF_1 & 0 \\ 0 & -(R_2 - C_2 - L_2 + G_2 + P_2 + F_2) \end{pmatrix}$$

$$det(J) = -(R_1 - C_1 - L_1 + P_1 + R + b_2R + W_1 + KF_1)(R_2 - C_2 - L_2 + G_2 + P_2 + F_2) \tag{20}$$

$$tr(J) = (R_1 - C_1 - L_1 + P_1 + R + b_2R + W_1 + KF_1) - (R_2 - C_2 - L_2 + G_2 + P_2 + F_2) \tag{21}$$

Situation ①+③, $det(J) > 0, tr(J) < 0$, ESS
Situation ①+④, $det(J) < 0, tr(J) \sim$,indeterminate point
Situation ②+③, $det(J) < 0, tr(J) \sim$,indeterminate point
Situation ②+④, $det(J) > 0, tr(J) > 0$, unstable point
Analyzing the point (1,1)

$$J = \begin{pmatrix} -(R_1 - C_1 - L_1 + P_1 + R + b_2R + W_1 + KF_1) & 0 \\ 0 & -(R_2 - C_2 - L_2 + P_2 + R + b_1R + W_2 + KF_2) \end{pmatrix}$$

$$det(J) = (R_1 - C_1 - L_1 + P_1 + R + b_2R + W_1 + KF_1)(R_2 - C_2 - L_2 + P_2 + R + b_1R + W_2 + KF_2) \tag{22}$$

$$tr(J) = -(R_1 - C_1 - L_1 + P_1 + R + b_2R + W_1 + KF_1) - (R_2 - C_2 - L_2 + P_2 + R + b_1R + W_2 + KF_2) \tag{23}$$

Situation ①+③, $det(J) > 0, tr(J) > 0$, unstable point
Situation ①+④, $det(J) < 0, tr(J) \sim$,indeterminate point
Situation ②+③, $det(J) < 0, tr(J) \sim$,indeterminate point
Situation ②+④, $det(J) > 0, tr(J) < 0$,ESS
Analyzing the point ($\boldsymbol{x}^*$,$\boldsymbol{y}^*$)

$$J = \begin{pmatrix} 0 & x^*(1 - x^*)(R + b_2R + W_1 + KF_1 - G_1 - F_1) \\ y^*(1 - y^*)(R + b_1R + W_2 + KF_2 - G_2 - F_2) & 0 \end{pmatrix}$$

Calculate the eigenvalues of the matrix J;

$$|\ \lambda E - J\ | = \begin{vmatrix} \lambda & -x^*(1 - x^*)(R + b_2R + W_1 + KF_1 - G_1 - F_1) \\ -y^*(1 - y^*)(R + b_1R + W_2 + KF_2 - G_2 - F_2) & \lambda \end{vmatrix}$$

$$\lambda^2 = x^*(1 - x^*)(R + b_2R + W_1 + KF_1 - G_1 - F_1)y^*(1 - y^*)(R + b_1R + W_2 + KF_2 - G_2 - F_2) \tag{24}$$

When $(R + b_2R + W_1 + KF_1 - G_1 - F_1)(R + b_1R + W_2 + KF_2 - G_2 - F_2) > 0$

$$\lambda = \pm\sqrt{x^*(1-x^*)(R+b_2R+W_1+KF_1-G_1-F_1)y^*(1-y^*)(R+b_1R+W_2+KF_2-G_2-F_2)} \tag{25}$$

When $(R + b_2R + W_1 + KF_1 - G_1 - F_1)(R + b_1R + W_2 + KF_2 - G_2 - F_2) < 0$

$$\lambda = \pm\sqrt{x^*(1-x^*).....(R+b_1R+W_2+KF_2-G_2-F_2)} \bullet i \tag{26}$$

Therefore, $det(J) < 0, tr(J) = 0$, it is a saddle point.

In summary, there are four different scenarios;

Scenario 1: When the parameters satisfy $G_1 - KF_1 > R + b_2R + W_1 - F_1$ and $G_2 - KF_2 > R + b_1R + W_2 - F_2$: the strategy pairs (0,0) and (1,1) are unstable points, whereas (1,0) and (0,1) are Evolutionarily Stable Strategies (ESS), and (x^*, y^*) forms a saddle point. Under these conditions, the strategy combinations of "Superficial Enforcement, Superficial Enforcement" and "Strict Enforcement, Strict Enforcement" are unstable, while "Strict Enforcement, Superficial Enforcement" and "Superficial Enforcement, Strict Enforcement" are ESS, and (x^*, y^*) remains a saddle point.

Scenario 2: When the parameters satisfy $G_1 - KF_1 > R + b_2R + W_1 - F_1$ and $G_2 - KF_2 < R + b_1R + W_2 - F_2$: all strategy pairs (0,0), (1,1), (1,0), and (0,1) are indeterminate, and (x^*, y^*) forms a saddle point. Under these conditions, all four strategy combinations remain indeterminate.

Scenario 3: When the parameters satisfy $G_1 - KF_1 < R + b_2R + W_1 - F_1$ and $G_2 - KF_2 > R + b_1R + W_2 - F_2$: the strategy pairs (0,0), (1,1), (1,0), and (0,1) are all indeterminate, and (x^*, y^*) is a saddle point. At this time, all four strategy combinations are indeterminate.

Scenario 4: When the parameters satisfy $G_1 - KF_1 < R + b_2R + W_1 - F_1$ and $G_2 - KF_2 < R + b_1R + W_2 - F_2$: the strategy pairs (1,0) and (0,1) are unstable, whereas (0,0) and (1,1) are ESS, and (x^*, y^*) forms a saddle point. Under these conditions, the strategies "Strict Enforcement, Superficial Enforcement" and "Superficial Enforcement, Strict Enforcement" are unstable, "Superficial Enforcement, Superficial Enforcement" and "Strict Enforcement, Strict Enforcement" are ESS, and (x^*, y^*) is a saddle point.

4.4. Analysis of model results

The primary aim of this paper is to explore how to get both local governments to adopt "Strict Enforcement" as the optimal stable strategy (ESS), as it most effectively reduces emissions and meets the actual demands of environmental targets. This strategy offers the greatest mutual benefit for environmental governance and is an ideal choice both theoretically and practically. Since Scenarios 2 and 3 lack stable points, and Scenario 1 cannot achieve the optimal stable strategy (ESS) of both local governments adopting "Strict Enforcement" for emission reduction, the discussion will now focus on Scenario 4.

Specifically, scenarios 2 and 3 lack stable strategy points, meaning that in these scenarios, the government's choice of enforcement strategy will be highly uncertain and unstable. This instability could lead to fluctuations in policy implementation, making it difficult to guarantee the effectiveness of environmental governance or to enact long-term and consistent environmental policies. Analyzing these scenarios may result in an inability to produce clear strategic recommendations that aid in achieving environmental governance goals. Although Scenario 1 has two evolutionary stable strategies (ESS), they are (Strict Enforcement, Superficial Enforcement) and (Superficial Enforcement, Strict Enforcement), which do not align with the research objective of having both governments adopt "Strict Enforcement." Furthermore, the optimal strategy in this scenario (Strict Enforcement, Strict Enforcement) is unstable, limiting its feasibility and effectiveness in practical policy applications.

Based on the above analysis, Scenario 4 becomes the focus because it provides a situation where (Strict Enforcement, Strict Enforcement) becomes an evolutionary stable strategy (ESS).This not only meets the main goal of the research but also offers a stable

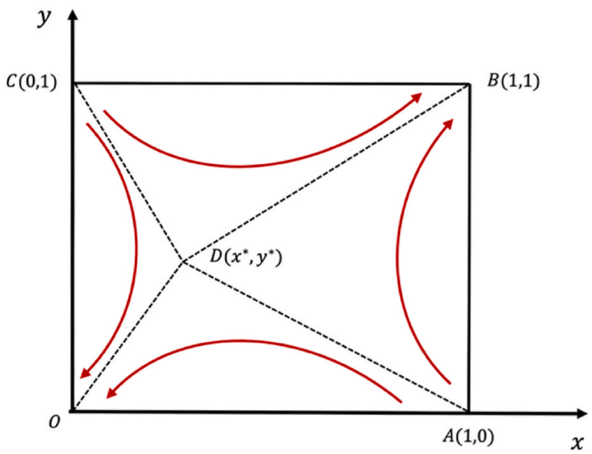

Fig. 4. Evolutionary diagram of the strict enforcement strategy of two local governments.

and effective strategy for environmental governance. Focusing on Scenario 4 allows us to thoroughly explore and analyze how policy adjustments and collaborative mechanisms can ensure that both local governments adopt the most effective environmental governance strategy.

According to the analysis of evolutionary stable points, equilibrium points O (0,0) and B (1,1), are identified as two Evolutionarily Stable Strategies (ESS), indicating scenarios where both local governments opt for either “Superficial Enforcement” or “Strict Enforcement”. C (0,1) and A (1,0) represent unstable conditions, while D (x^*, y^*) is a saddle point. The evolutionary trajectory of the strict emission reduction strategy employed by both local governments is depicted in Fig. 4.

The evolution of points O (0,0) and B (1,1) indicates two stable outcomes, demonstrating that the replicator dynamics curves of both local governments tend to converge at these points. When both curves converge at O (0,0), the governments opt for “Superficial Enforcement.” When convergence occurs at B (1,1), they choose “Strict Enforcement.” The point D (x^*, y^*) plays a critical role in determining the likelihood of the replicator dynamics curves converging towards O (0,0) and B (1,1). As illustrated in Fig. 4, if the initial states of both local governments are proximate to point D, minor changes can shift their dynamic evolutionary outcomes. The ultimate direction of both governments depends on comparing the area of quadrilateral ABCD, denoted as S_1, with that of quadrilateral AOCD, denoted as S_2. When $S_1 > S_2$, the evolution favors both governments adopting “Strict Enforcement”; when $S_1 < S_2$, it tends towards “Superficial Enforcement.” To analyze factors that can affect the stability of the two local governments, it is necessary to examine the parameters influencing the size of S_1;

$$\begin{aligned} S_1 &= \frac{1}{2} - \frac{1}{2}(y^* + x^*) \\ &= \frac{1}{2} - \frac{1}{2}\frac{R_1 - C_1 - L_1 + G_1 + P_1 + F_1}{G_1 + F_1 - R - b_2R - W_1 - KF_1} - \frac{1}{2}\frac{R_2 - C_2 - L_2 + G_2 + P_2 + F_2}{G_2 + F_2 - R - b_1R - W_2 - KF_2} \end{aligned} \tag{27}$$

Analyzing the impact of parameter changes on the stable state by taking the partial derivative of S_1, as shown in Table 3;

5. Numerical simulation

5.1. Parameter selection

In response to the “Comprehensive Air Pollution Control Action Plan for the Beijing-Tianjin-Hebei Region and the Fen-Wei Plain for the Autumn and Winter Seasons of 2023–2024”[1]issued by the Ministry of Ecology and Environment of China, this study employs a numerical simulation model to deeply explore the strategic choices and their impacts made by 11 cities in the Fen-Wei Plain regarding environmental governance.

To ensure the model’s realism and broad applicability, the parameter settings are carefully crafted to integrate the extensive environmental governance experience and data accumulated by these cities over the years. The parameters comprehensively reflect the average performance of local governments in managing environmental governance costs, effects, losses, and benefits. They also account for the influences of the central government’s incentive mechanisms. Detailed below are the specific parameter settings, designed to offer a balanced perspective for evaluating and optimizing the implementation of environmental policies:①Regional GDP: Assume that the GDP of two adjacent regions is 1000 each (dimensionless).

②Environmental governance cost C: According to the “China City Statistical Yearbook”, local fiscal expenditure on environmental protection averages 0.8 % of GDP. Consequently, we set the environmental governance cost as $C_1 = 8$, $C_2 = 8$.

③Governance effect L: Referring to the study by Li et al. [45], we set the governance effects for the two regions as $L_1 = 9, L_2 = 10$.

④Environmental loss P: Based on the research by Yang et al. [46] and Sumei & He (2014), it is assumed that the additional environmental loss due to local governments not fully implementing environmental policies amounts to 1 % of the annual GDP, thus setting $P_1 = 1$, $P_2 = 1$.

⑤Environmental governance benefit R: Research by Wang et al. [47] indicates that the cost-benefit ratio of environmental governance is approximately 0.4, meaning that the benefits are typically lower than the costs. Therefore, we set the environmental governance benefits as $R_1 = 1$, $R_2 = 1.5$, and $R = 0.5$.

⑥Rewards and penalties from the central government (W and F), and ecological compensation G: These values should be close to the governance cost C, with ecological compensation G exceeding the reward W.

As previously mentioned, when the parameters satisfy $G_1 - KF_1 < R + b_2R + W_1 - F_1$ and $G_2 - KF_2 < R + b_1R + W_2 - F_2$, points (0,0) and (1,1) are ESS. Further mathematical rearrangement provides the specific parameter constraints as follows:

$$\begin{cases} R_1 - C_1 - L_1 + G_1 + P_1 + F_1 < 0 \\ R_1 - C_1 - L_1 + P_1 + R + b_2R + W_1 + KF_1 > 0 \end{cases} \tag{28}$$

$$\begin{cases} R_2 - C_2 - L_2 + G_2 + P_2 + F_2 < 0 \\ R_2 - C_2 - L_2 + P_2 + R + b_1R + W_2 + KF_2 > 0 \end{cases} \tag{29}$$

[1] https://www.mee.gov.cn/xxgk2018/xxgk/xxgk03/202312/t20231229_1060184.html?keywords=2023.

Table 3
Impact of parameter changes on the collaborative energy-saving and emission reduction policy between local governments.

Parameter Changes	Saddle Point Changes	Changes in Phase Area and Evolutionary Direction
R_1 ↑	y^* ↓	S_1 ↑, (Strict …, Superficial …)
R_2 ↑	x^* ←	S_1 ↑, (Strict …, Superficial …)
C_1 ↓	y^* ↓	S_1 ↑, (Strict …, Superficial …)
C_2 ↓	x^* ←	S_1 ↑, (Strict …, Superficial …)
L_1 ↓	y^* ↓	S_1 ↑, (Strict …, Superficial …)
L_2 ↓	x^* ←	S_1 ↑, (Strict …, Superficial …)
P_1 ↑	y^* ↓	S_1 ↑, (Strict …, Superficial …)
P_2 ↑	x^* ←	S_1 ↑, (Strict …, Superficial …)
W_1 ↑	y^* ↓	S_1 ↑, (Strict …, Superficial …)
W_2 ↑	x^* ←	S_1 ↑, (Strict …, Superficial …)
G_1 ↑	y^* ↓	S_1 ↑, (Strict …, Superficial …)
G_2 ↑	x^* ←	S_1 ↑, (Strict …, Superficial …)
F_1 ↑	y^* ↓	S_1 ↑, (Strict …, Superficial …)
F_2 ↑	x^* ←	S_1 ↑, (Strict …, Superficial …)
R ↑	y^* ↓, x^* ←	S_1 ↑, (Strict …, Superficial …)

Ultimately, values are assigned to the parameters: $R_1 = 1, R_2 = 1.5, C_1 = 8, C_2 = 8, L_1 = 9, L_2 = 10, P_1 = P_2 = 1, W_1 = 6, W_2 = 6, F_1 = F_2 = 5, G_1 = G_2 = 7, K = 2.5, R = 0.5, b_1 = 0.1, b_2 = 0.2$

5.2. Steady-state analysis

For the numerical simulation, various initial values of (x, y) are set, including (0.1, 0.6), (0.2, 0.9), (0.3, 0.5), (0.4, 0.6), (0.7, 0.2), and (0.9, 0.2), to reflect the diverse initial conditions and preferences of different local governments in the Fen-Wei Plain regarding the execution of environmental governance strategies. This setting captures the actual heterogeneity among the cities in the region concerning economic development levels, intensity of environmental policy enforcement, and governance capabilities. The evolutionary paths of the strategy choices by local governments are illustrated in Fig. 5. When the probabilities (x, y) of both local governments adopting "Strict Enforcement" are set to different initial values, the final evolutionary outcomes tend towards distinct points. According to Fig. 5, when (x, y) falls within the AOCD region, the initial values converge to (0,0), leading the players to choose the strategy of (Superficial Enforcement, Superficial Enforcement). Conversely, When (x, y) falls within the ABCD region, the initial values

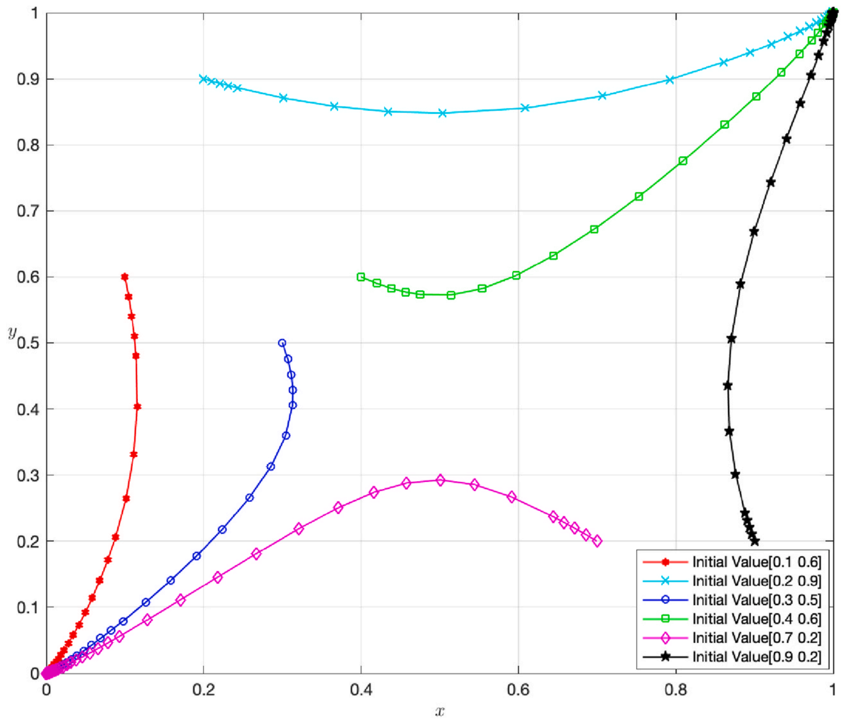

Fig. 5. Evolutionary path of local governments' collaborative emission reduction strategy.

converge to (1,1), leading to the choice of (Strict Enforcement, Strict Enforcement). This demonstrates the dependency of the evolutionary outcomes on the initial values of (x, y).

5.3. Parameter sensitivity analysis

Selecting the collaborative benefit R, penalty F, penalty coefficient K, reward W, and ecological compensation G as variables for the two local governments, the value range of these five variables is strictly defined under constraints. Other parameter values are consistent with the previous section, setting the probability that both local governments adopt a strict enforcement strategy as (0.5, 0.5), with the time period set as [0,5].

The selection of a 5-year simulation cycle is justified as follows: This cycle coincides with the period of China's five-year plans, which is a standard timeframe for environmental policy planning and implementation. A five-year duration is sufficient to observe and assess the long-term effects of policy measures, and it provides flexibility for policy adjustments and optimization. Furthermore, the 5-year cycle allows researchers to track the impact of policy changes on local government behavior and the evolution of strategic choices over time.The rationale for setting the probability of both local governments adopting a "Strict Enforcement" strategy at (0.5, 0.5) is as follows: This configuration provides a balanced starting point by assuming that at the outset of the simulation, both governments are equally inclined towards a strict enforcement approach, thereby ensuring the fairness and neutrality of the analysis. This setup facilitates the examination of dynamic changes in strategy selection under various incentive mechanisms, rather than outcomes driven by initial bias. Furthermore, this symmetric assumption simplifies the model's analysis, allowing the research to more effectively focused on exploring the impact of policy incentives on strategy stability.Fig. 6 demonstrates that an increase in the collaborative benefit R significantly boosts the probability that both local governments will adopt "strict enforcement" strategies for emission reduction. This trend underscores the effectiveness of collaborative benefits as a lever to accelerate environmental governance.

The dynamic in Fig. 7 shows that increasing penalties for "superficial enforcement" significantly boosts the adoption of "strict enforcement" strategies by local governments. This suggests that well-designed punishment mechanisms are crucial for promoting long-term environmental protection efforts.

As depicted in Fig. 8, when the central government imposes lighter penalties for "superficial enforcement," local governments tend to lower their commitment to "strict enforcement" strategies over time. However, increasing the penalty coefficient K leads to a marked shift towards "strict enforcement," illustrating the critical role of punitive measures in enforcing environmental policies.

Figs. 9 and 10 highlight the impact of raising rewards (W) and ecological compensation (G) on the adoption of "strict enforcement" strategies by local governments. A noticeable increase in these incentives significantly motivates local governments towards robust environmental actions, suggesting that both rewards and compensations are effective tools in enhancing environmental governance.

6. Discussion

This study enhances our understanding of the behavioral motivations of local governments in regional environmental governance.

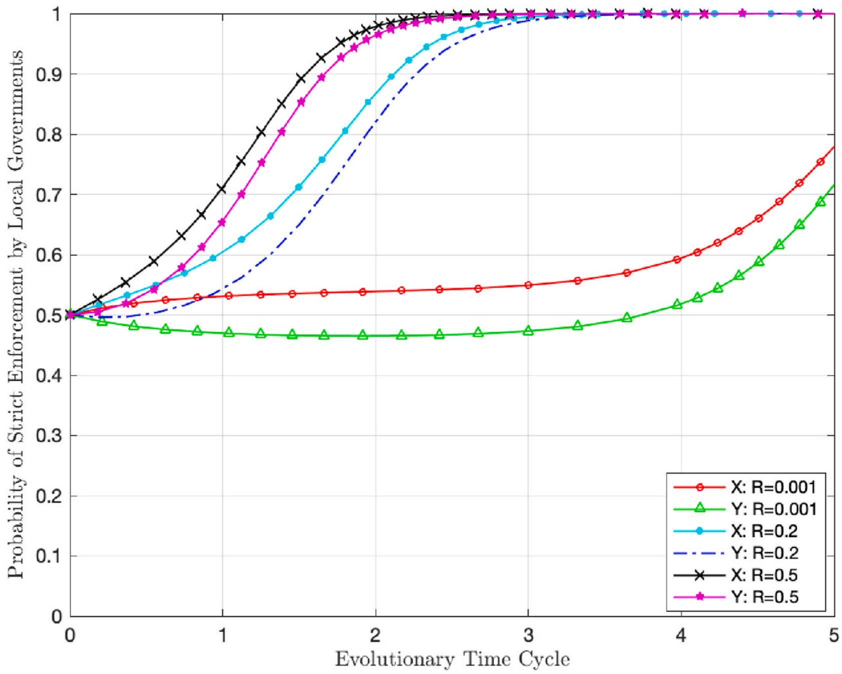

Fig. 6. The impact of collaborative benefit R on the evolutionary outcome of local governments' strict emission reduction strategy.

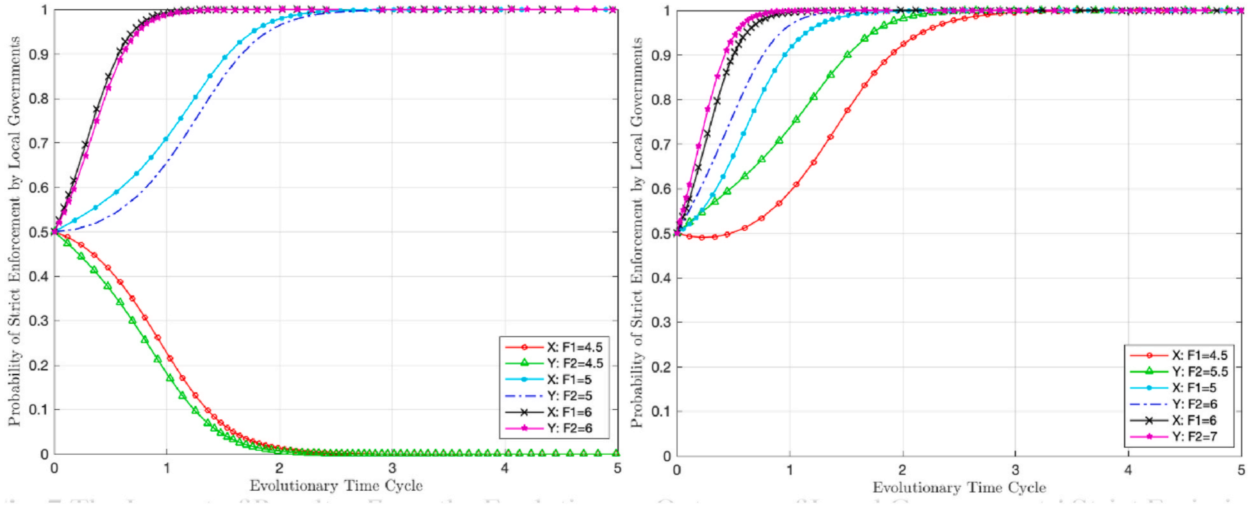

Fig. 7. The impact of penalty *F* on the evolutionary outcome of local governments' strict emission reduction strategy.

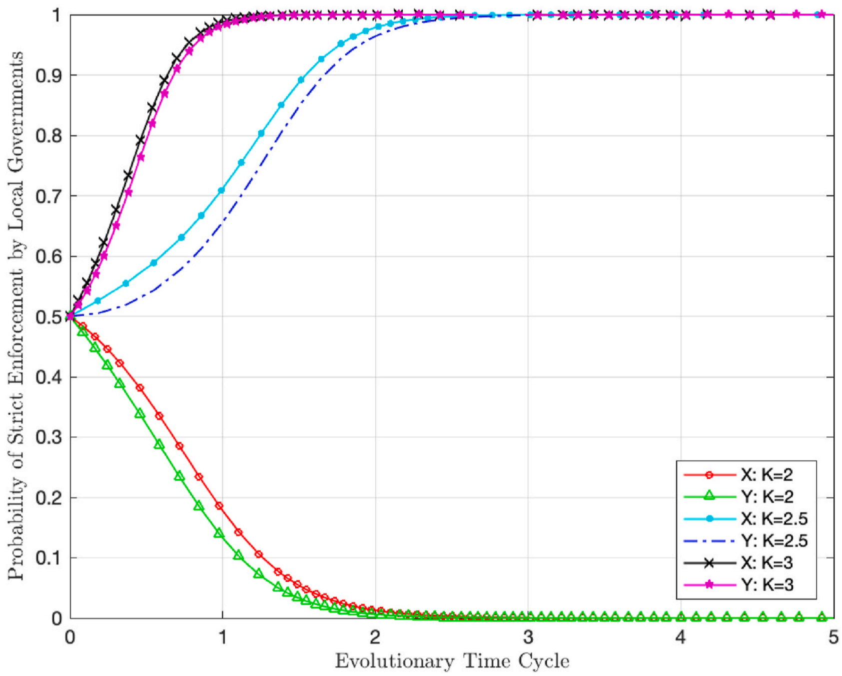

Fig. 8. The impact of penalty coefficient *K* on the evolutionary outcome of local governments' strict emission reduction strategy.

Consistent with prior research, it reaffirms the significance of incentive mechanisms in promoting local government participation in environmental governance [36,40,41]. Unlike existing literature, however, this research places greater emphasis on the role of the central government in collaborative governance, particularly under a centralized system. Moreover, through the evolutionary game model, this study exposes how collaborative benefits, punishment mechanisms, and reward compensation strategies impact the strategic choices of local governments, an area not fully explored in previous research [44].

A key finding of this study is the significant impact of the central government's reward and punishment mechanisms on the environmental protection actions of local governments. The study reveals that under the central government's reward mechanism, local governments in the Fen-Wei Plain area are more inclined to adopt a "Strict Enforcement" strategy to balance the needs of economic development and environmental protection. To help local governments achieve the optimal evolutionary stable strategy more swiftly, the central government can enhance cooperative governance efficiency, reduce governance costs, increase reward measures, and alleviate the economic burden of managing haze pollution. Taking Xi'an as an example, the city has enacted a series of environmentally friendly policies and measures supported by the central government's reward mechanism, such as promoting green

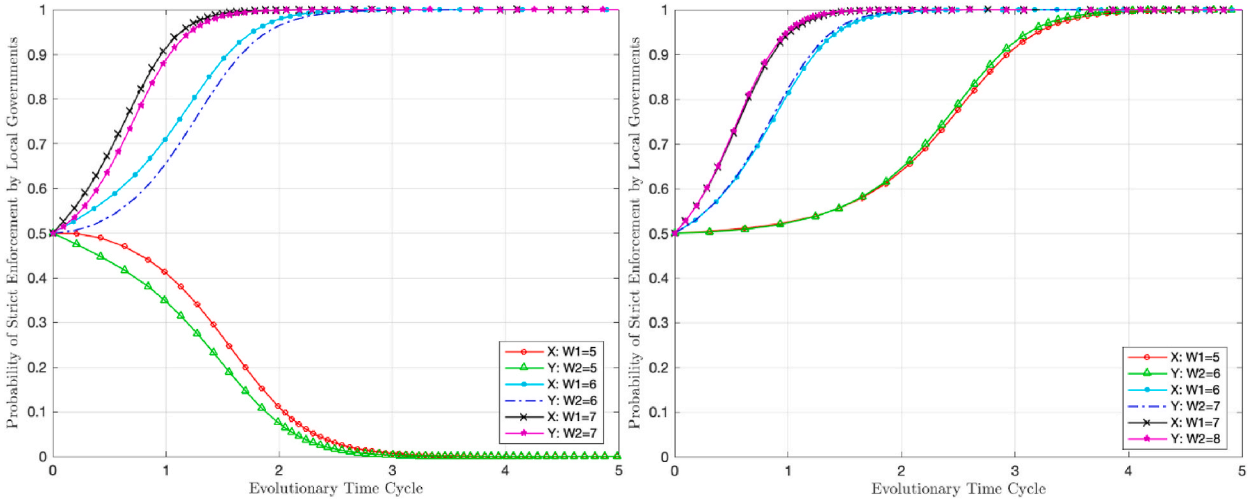

Fig. 9. The impact of reward *W* on the evolutionary outcome of local governments' strict emission reduction strategy.

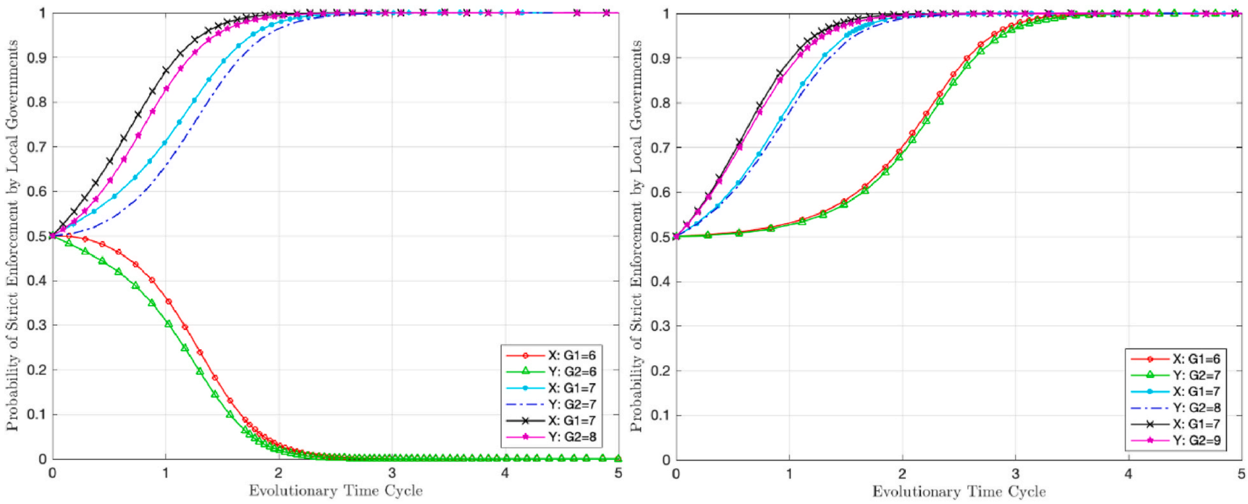

Fig. 10. The impact of ecological compensation *G* on the evolutionary outcome of local governments' strict emission reduction strategy.

energy use, enhancing industrial emission standards, and strengthening urban greening, which have effectively improved air quality [48].

Compared to reward mechanisms, the central government's initial punitive measures may lead local governments to adopt a "Superficial Enforcement" strategy, particularly when the costs of strict enforcement are perceived too high. However, as penalties imposed by the central government intensify, there is a noticeable shift in local government strategies towards "Strict Enforcement" to avoid significant penalties. Since 2018, with the inclusion of the Fen-Wei Plain as a key area in the "Three-Year Action Plan to Win the Battle for a Blue Sky" and the implementation of the "Fen-Wei Plain 2019–2020 Autumn and Winter Air Pollution Comprehensive Management Action Plan," stricter environmental governance standards have been set, In response to the central government's stringent requirements and to avert severe economic and administrative consequences, local governments, such as Lin-Fen City, have implemented stricter environmental protection measures. This includes enhancing the supervision of polluting enterprises, promoting industrial restructuring, and increasing public awareness of environmental protection, thereby effectively improving the region's air quality [46].

Thus, reward mechanisms can boost the enthusiasm of local governments to adopt preliminary measures for improving environmental quality, while punishment mechanisms ensure the sustainability and rigor of these measures, particularly when faced with potential economic or administrative penalties.While this study is grounded in China's specific political and administrative context, its insights and model possess extensive global applicability. The profound influence of collaborative benefits and central government incentives on local government behavior transcends diverse political systems. In countries like India and Brazil, where central governments significantly impact local authorities during rapid industrialization and urbanization phases, these governments can leverage specific policy tools to promote environmental protection. For instance, central government could establish special funds to reward local governments that excel in environmental governance, such as improving air quality or reducing industrial wastewater discharge. This reward mechanism could be directly linked to financial support for local governments, thereby boosting their motivation to enforce environmental policies. Furthermore, central governments can institute strict regulatory frameworks, imposing economic or administrative penalties on local governments that heavily pollute or fail to meet environmental targets. Simultaneously, by offering technical support and capacity building, central governments can aid local authorities in enhancing their environmental governance capabilities, particularly in addressing new challenges brought about by industrialization and urbanization.

7. Conclusion

This study employs Evolutionary Game Theory to analyze the strategic choices of governments in the Fen-Wei Plain region concerning collaborative governance of haze pollution. Based on the findings, several conclusions are drawn:

To enhance the efficiency of collaborative governance of haze pollution, local governments balance economic development with environmental protection. Their decisions and actions are shaped not only by local interests but also by interactions that influence overall regional environmental quality. Local governments may adopt an Evolutionarily Stable Strategy (ESS) characterized by “Strict Enforcement” and “Superficial Enforcement.” Local governments may adopt an Evolutionarily Stable Strategy (ESS) characterized by “Strict Enforcement” and “Superficial Enforcement.” To accelerate the attainment of an ESS, it is essential to enhance cooperative governance benefits, reduce governance costs, increase central government rewards, and minimize the economic losses from haze pollution management. Implementing policies to eliminate barriers that hinder effective haze pollution governance by local governments is critical. Furthermore, the development and implementation of a combination of financial incentives, reputational incentives, and penalties play a crucial role in promoting environmental governance in the Fen-Wei Plain region. Based on the research in this paper, here are specific policy implications and recommendations for the Fen-Wei Plain and its surrounding areas Table. 2:

For the Fen-Wei Plain area: (1) Establish a performance-oriented collaborative governance incentive mechanism: Research indicates that local governments are more likely to adopt a “Strict Enforcement” strategy when the benefits of collaborative governance among them surpass the benefits of acting independently. To facilitate this, the central government should design a performance-based incentive mechanism to reward regions that excel in haze management. For example, additional financial subsidies or technical support could be provided based on each region’s actual progress in improving air quality. Furthermore, establishing a cross-regional information sharing platform would facilitate the exchange of experiences and collaboration among local governments, enabling them to jointly tackle pollution management challenges.

(2) Optimize and differentiate the reward and punishment mechanism: In light of the impact of the central government’s rewards and punishments have on local government behavior, the central government should design a fair and effective reward and punishment system. This system should be capable of identifying and rewarding local governments that implement effective emission reduction measures, while appropriately penalizing areas that fail to meet governance targets. For example, standards for rewards and punishments could be established through environmental performance assessments, ensuring the fairness and transparency of these standards.

(3) Emphasize sustainable and adaptive governance strategies: Given that the effectiveness of regional haze governance changes over time, the government need to focus on the sustainability and adaptability of long-term governance effects. Policymakers should flexibly adjust strategies based on the environmental conditions and governance effects of different years, such as intensifying governance during periods of increased pollution and moderately relaxing controls when pollution decreases. Additionally, governments should invest in innovative technologies and methods to enhance the efficiency and cost-effectiveness of governance efforts, while minimizing adverse impacts on economic development. In summary, effective haze pollution control necessitates close collaboration among local governments and precise incentives from the central government. By establishing performance-oriented collaborative governance incentive mechanisms, optimizing reward and punishment systems, and emphasizing the continuity and adaptability of governance strategies, it is possible to improve air quality and promote fairness and cooperation among regions. These policy insights offer valuable lessons and guidance for China and other countries and regions facing similar challenges.

Expanding to the surrounding areas of the Fen-Wei Plain: Based on the experiences in the Fen-Wei Plain area, we recommend that surrounding areas adopt customized incentive mechanisms designed according to their own environmental and socio-economic conditions. For example, larger financial subsidies and technical support could be provided to areas with significant industrial pollution, encouraging them to implement stricter pollution control measures. Additionally, by establishing a platform for sharing environmental quality data, regional governments can enhance the flow of information and resource sharing, collectively improving environmental governance efficiency across the region.

This research utilizes Evolutionary Game Theory to analyze the collaborative governance strategies of local governments in the Fen-Wei Plain for haze pollution but recognizes certain limitations. Future research could extend to using stochastic evolutionary game methods to more comprehensively simulate the impacts of uncertainties on policy outcomes. Moreover, during numerical simulations, the model parameters should be more precisely calibrated, and more empirical data should be integrated to validate and refine the model, ensuring it aligns more closely with real-world policy implementation and environmental governance scenarios. Expanding the research to regions with diverse geographical and socio-economic conditions would help reveal the universality and heterogeneity in local governments’ collaborative governance strategies. Additionally, further research could also explore the specific impacts of different policy incentives—such as administrative mandates, market incentives, and public participation—on local government behaviors, and the effectiveness of these incentives under varying environmental pressures, thereby providing a scientific basis for formulating more effective environmental policies.

CRediT authorship contribution statement

Xinting Ding: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Jifan Ren:** Writing – review & editing, Resources, Funding acquisition. **Haiyan Lu:** Writing – review & editing, Validation, Supervision, Project administration. **Jafar Hussain:** Writing – review & editing, Supervision, Software. **Renzhong Zhou:** Writing – review & editing, Software.

Data availability

The data supporting the findings of this study are not publicly available but are available from the corresponding author upon reasonable request. Specific requests for data access can be directed to the corresponding author of this article.

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.

Appendix

Table A1
Comparative Analysis of Regional Environmental Governance Studies: Previous Research Versus Current Study on the Fen-Wei Plain

Aspect	Previous Research (Summarized)	Current Study (Fen-Wei Plain)
Geographical Focus	Focuses on regional areas like Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta (Cao et al., 2023; Chang et al., 2019; Hou et al., 2021; Wang & Zhao, 2021; Wu et al., 2021).	Specifically targets the Fen-Wei Plain.
Methodologies Used	Focuses on the source analysis and impact assessment of haze in the Fen-Wei Plain (Feng et al., 2021; Gu et al., 2023; Jia et al., 2023; Ren et al., 2023; Wang et al., 2022; Xiao et al., 2023; Gu et al., 2023; Feng et al., 2021, 2023; Xiao et al., 2023; Dai et al., 2022).	Employs evolutionary game theory integrated with numerical simulations to analyze strategic choices under different policy and environmental conditions.
Main Findings	Effective regional governance has improved air quality and facilitated policy coordination across administrative boundaries (Lin et al., 2023; Zhou et al., 2022; Jiang et al., 2023; Ge et al., 2023).	Identifies that central government incentives and penalties are critical in influencing local government strategies towards strict or superficial enforcement of pollution controls.

References

[1] Md Mostafijur Rahman, McConnell Rob, Schlaerth Hannah, Ko Joseph, Silva Sam, Lurmann Frederick, Palinkas Lawrence, Jill Johnston, Hurlburt Michael, Hao Yin, Ban-Weiss George, Erika Garcia, The effects of Co-exposure to extremes heat and particulate air pollution on mortality in California, ISEE Conf. Abstr. (1) (2022) 2022, https://doi.org/10.1289/isee.2022.O-OP-223.
[2] L. Schwarz, K. Hansen, A. Alari, S.D. Ilango, N. Bernal, R. Basu, A. Gershunov, T. Benmarhnia, Spatial variation in the joint effect of extreme heat events and ozone on respiratory hospitalizations in California, Proc. Natl. Acad. Sci. U.S.A. 118 (22) (2021) e2023078118, https://doi.org/10.1073/pnas.2023078118.
[3] R. Xu, S. Huang, C. Shi, R. Wang, T. Liu, Y. Li, Y. Zheng, Z. Lv, J. Wei, H. Sun, Y. Liu, Extreme temperature events, fine particulate matter, and myocardial infarction mortality, Circulation 148 (2023) 312–323, https://doi.org/10.1161/CIRCULATIONAHA.122.063504.
[4] M.B. Rice, J.M. Samet, Environmental health: lessons from the past and looking to the future, Ann. Am. Thorac. Soc. 14 (9) (2017) 1378–1382, https://doi.org/10.1513/AnnalsATS.201706-455PS.
[5] J. Wang, L. Jia, P. He, P. Wang, L. Huang, Engaging stakeholders in collaborative control of air pollution: a tripartite evolutionary game of enterprises, public and government, J. Clean. Prod. 418 (2023) 138074, https://doi.org/10.1016/j.jclepro.2023.138074.
[6] Ministry of Ecology and Environment, The Beijing-Tianjin-Hebei region experiences a process of severe air pollution. https://www.mee.gov.cn/gkml/sthjbgw/qt/201506/t20150624_304232.html, 2015.
[7] Ministry of Ecology and Environment, Officials from the Ministry of Ecology and environment respond to journalists' questions on the "2019-2020 autumn-winter comprehensive air pollution control action plan for the beijing-tianjin-hebei region and surrounding areas. https://www.mee.gov.cn/xxgk2018/xxgk/xxgk15/201910/t20191017_737966.html, 2019.
[8] H. Lu. City Branding in Chinese Megacity Regions: Against the Background of Ecological Modernization, 1st ed., Routledge, 2024 https://doi.org/10.4324/9781003409953.
[9] Z. Zhang, G. Zhang, Y. Hu, Y. Jiang, C. Zhou, J. Ma, The evolutionary mechanism of haze collaborative governance: novel evidence from a tripartite evolutionary game model and a case study in China, Humanit. Soc. Sci. Commun. 10 (1) (2023) 69, https://doi.org/10.1057/s41599-023-01555-8.
[10] K Wu, D Wang, H Lu, et al., Temporal and spatial heterogeneity of land use, urbanization, and ecosystem service value in China: A national-scale analysis[J], J. Clean. Prod. 418 (2023), https://doi.org/10.1016/j.jclepro.2023.137911.
[11] Y. Hou, K. Zhang, Y. Zhu, W. Liu, Spatial and temporal differentiation and influencing factors of environmental governance performance in the Yangtze River Delta, China. Sci. Total Environ. 801 (2021) 149699, https://doi.org/10.1016/j.scitotenv.2021.149699.

[12] X. Liu, M. Yang, Q. Niu, Y. Wang, J. Zhang, Cost accounting and sharing of air pollution collaborative emission reduction: a case study of Beijing-Tianjin-Hebei region in China, Urban Clim. 43 (2022) 101166, https://doi.org/10.1016/j.uclim.2022.101166.
[13] W. Lin, K. Lin, L. Du, J. Du, Can regional joint prevention and control of atmospheric reduce border pollution? Evidence from China's 12th Five-Year Plan on air pollution, J. Environ. Manag. 342 (2023) 118342, https://doi.org/10.1016/j.jenvman.2023.118342.
[14] D. Zhou, Z. Zhong, L. Chen, W. Gao, M. Wang, Can the joint regional air pollution control policy achieve a win-win outcome for the environment and economy? Evidence from China, Econ. Anal. Pol. 74 (2022) 13–33, https://doi.org/10.1016/j.eap.2022.01.011.
[15] Y. Jiang, L. Tang, C. Huang, Does environmental regulation improve firms' export product quality? Empirical evidence based on China's key regional air pollution and control policy, J. Clean. Prod. 433 (2023) 139822, https://doi.org/10.1016/j.jclepro.2023.139822.
[16] T. Ge, X. Chen, Y. Geng, K. Yang, Does regional collaborative governance reduce air pollution? Quasi-experimental evidence from China, J. Clean. Prod. 419 (2023) 138283, https://doi.org/10.1016/j.jclepro.2023.138283.
[17] H Lu, Y Fu, C Xia, et al., Low-carbon urban experiments from vision to reality: a systematic review of the literature from 2005 to 2020[J], Clim. Pol. 23 (8) (2023) 1058–1077, https://doi.org/10.1080/14693062.2023.2205371.
[18] Y. Gu, H. Xu, R. Feng, B. Zhang, M. Gao, J. Sun, Z. Shen, L. Qu, S.S.H. Ho, J. Cao, Insight into personal exposure characteristics and health effects of PM2.5 and PM0.25-bound PAHs and their derivatives with different heating ways in the Fenwei Plain, China, Environ. Pollut. 338 (2023) 122699, https://doi.org/10.1016/j.envpol.2023.122699.
[19] R. Feng, H. Xu, K. He, Z. Wang, B. Han, R. Lei, K.F. Ho, X. Niu, J. Sun, B. Zhang, P. Liu, Z. Shen, Effects of domestic solid fuel combustion emissions on the biomarkers of homemakers in rural areas of the Fenwei Plain, China, Ecotoxicol. Environ. Saf. 214 (2021) 112104, https://doi.org/10.1016/j.ecoenv.2021.112104.
[20] R. Feng, H. Xu, H. Lu, B. Han, Y. Cheng, Y. Gu, J. Sun, L. Yang, Z. Shen, J. Cao, Effects of PM2.5 emissions from household fuel combustion on biomarkers and pulmonary function in rural areas of Fenwei Plain, China. Atmos. Pollut. Res. 14 (12) (2023) 101923, https://doi.org/10.1016/j.apr.2023.101923.
[21] C. Xiao, J. Zhou, F. Meng, J. Cullen, X. Wang, Y. Zhu, Regional characteristics and spatial correlation of haze pollution: interpretative system analysis in cities of Fenwei Plain in China, Sci. Total Environ. 869 (2023) 161779, https://doi.org/10.1016/j.scitotenv.2023.161779.
[22] X. Dai, B. Zhang, X. Jiang, L. Liu, D. Fang, Z. Long, Has the Three-Year Action Plan improved the air quality in the Fenwei Plain of China? Assessment based on a machine learning technique, Atmos. Environ. 286 (2022) 119204, https://doi.org/10.1016/j.atmosenv.2022.119204.
[23] M. Jia, F. Jiang, N. Evangeliou, S. Eckhardt, X. Huang, A. Ding, A. Stohl, Rapid decline of carbon monoxide emissions in the Fenwei Plain in China during the three-year Action Plan on defending the blue sky, J. Environ. Manag. 337 (2023) 117735, https://doi.org/10.1016/j.jenvman.2023.117735.
[24] H.H. Ren, Y. Cheng, F. Wu, Z.L. Gu, J.J. Cao, Y. Huang, Y.G. Xue, L. Cui, Y.W. Zhang, J.C. Chow, J.G. Watson, R.J. Zhang, S.C. Lee, Y.L. Wang, S. Liu, Spatiotemporal characteristics of ozone and the formation sensitivity over the Fenwei Plain, Sci. Total Environ. 881 (2023) 163369, https://doi.org/10.1016/j.scitotenv.2023.163369.
[25] S. Wang, J. Liu, H. Yi, X. Tang, Q. Yu, S. Zhao, F. Gao, Y. Zhou, T. Zhong, Y. Wang, Trends in air pollutant emissions from the sintering process of the iron and steel industry in the Fenwei Plain and surrounding regions in China, 2014–2017, Chemosphere 291 (2022) 132917, https://doi.org/10.1016/j.chemosphere.2021.132917.
[26] C. Ansell, A. Gash, Collaborative governance in theory and practice, J. Publ. Adm. Res. Theor. 18 (4) (2008) 543–571, https://doi.org/10.1093/jopart/mum032.
[27] C. Pahl-Wostl, The importance of social learning in restoring the multifunctionality of rivers and floodplains, Ecol. Soc. 11 (1) (2006), https://doi.org/10.5751/ES-01542-110110.
[28] H. Bulkeley, M.M. Betsill, Rethinking sustainable cities: multilevel governance and the "urban" politics of climate change, Environ. Polit. 14 (1) (2005) 42–63, https://doi.org/10.1080/0964401042000310178.
[29] A.M. Carter, Animal models of human placentation—a review, Placenta 28 (2007) S41–S47, https://doi.org/10.1016/j.placenta.2006.11.002, 2007.
[30] T. Cao, F. Sun, T. Sun, Spatial test of collaborative treatment efficiency measurement and driving factors of air pollution in China's Yangtze River Delta urban agglomeration, Urban Clim. 49 (2023) 101454, https://doi.org/10.1016/j.uclim.2023.101454.
[31] X. Chang, S. Wang, B. Zhao, J. Xing, X. Liu, L. Wei, Y. Song, W. Wu, S. Cai, H. Zheng, D. Ding, M. Zheng, Contributions of inter-city and regional transport to PM2.5 concentrations in the Beijing-Tianjin-Hebei region and its implications on regional joint air pollution control, Sci. Total Environ. 660 (2019) 1191–1200, https://doi.org/10.1016/j.scitotenv.2018.12.474.
[32] Y. Wang, Y. Zhao, Is collaborative governance effective for air pollution prevention? A case study on the Yangtze river delta region of China, J. Environ. Manag. 292 (2021) 112709, https://doi.org/10.1016/j.jenvman.2021.112709.
[33] Y. Wu, J. Hu, M. Irfan, M. Hu, Vertical decentralization, environmental regulation, and enterprise pollution: an evolutionary game analysis, J. Environ. Manag. 349 (2024) 119449, https://doi.org/10.1016/j.jenvman.2023.119449.
[34] T. Xie, Y. Yuan, H. Zhang, Information, awareness, and mental health: evidence from air pollution disclosure in China, J. Environ. Econ. Manag. 120 (2023) 102827, https://doi.org/10.1016/j.jeem.2023.102827.
[35] Y. Wu, M. Liao, M. Hu, C. Xu, Y. Tao, J. Zhou, Effectiveness assessment of air pollution prevention and control under collaborative supervision in the Beijing-Tianjin-Hebei region based on combination weights and grey fuzzy synthetic evaluation analysis, Sustain. Cities Soc. 64 (2021) 102543, https://doi.org/10.1016/j.scs.2020.102543.
[36] C. Meng, Q. Tang, Z. Yang, H. Cheng, Z. Li, K. Li, Collaborative control of air pollution in the Beijing–Tianjin–Hebei region, Environ. Technol. Innov. 23 (2021) 101557, https://doi.org/10.1016/j.eti.2021.101557.
[37] X. Yu, P. Wang, Economic effects analysis of environmental regulation policy in the process of industrial structure upgrading: evidence from Chinese provincial panel data, Sci. Total Environ. 753 (2021) 142004, https://doi.org/10.1016/j.scitotenv.2020.142004.
[38] J.M. Smith, G.R. Price, The logic of animal conflict, Nature 246 (5427) (1973) 15–18, https://doi.org/10.1038/246015a0.
[39] Jichuan Sheng, Weihai Zhou, Bangzhu Zhu, The coordination of stakeholder interests in environmental regulation: lessons from China's environmental regulation policies from the perspective of the evolutionary game theory—ScienceDirect, J. Clean. Prod. 249 (2019), https://doi.org/10.1016/j.jclepro.2019.119385.
[40] Z. Chu, C. Bian, J. Yang, Joint prevention and control mechanism for air pollution regulations in China: a policy simulation approach with evolutionary game, Environ. Impact Assess. Rev. 91 (2021) 106668, https://doi.org/10.1016/j.eiar.2021.106668.
[41] C. Zhang, X. Zhang, Evolutionary game analysis of air pollution co-investment in emission reductions by steel enterprises under carbon quota trading mechanism, J. Environ. Econ. Manag. 317 (2022) 115376, https://doi.org/10.1016/j.jenvman.2022.115376.
[42] P. Wang, D. Liu, A. Mukherjee, M. Agrawal, H. Zhang, E. Agathokleous, X. Qiao, X. Xu, Y. Chen, T. Wu, M. Zhu, E. Saikawa, S.B. Agrawal, Z. Feng, Air pollution governance in China and India: comparison and implications, Environ. Sci. Pol. 142 (2023) 112–120, https://doi.org/10.1016/j.envsci.2023.02.006.
[43] K. Jiang, D. You, R. Merrill, Z. Li, Implementation of a multi-agent environmental regulation strategy under Chinese fiscal decentralization: an evolutionary game theoretical approach, J. Clean. Prod. 214 (MAR.20) (2019) 902–915, https://doi.org/10.1016/j.jclepro.2018.12.252.
[44] M. Zhang, H. Li, New evolutionary game model of the regional governance of haze pollution in China, Appl. Math. Model. 63 (2018) 577–590, https://doi.org/10.1016/j.apm.2018.07.008.
[45] G. Li, M. Dong, K. Shen, The impact of strengthened environmental regulation policies on China's economy: an assessment based on a CGE model, China Ind. Econ. 11 (2012) 5–17, https://doi.org/10.19581/j.cnki.ciejournal.2012.11.001 (In Chinese).
[46] J. Yang, J. Xu, X. Wu, Economic growth and the environmental and social health costs, Econ. Res. J. 12 (48) (2013) 17–29 (In Chinese). CNKI:SUN:JJYJ.0.2013-12-002.
[47] J. Wang, H. Ma, Q. Cao, T. Chen, Cost-benefit measurement and model selection of regional environmental governance in China: an empirical study based on data from 30 provinces, Economist 6 (2017) 67–77, https://doi.org/10.16158/j.cnki.51-1312/f.2017.06.009 (In Chinese).
[48] J. Zhang, L. Kang, H. Li, P. Ballesteros-Pérez, M. Skitmore, J. Zuo, The impact of environmental regulations on urban Green innovation efficiency: the case of Xi'an, Sustain. Cities Soc. 57 (2020) 102123, https://doi.org/10.1016/j.scs.2020.102123.