EVOLUTIONARY GAME ANALYSIS OF LOCAL GOVERNMENTS ENVIRONMENTAL REGULATION STRATEGIES FROM A COMPETITIVE PERSPECTIVE

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Abstract. Against the backdrop of multi-level governance, intergovernmental cooperation on environmental regulation among local governments often involves complex interactions between strategic adjustments and institutional incentives. From the perspective of competitive evolutionary games, this study constructs a multi-dimensional dynamic model that incorporates institutional incentives, capacity heterogeneity, and feedback from benefit structures. It identifies and analyzes three evolutionary modes "race to the bottom", "race to the top", and "differentiated competition" and conducts numerical simulations across four key dimensions: institutional incentives, initial conditions, benefit structures, and cost configurations. The results reveal that local governments' environmental regulatory behaviors exhibit significant path dependence and a "trust window" effect. Institutional incentives, by reshaping marginal returns, enhance the strategic appeal of cooperative regulation and serve as a key driver of a stable equilibrium. The sustainability of cooperation is largely determined by benefit distribution, while cost structures—especially their elasticity—directly influence strategic preferences. This study contributes to understanding multi-tiered environmental governance and provides theoretical support and policy implications for strengthening incentives, enhancing cooperation stability, and refining differentiated regulatory frameworks.
Keywords: *institutional incentives, evolutionary mode, path dependence, local governments, competitive perspective*

Introduction

Driven by the "dual carbon" strategy and the goal of high-quality development, ecological and environmental governance has become a core issue in the modernization of national governance systems and governance capacity. The 20th National Congress of the Communist Party of China explicitly emphasized "promoting green development and fostering harmony between humanity and nature." A series of policy documents, including the "14th Five-Year Plan for Ecological and Environmental Supervision" and the "Opinions on Strengthening the Supervision of Zoning in Ecological and Environmental Protection," continue to clarify the institutional signals of the central government's emphasis on collaborative green governance among local governments. However, within a unified environmental regulatory framework, local governments still face challenges in achieving collaborative responses in a system that differentiates in both incentives and capacities, as they serve simultaneously as both the implementers of pollution control and the subjects of performance evaluation.

This study explicitly targets the local government level. While local governments operate under the overarching framework of national environmental policies, they also interact with and are influenced by international agreements such as the Paris Accord. Local governments therefore constitute the primary actors in implementing, adjusting,

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and competing over environmental regulation strategies. By clarifying this analytical level, the study emphasizes that its focus is on the strategic interactions among local governments themselves, rather than between national governments, as the central object of investigation.

Driven by the “carbon peaking and carbon neutrality” goals, environmental regulation has become a critical lever for promoting ecological conservation and high-quality development. Acting through constraint mechanisms and policy evolution via behavioral feedback, the current academic literature has formed three main lines of research:

(1) The mechanism of environmental regulation and green development performance. Many studies examine the comprehensive impact of environmental regulation on green development, often using green total factor productivity (GTFP) or green economic efficiency as core indicators. Empirical evidence suggests that the economic effects of environmental regulation follow a staged pattern: in the early stage, regulations increase firms’ overall costs, while in later stages, green innovation and structural optimization are incentivized, ultimately contributing to improved green productivity (Wang et al., 2022, 2023). Some studies further reveal a “U-shaped” or “inverted U-shaped” relationship between environmental regulation and performance, indicating the existence of nonlinear thresholds (Zhao et al., 2022; Dźwigoł et al., 2023). In addition, spatial econometric analyses show that environmental regulation policies may exhibit significant positive spillover and feedback effects at the regional level, while the degree of local governance capacity and fiscal autonomy significantly shapes the effectiveness of regulatory enforcement (Ye et al., 2021; Han et al., 2023; Wang et al., 2023).

(2) The design of environmental regulation instruments and firms’ innovation behavior has sparked ongoing debate around whether “environmental regulation promotes innovation.” Some studies explore this issue from a micro-mechanism perspective, emphasizing that stricter regulations increase marginal costs and encourage firms to upgrade technologies and optimize production processes, thereby driving green innovation (Guo et al., 2017; Zhang et al., 2024). Other studies investigate intermediary mechanisms, suggesting that environmental regulations may enhance green productivity by stimulating green investment and R&D expenditure (Wang et al., 2024; Zhang et al., 2025). In addition, comparative research on regulatory instrument types shows that single-tool policies may suffer from limited long-term incentive effects. In contrast, policy combinations involving taxes, subsidies, transaction mechanisms, and cooperation strategies tend to produce more stable and adaptive behavioral responses (Ellis, 1992; Meckling, 2015). Notably, regulatory stringency, enforcement persistence, and the consistency of regulatory signals have been identified as key institutional variables that significantly influence the effectiveness of innovation incentives (Zhong et al., 2023; Song et al., 2024).

(3) The evolution of environmental regulation behavior is closely related to the game structure among local governments, providing a theoretical foundation for understanding the differentiation in environmental regulation effectiveness and local behavioral heterogeneity. Accordingly, many scholars have shifted from static models to dynamic evolutionary game perspectives to analyze the strategy selection processes of multiple agents. Existing findings suggest that factors such as the strength of institutional incentives and the tolerance level of external monitoring mechanisms jointly shape the behavioral tendencies of local governments, firms, and the public (Sheng et al., 2020; Yu et al., 2025). Some studies further develop multi-stage interaction models, revealing that behavioral evolution may follow a dynamic trajectory of “strategy stabilization–

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imbalance–differentiation" (Wu et al., 2024; Hu et al., 2024). In particular, in the context of horizontal interactions among local governments, varying intensities of performance assessment, administrative capacity, and fiscal autonomy across regions result in non-unified regulatory behavior paths (Cao et al., 2024; Zhang et al., 2023). Other research highlights that imitation-based behavior combined with short-term incentive structures may intensify policy risks and increase the likelihood of cooperation failure (Zhong et al., 2023).

Overall, while current research has made notable progress in understanding the effectiveness of environmental regulation responses—particularly in terms of policy tool design and firm behavioral adaptation—the evolutionary dynamics of strategic interactions among local governments, especially regarding strategy stabilization and institutional boundary conditions, remain underexplored.

Although prior research has produced valuable insights, important questions remain unresolved. Most existing work emphasizes the economic impacts of environmental regulation or the adaptive responses of firms, while the evolutionary processes of strategic interaction among local governments have received comparatively limited attention. Specifically, the mechanisms through which institutional incentives affect the durability of cooperation, the ways in which administrative diversity alters strategic pathways, and the emergence of path dependence or temporary "trust windows" in local regulatory contexts are still insufficiently examined. To address these shortcomings, this paper introduces a multi-dimensional evolutionary game model that explores the complex patterns of local government interaction under diverse institutional arrangements.

This study attempts to contribute in the following ways:

(1) It moves beyond traditional evolutionary game models that rely heavily on single-incentive mechanisms by developing a multi-dimensional interactive framework integrating institutional incentives, administrative heterogeneity, and dynamic cost-benefit feedback under bounded rationality. This framework reveals the path dependence in environmental regulation strategy evolution and the formation logic of the "trust window" effect.

(2) Through an innovative theoretical design encompassing five scenarios and eight hypotheses, the study constructs and empirically validates the nonlinear effects of institutional incentives using numerical simulations. Sensitivity analyses further quantify the influence of incentive intensity, initial cooperation intentions, and cost heterogeneity on the evolutionary trajectories of local government strategies.

Materials and methods

Theoretical mechanism

To reveal the underlying behavioral logic and dynamic evolution mechanism in local governments' environmental regulation strategy selection, this study constructs a multidimensional interactive system that incorporates hierarchical institutional incentives, intergovernmental competition, heterogeneous capacities, and strategic adjustments. Based on this framework, a theoretical mechanism diagram illustrating the interactive dynamics of environmental regulation strategies among local governments is developed (*Fig. 1*). Theoretically, this study is grounded in the analytical perspective of "central-local institutional nesting and horizontal intergovernmental strategy co-evolution," and integrates established paradigms in economics. It seeks to build an explanatory framework that emphasizes both systematic logic and dynamic interactions.

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First, the theory of intergovernmental competition suggests that under a decentralized fiscal system, local governments—functioning as quasi-corporate entities—compete for tax revenues, industries, and population by employing competitive policy instruments (land prices, environmental standards) to attract investment. In the absence of cross-regional coordination and a unified performance evaluation mechanism, such competition may evolve into non-cooperative dynamics, leading to a "race to the bottom," whereby local governments tend to relax environmental regulations in exchange for short-term economic gains (Tiebout, 1956; Zhang, 1998). This theoretical lens offers critical insight into understanding the "behavioral drivers" and "competitive pressures" that shape local governments' strategic choices.

Second, the interactions among local governments are not conducted in isolation but rather embedded in a dynamic network of strategic observation, imitation, and response. According to the theory of policy diffusion, one local government's decisions on environmental regulatory strategies and performance outcomes may be influenced by information disclosure, ranking comparisons, and interjurisdictional cooperation mechanisms, thereby generating "horizontal spillover effects." Such diffusion paths may take the form of experiential learning (e.g., adopting benchmarks set by leading regions), strategic competition (e.g., lowering local standards to retain capital), or policy emulation (e.g., revising policies based on others' responses). Therefore, intergovernmental environmental regulation is not characterized by static policy confrontation but instead involves continuous observation, adjustment, and evolution (Berry et al., 1990; Shipan et al., 2008). As external pressures diffuse, regulatory strategies tend to exhibit both phased stability and persistent adaptation.

Third, from an institutional perspective, local governments' policy decisions are deeply shaped by the central government's performance evaluation and fiscal incentive mechanisms. According to principal-agent theory, the central government establishes performance evaluation indicators (such as green GDP and ecological civilization indices), and provides a suite of incentive tools (including fiscal transfers and accountability mechanisms such as performance audits and target-based responsibility systems) (Tirole, 1986; Xu, 2011). These instruments are intended to incorporate environmental regulation into promotion logic and encourage officials' compliance via performance-based rewards. However, local governments are not merely passively responsive to incentive signals. Instead, they make strategic decisions based on cost-risk assessments and horizontal competition dynamics. Under the combined influence of differentiated capacities for environmental governance and heterogeneous fiscal-endowment conditions, localities may diverge significantly in their interpretation of incentive signals. This divergence leads to different implementation strategies, such as "proactive compliance," "symbolic response," or even "selective avoidance" of regulatory requirements.

From the perspective of the three theoretical frameworks discussed above, the evolutionary logic of intergovernmental environmental regulatory strategy interaction can be understood as follows: the central government exerts vertical pressure on local governments (governments A and B) through institutional incentives and performance evaluations. However, local governments are not directly driven by a unified institutional signal; rather, they make strategic decisions based on their own fiscal capacities and administrative capabilities. This results in differing preferences for "proactive regulation" versus "regulatory shirking."

Meanwhile, interlocal interactions—such as competition over pollution spillovers, industrial attraction, and performance rankings—further drive strategic responses. These

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are often manifested through imitation and diffusion, where demonstration effects or policy benchmarking allow one locality's regulatory choices to influence others. Over time, such strategic interactions may evolve into one of three distinct modes:

(1) A "race to the bottom" mode, where institutional incentives are weak and jurisdictions with limited political authority or administrative capacity tend to relax environmental regulation to pursue short-term economic growth, resulting in horizontal regulatory competition;

(2) An "upward competition" mode, where strong central incentives and clear ecological performance metrics induce jurisdictions to emulate best practices and converge toward higher regulatory standards;

(3) A "differentiated competition" mode, which arises under conditions of pronounced disparities in administrative capability or performance pressures. In such contexts, local regulatory choices become segmented, reflecting the logic of "multi-actor, region-specific interaction."

This typology offers a pathway-based foundation for developing an evolutionary game-theoretic model of intergovernmental environmental regulation strategy interaction.

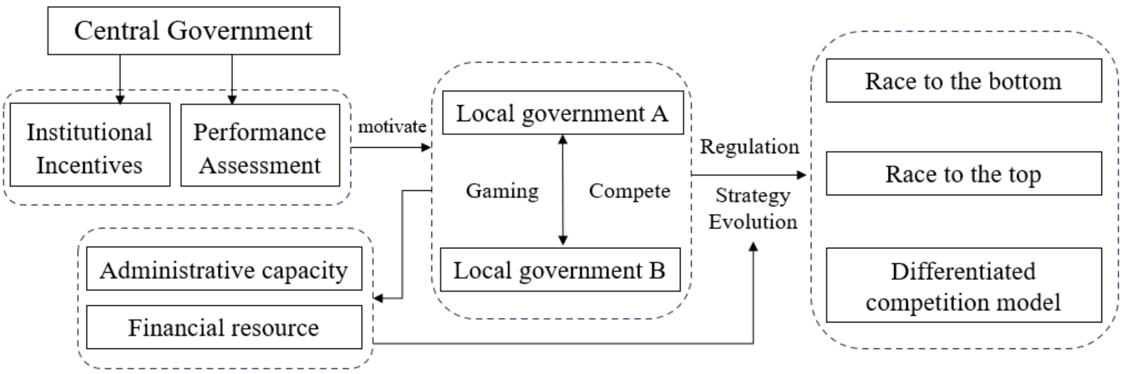

Figure 1. *Interaction mechanism of environmental regulation strategies among local governments*

Model assumptions

Building on the theoretical mechanism outlined above, this section further analyzes how incentive mechanisms, resource endowments, and administrative heterogeneity influence the evolutionary stability of environmental regulation strategies among local governments. Local authorities are confronted with dual responsibilities: promoting economic development and protecting the interests of enterprises on the one side, while fulfilling environmental policy implementation on the other. The reconciliation of these tasks depends not only on local economic and social conditions but also on the overarching administrative arrangements in which they are embedded. Because institutional structures vary considerably, the ability of governments to respond is highly uneven; nevertheless, hierarchical mandates and central oversight usually delimit the range of choices available to local governments. These combined pressures and responsibilities ultimately shape their strategic conduct in environmental regulation.

In reality, intergovernmental environmental regulation typically engages a wide range of stakeholders, such as central agencies, enterprises, and the general public. For the

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purposes of this analysis, however, the system is reduced to a two-player framework that models local governments A and B. This abstraction is intended to ensure conceptual clarity and to emphasize the fundamental mechanisms of strategic adjustment and institutional incentives without overcomplicating the model. The two-party structure is sufficient to capture the core dynamics of horizontal rivalry and cooperation among local governments, while at the same time offering a baseline that can be extended to multi-actor scenarios in subsequent studies.

Relevant parameters are defined (*Table 1*), and the following research assumptions are proposed:

Assumption 1. Local governments A and B are participants in the evolutionary game under the environmental regulation interaction and competition mechanism. Throughout the entire game process, both parties are assumed to be boundedly rational actors who continuously adjust their strategic choices to pursue equilibrium. Each participant possesses two available strategies: {strict regulation, lax regulation}.

Assumption 2. The parameter μ represents the relative importance of environmental performance in the central government's performance evaluation system. It reflects the local governments' ability to perceive the benefits of pollution reduction (or losses from environmental externalities). When μ exceeds 0 but remains relatively low, environmental performance is weakly emphasized, and local governments tend to prioritize short-term economic growth, thereby favoring the "lax regulation" strategy. When μ exceeds 1, it indicates a high sensitivity to environmental performance, which triggers a shift toward "positive response to incentives" and promotes the diffusion of the "strict regulation" strategy across regions. The parameter P denotes the central government's punishment intensity for local governments implementing lax regulation. The coordination between μ and P forms a core incentive-constraint mechanism within the central-local governance framework and plays a guiding role in the strategic evolution direction of the game model.

Assumption 3. The strategic adjustments of local governments A and B are influenced by the externalities of environmental behaviors in adjacent regions. Parameters λ_1 and λ_2 are introduced to capture the degree of spatial externalities arising from pollution control behaviors, thereby depicting the extent of strategic interdependence across spatial dimensions. When the parameter λ approaches 0, the impact of pollution is confined to the local region, and the strategic choices of local governments tend to be "independent." When the parameter λ exceeds 1, pollution behavior exhibits significant spatial externalities, meaning that a local government may be forced to bear the environmental governance costs caused by pollution spillovers ("pollution transfer") from neighboring regions. This leads to an amplification of the effects of "policy imitation" and "regulatory response."

Assumption 4. When local government A adopts the "proactive regulation" strategy, it must incur a cost denoted by C_1, leading to a reduction in local environmental pollution by M_1 (which accounts for external environmental spillovers via coefficient λ_1). Meanwhile, government B's pollution increases by N_2 (which reflects the external impact weighted by coefficient λ_2), causing economic loss W_1 due to the "free-rider" effect. Conversely, if local government A adopts the "negative regulation" strategy, it may gain short-term economic returns denoted by R_1, but it also faces administrative penalties P and an increase in environmental pollution by N_1 and N_2 (again considering spillover coefficients λ_1 and λ_2). The strategic behavior of local government B follows a similar logic to that of government A and will not be repeated here.

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Table 1. *Parameter definition*

Parameter	Definitions	Range
x	Probability that local government A adopts the proactive regulation strategy	$0 \le x \le 1$
y	Probability that local government B adopts the proactive regulation strategy	$0 \le y \le 1$
R_1	Short-term economic gain of local government A under negative regulation	$R_1 \ge 0$
R_2	Short-term economic gain of local government B under negative regulation	$R_2 \ge 0$
M_1	Pollution reduction achieved by local government A under proactive regulation	$M_1 \ge 0$
M_2	Pollution reduction achieved by local government B under proactive regulation	$M_2 \ge 0$
N_1	Pollution increase caused by local government A under negative regulation	$N_1 \ge 0$
N_2	Pollution increase caused by local government B under negative regulation	$N_2 \ge 0$
C_1	Regulatory cost incurred by local government A under proactive regulation	$C_1 \ge 0$
C_2	Regulatory cost incurred by local government B under proactive regulation	$C_2 \ge 0$
W_1	Economic loss to local government A caused by B's negative regulation	$W_1 \ge 0$
W_2	Economic loss to local government B caused by A's negative regulation	$W_2 \ge 0$
P	Penalty imposed on A or B under negative regulation	$P \ge 0$
λ_1	External spillover coefficient of A's pollution behavior	$0 < \lambda_1 < 1$
λ_2	External spillover coefficient of B's pollution behavior	$0 < \lambda_2 < 1$
μ	Weight of environmental performance in the central government's evaluation system	$0 < \mu < 1$

Model construction

According to the above assumptions, the payoff matrix for the evolutionary game between local governments A and B can be constructed (*Table 2*).

Table 2. *The profit matrix of the strategy choices of local government A and B*

	Strategy	Local government B	
		Active regulation (y)	Negative regulation $(1-y)$
Local government A	Active regulation (x)	$\mu[(1-\lambda_1)M_1+\lambda_2 M_2]-C_1$ $\mu[(1-\lambda_2)M_2+\lambda_1 M_1]-C_2$	$\mu[(1-\lambda_1)M_1-\lambda_2 N_2]-C_1-W_1$ $\mu[\lambda_1 M_1-(1-\lambda_2)N_2]+R_2-P$
	Negative regulation $(1-x)$	$\mu[\lambda_2 M_2-(1-\lambda_1)N_1]+R_1-P$ $\mu[(1-\lambda_2)M_2-\lambda_1 N_1]-C_2-W_2$	$R_1-P-\mu[\lambda_2 N_2+(1-\lambda_1)N_1]$ $R_2-P-\mu[\lambda_1 N_1+(1-\lambda_2)N_2]$

According to the payoff matrix, the expected payoffs for the two players can be calculated as follows:

1. Expected payoff of local government A

When local government A adopts an active regulation strategy, the expected payoff is *Equation 1*:

$$E_{x1} = y\left[\mu\left[(1-\lambda_1)M_1+\lambda_2 M_2\right]-C_1\right]+(1-y)\left[\mu\left[(1-\lambda_1)M_1-\lambda_2 N_2\right]-C_1-W_1\right] \quad \text{(Eq.1)}$$

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When local government A adopts a negative regulation strategy, the expected payoff is *Equation 2*:

$$E_{x2} = y\left[\mu\left[\lambda_2 M_2 - (1-\lambda_1)N_1\right] + R_1 - P\right] + (1-y)\left[R_1 - P - \mu\left[\lambda_2 N_2 + (1-\lambda_1)N_1\right]\right] \quad \text{(Eq.2)}$$

Thus, the average expected payoff for local government A is *Equation 3*:

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

Accordingly, the replicator dynamic equation for local government A is given by *Equation 4*:

$$F(x,y) = x(E_{x1} - E_x) = x(1-x)(E_{x1} - E_{x2}) \quad \text{(Eq.4)}$$

2. Expected payoff of local government B

When local government B adopts an active regulation strategy, the expected payoff is *Equation 5*:

$$E_{y1} = x\left[\mu\left[(1-\lambda_2)M_2 + \lambda_1 M_1\right] - C_2\right] + (1-x)\left[\mu\left[(1-\lambda_2)M_2 - \lambda_1 N_1\right] - C_2 - W_2\right] \quad \text{(Eq.5)}$$

When local government B adopts a negative regulation strategy, the expected payoff is *Equation 6*:

$$E_{y2} = x\left[\mu\left[\lambda_1 M_1 - (1-\lambda_2)N_2\right] + R_2 - P\right] + (1-x)\left[R_2 - P - \mu\left[\lambda_1 N_1 + (1-\lambda_2)N_2\right]\right] \quad \text{(Eq.6)}$$

Thus, the average expected payoff for local government B is *Equation 7*:

$$E_y = yE_{y1} + (1-y)E_{y2} \quad \text{(Eq.7)}$$

Accordingly, the replicator dynamic equation for local government B is given by *Equation 8*:

$$G(x,y) = y(E_{y1} - E_y) = y(1-y)(E_{y1} - E_{y2}) \quad \text{(Eq.8)}$$

Jointly considering the replicator dynamic equations of local governments A and B, the two-dimensional dynamic system (I) can be obtained as *Equation 9*:

$$\begin{cases} F(x,y) = x(1\text{-}x)\left[(y-1)W_1 + \mu(1-\lambda_1)(M_1 + N_1) + P - C_1 - R_1\right] \\ G(x,y) = y(1\text{-}y)\left[(x-1)W_2 + \mu(1-\lambda_2)(M_2 + N_2) + P - C_2 - R_2\right] \end{cases} \quad \text{(Eq.9)}$$

Results and analysis of equilibrium points

Let $F(x,y)=0$, $G(x,y)=0$, the system admits five equilibrium points： $E_1(0,0)$, $E_2(1,0)$, $E_3(0,1)$, $E_4(1,1)$, $E_5(x^*,y^*)$, as illustrated by *Equation 10*.

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$$x^* = \frac{\mu(\lambda_2 - 1)(M_2 + N_2) + C_2 + R_2 + W_2 - P}{W_2}, y^* = \frac{\mu(\lambda_1 - 1)(M_1 + N_1) + C_1 + R_1 + W_1 - P}{W_1} \quad \text{(Eq.10)}$$

To further examine the local stability of these equilibrium points, as illustrated by *Equation 11* and *Table 3,* the Jacobian matrix J of the two-dimensional dynamical system (I) is derived by computing the partial derivatives with respect to each variable.

$$J = \begin{bmatrix} (1-2x)[(y-1)W_1 + P - C_1 - R_1 + \mu(1-\lambda_1)(M_1 + N_1)] & x(1-x)W_1 \\ y(1-y)W_2 & (1-2y)[(x-1)W_2 + P - C_2 - R_2 + \mu(1-\lambda_2)(M_2 + N_2)] \end{bmatrix} \quad \text{(Eq.11)}$$

Table 3. $\det J$ *and* $\mathrm{tr}J$

	$\det J$	$\mathrm{tr}J$
$E_1(0,0)$	$\left[\mu(1-\lambda_1)(M_1+N_1)-C_1-R_1-W_1+P\right]\times$ $\left[\mu(1-\lambda_2)(M_2+N_2)-C_2-R_2-W_2+P\right]$	$\mu(1-\lambda_1)(M_1+N_1)+\mu(1-\lambda_2)(M_2+N_2)$ $-C_1-C_2-R_1-R_2-W_1-W_2+2P$
$E_2(1,0)$	$-\left[\mu(1-\lambda_1)(M_1+N_1)-C_1-R_1-W_1+P\right]$ $\times\left[\mu(1-\lambda_2)(M_2+N_2)-C_2-R_2+P\right]$	$-\mu(1-\lambda_1)(M_1+N_1)+\mu(1-\lambda_2)(M_2+N_2)$ $+C_1-C_2+R_1-R_2+W_1$
$E_3(0,1)$	$\left[\mu(1-\lambda_1)(M_1+N_1)-C_1-R_1+P\right]\times$ $-\left[\mu(1-\lambda_2)(M_2+N_2)-C_2-R_2-W_2+P\right]$	$\mu(1-\lambda_1)(M_1+N_1)-\mu(1-\lambda_2)(M_2+N_2)$ $-C_1+C_2-R_1+R_2+W_2$
$E_4(1,1)$	$\left[\mu(1-\lambda_1)(M_1+N_1)-C_1-R_1+P\right]\times$ $\left[\mu(1-\lambda_2)(M_2+N_2)-C_2-R_2+P\right]$	$-\mu(1-\lambda_1)(M_1+N_1)-\mu(1-\lambda_2)(M_2+N_2)$ $+C_1+C_2+R_1+R_2-2P$
$E_5(x^*,y^*)$	$\det J(x^*,y^*)$	0

Let: $T_1 = \mu(1-\lambda_1)M_1 - C_1$, $T_2 = \mu(1-\lambda_2)M_2 - C_2$, $S_1 = R_1 - \mu(1-\lambda_1)N_1 - P$, $S_2 = R_2 - \mu(1-\lambda_2)N_2 - P$. Specifically, T_1 denotes the net incentive return of local government A under the active regulation strategy, representing the difference between its pollution abatement benefits and the regulatory cost incurred. T_2 indicates the net incentive return of local government B under active regulation. S_1 represents the net incentive return of local government A under the passive regulation strategy, which reflects the loss of short-term economic gains and negative externalities due to unregulated pollution. S_2 indicates the net incentive return of local government B under passive regulation. W_1 and W_2 represent the losses incurred by each government under passive regulation in the evolutionary game due to the other's choice of non-cooperation. *Tables 4* and *5* present the results of the local stability analysis for each equilibrium point.

Scenario 1: When the condition $T_1 - S_1 < 0$ and $T_2 - S_2 < 0$ is satisfied, the system (I) stabilizes at $E_1(0,0)$. This scenario represents an evolutionarily stable strategy of "dual passive regulation," in which both local governments A and B find the net payoff under active regulation T_i lower than that under passive regulation S_i, thus opting for the passive regulation strategy. Such behavior typically occurs when central performance evaluation pressure is weak (small μ), marginal abatement benefits are limited (small M_i, N_i), and the spillover scope is narrow (large W_i), among other combined conditions.

Scenario 2: When the condition $T_1 - S_1 > W_1$ and $T_2 - S_2 < 0$ is satisfied, the system (I) converges to $E_2(1,0)$. In this case, local government B selects the passive regulation strategy because its net benefit under passive regulation is greater than that under active regulation ($S_2 > T_2$). Meanwhile, local government A prefers the active regulation strategy ($T_1 > S_1$). This scenario typically arises under conditions where government A faces stronger pressure from environmental performance evaluation, while regulation incentives in region B are relatively weak.

Scenario 3: When the condition $T_2 - S_2 > W_2$ and $T_1 - S_1 < 0$ is satisfied, the system (I) converges to $E_3(0,1)$. In this case, the regulatory incentive for local government A is entirely negative ($T_1 < S_1$), while local government B, despite receiving lower net returns from active regulation ($T_2 - S_2$), is able to compensate for losses under non-cooperative conditions through the value of W_2. As a result, government B remains in favor of active regulation, leading the system to stabilize. This scenario reflects the “mirror” state of Case 2 and frequently occurs in practice when regulatory incentive policies are unevenly distributed or when responsibility is not equally shared across regions.

Scenario 4: When the condition $T_1 - S_1 > W_1$ and $T_2 - S_2 > W_2$ is satisfied, the system (I) converges to $E_4(1,1)$. In this case, both local governments A and B obtain higher net benefits from active regulation compared to passive strategies. Even under non-cooperative conditions, each party is still able to ensure higher comprehensive returns ($T_i - S_i > W_i$), thereby resulting in a stable equilibrium characterized as “bilateral coordination.” This scenario reflects the optimal pattern of coordinated regulation, where incentives are visible, losses are controllable, and cooperation is sustainable.

Scenario 5: When the condition $0 < T_1 - S_1 < W_1$ and $0 < T_2 - S_2 < W_2$ is satisfied, the system (I) no longer converges toward a single boundary equilibrium, but simultaneously tends toward both $E_1(0,0)$ and $E_4(1,1)$, forming a “dual-attraction” evolutionary stable state. The evolutionary trajectories under this scenario are illustrated in *Figure 2*. Although both local governments A and B possess a certain level of cooperative motivation ($T_i > S_i$), they fail to compensate for externality-induced losses ($T_i - S_i < W_i$), making them susceptible to deviation from cooperative strategies. Moreover, initial conditions exert a significant influence on the evolution path, and the system is likely to remain trapped in a long-term non-optimal state, resulting in a dilemma of “co-regulation failure.”

Table 4. *Determination of local stability of each equilibrium point*

Equilibrium points	**Scenario 1**			**Scenario 2**			**Scenario 3**		
	$\det J$	tr$J$	**Stability**	$\det J$	tr$J$	**Stability**	$\det J$	tr$J$	**Stability**
$E_1(0,0)$	+	−	ESS	−	Uncertain	Saddle point	Uncertain	−	Saddle point
$E_2(1,0)$	−	Uncertain	Saddle point	+	−	ESS	−	Uncertain	Saddle point
$E_3(0,1)$	−	Uncertain	Saddle point	+	+	Unstable	+	−	ESS
$E_4(1,1)$	+	+	Unstable	−	−	Saddle point	+	+	Unstable
$E_5(x^*, y^*)$	△	0	Saddle point	△	0	Saddle point	△	0	Saddle point

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Table 5. *Determination of local stability of each equilibrium point*

Equilibrium points	Scenario4			Scenario5		
	$\det J$	tr$J$	**Stability**	$\det J$	tr$J$	**Stability**
$E_1(0,0)$	+	+	Unstable	+	-	ESS
$E_2(1,0)$	−	Uncertain	Saddle point	+	+	Unstable
$E_3(0,1)$	−	Uncertain	Saddle point	+	+	Unstable
$E_4(1,1)$	+	+	ESS	+	−	ESS
$E_5(x^*,y^*)$	△	0	Saddle point	△	0	Saddle point

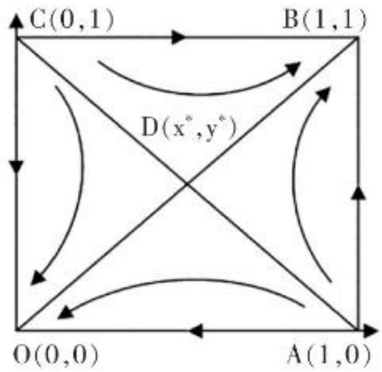

Figure 2. *Phase diagram*

Based on Scenario 5, and incorporating the equilibrium point $E_5(x^*,y^*)$ and the phase diagram of the system's evolutionary trajectories (*Fig. 2*), we introduce area functions H_1 and H_2, where $H_2 = 1 - H_1$, as illustrated by *Equation 12*. Specifically, H_1 (the area of quadrilateral S_{OADC}) represents the evolutionary probability of system (I) converging to $E_1(0,0)$, while the residual area H_2 (S_{ABCD}) reflects the probability of system (I) evolving toward $E_4(1,1)$. The actual evolutionary equilibrium of system (I) is strongly influenced by the relative magnitude of H_1 and H_2. When $H_1 > H_2$, system (I) tends to converge to the "dual non-regulation" strategy. When $H_1 < H_2$, the system is more likely to evolve toward the "dual regulation" strategy. When $H_1 = H_2$, system (I) remains in a structurally indeterminate state, and the resulting evolutionary outcome is highly sensitive to the initial condition.

$$H_1 = \frac{1}{2}(x^*+y^*) = \frac{1}{2}\left[\frac{\mu(\lambda_2-1)(M_2+N_2)+C_2+R_2+W_2-P}{W_2}+\frac{\mu(\lambda_1-1)(M_1+N_1)+C_1+R_1+W_1-P}{W_1}\right] \quad \text{(Eq.12)}$$

To illustrate the evolutionary trends of equilibrium strategies under varying parameter conditions, this section further analyzes the system by calculating the relevant partial derivatives. Based on this analysis, eight theoretical propositions are proposed as follows.

Proposition 1: When the central government places increasing emphasis on environmental performance assessments, local governments A and B are more inclined to adopt proactive regulatory strategies.

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$$\frac{\partial H_1}{\partial \mu}=\frac{(M_2+N_2)(\lambda_2-1)W_1+(M_1+N_1)(\lambda_1-1)W_2}{2W_1W_2}<0 \tag{Eq.13}$$

As illustrated by *Equation 13*. Since the derivative is negative, an increase in μ will lead to a decrease in H_1, indicating that system I is more likely to evolve toward the equilibrium point $E_4(1,1)$.

Proposition 2: As the penalties incurred by local governments A and B under passive regulation become more severe, they increasingly tend to adopt proactive regulatory strategies.

$$\frac{\partial H_1}{\partial P}=-\frac{W_1+W_2}{2W_1W_2}<0 \tag{Eq.14}$$

As illustrated by *Equation 14*. Since the partial derivative is negative, a higher value of P leads to a lower value of H_1, indicating that system (I) is more likely to evolve toward the equilibrium point $E_4(1,1)$.

Proposition 3: As the external environmental impact exerted by local government A on B increases, both parties are more likely to opt for passive regulatory strategies.

$$\frac{\partial H_1}{\partial \lambda_1}=\frac{\mu(M_1+N_1)}{2W_1}>0,\frac{\partial H_1}{\partial \lambda_2}=\frac{\mu(M_2+N_2)}{2W_2}>0 \tag{Eq.15}$$

As illustrated by *Equation 15*. Since the partial derivatives are consistently positive, an increase in λ_1 (which corresponds to a larger H_1 and a higher degree of pollution spillover) implies that most of the pollution mitigation benefits are captured by local government B. This reduces the net benefit retained by local government A, leading system (I) to ultimately evolve toward $E_1(0,0)$. (The analysis of λ_2 follows the same logic as λ_1 and is omitted for brevity.)

Proposition 4: When the marginal emission reduction benefits of adopting active regulatory strategies increase for local governments, both parties tend to be more inclined toward selecting active regulatory strategies.

$$\frac{\partial H_1}{\partial M_1}=\frac{\mu(\lambda_1-1)}{2W_1}<0,\frac{\partial H_1}{\partial M_2}=\frac{\mu(\lambda_2-1)}{2W_2}<0 \tag{Eq.16}$$

As illustrated by *Equation 16*. Since the partial derivatives are negative, an increase in M_1 or M_2 leads to a decrease in H_1, thereby causing system (I) to evolve toward the equilibrium state $E_4(1,1)$.

Proposition 5: As pollution resulting from passive regulation becomes more severe—especially when the environmental costs are primarily borne by local governments—their motivation to avoid adopting passive regulatory strategies is strengthened. This facilitates both local governments' participation in active regulation.

$$\frac{\partial H_1}{\partial N_1}=\frac{\mu(\lambda_1-1)}{2W_1}<0,\frac{\partial H_1}{\partial N_2}=\frac{\mu(\lambda_2-1)}{2W_2}<0 \tag{Eq.17}$$

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As illustrated by *Equation 17*. Given that the partial derivatives are negative, an increase in N_1 or N_2 leads to a decrease in H_1, thereby pushing system (I) to evolve toward the equilibrium state $E_4(1,1)$.

Proposition 6: As the implementation cost of active regulation increases, the marginal burden on local governments rises accordingly. This, in turn, weakens the cooperative incentives between local governments and discourages them from adopting active regulatory strategies, thus making passive regulation more attractive.

$$\frac{\partial H_1}{\partial C_1} = \frac{1}{2W_1} > 0, \frac{\partial H_1}{\partial C_2} = \frac{1}{2W_2} > 0 \tag{Eq.18}$$

As illustrated by *Equation 18*. Since the partial derivatives are positive, an increase in C_1 or C_2 leads to an increase in H_1, which drives system (I) to evolve toward the equilibrium state $E_1(0,0)$.

Proposition 7: When either party suffers significant marginal losses due to the other party's failure to cooperate, the expected returns from continued collaboration diminish. This weakens the stability of cooperative strategies and makes both local governments more inclined to adopt non-cooperative paths (passive regulatory strategies).

$$\frac{\partial H_1}{\partial W_1} = \frac{-C_1 + P - R_1 - \mu(M_1 + N_1)(\lambda_1 - 1)}{2W_1^2}, \frac{\partial H_1}{\partial W_2} = \frac{-C_2 + P - R_2 - \mu(M_2 + N_2)(\lambda_2 - 1)}{2W_2^2} \tag{Eq.19}$$

As illustrated by *Equation 19*. Since the sign of the derivatives cannot be determined analytically, W represents the marginal cost borne by a government when choosing an active regulation strategy under non-cooperation. A higher W indicates greater expected loss due to "defection" by the opponent, which reduces the government's risk tolerance and expected net return. Consequently, system (I) tends to evolve toward the equilibrium point $E_1(0,0)$.

Proposition 8: When the short-term returns generated by passive environmental regulation increase, weaker local governments become more inclined to deviate from active regulation strategies. Eventually, both parties gravitate toward adopting "dual passive regulation" as their strategic choice.

$$\frac{\partial H_1}{\partial R_1} = \frac{1}{2W_1} > 0, \frac{\partial H_1}{\partial R_2} = \frac{1}{2W_2} > 0 \tag{Eq.20}$$

As illustrated by *Equation 20*. Since the coefficients are positive, as R_1 or R_2 increase (which enhances the motivation for both governments to "free ride"), the value of H_1 increases, and system (I) tends to evolve toward the equilibrium point $E_1(0,0)$.

Discussion

In this paper, the numerical parameters are not taken from empirical observations; instead, they are specified on the basis of the theoretical framework developed earlier in the model. Such parameterization follows a well-recognized convention in evolutionary game research, where scholars often employ standardized or scenario-based values to

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examine the stability of equilibria and the responsiveness of evolutionary paths (Zhang, et al., 2023). Rather than reproducing empirical magnitudes, the settings are designed to illustrate the theoretical dynamics of intergovernmental regulatory strategies, which is the central aim of this paper.

To further validate the robustness of the evolutionary game model and better capture the impact of various factors on the stability of intergovernmental environmental regulatory strategies from a competitive perspective, numerical simulations were conducted under the parameter conditions defined in Scenario 5. The specific parameter settings are as follows: $\mu = 0.6$, $P = 1.55$, $\lambda_1 = 0.4$, $\lambda_2 = 0.5$, $M_1 = 1.2$, $M_2 = 1.1$, $N_1 = 0.85$, $N_2 = 0.9$, $R_1 = 0.9$, $R_2 = 0.95$, $C_1 = 0.6$, $C_2 = 0.7$, $W_1 = 1.5$, $W_2 = 1.2$.

The impact of initial state on evolutionary results

The choice of initial strategies by local governments A and B significantly affects the evolutionary trajectory of the game, as evidenced by the sensitivity of outcomes to initial conditions (*Fig. 3*). Under the parameter settings of Scenario 5, System (I) exhibits a "dual-attractor" structure in which both "double active" and "double passive" regulatory equilibria may emerge. When the initial strategic configuration favors passive regulation ($x_0 < 0.3, y_0 < 0.7$), the system is more likely to evolve toward a "double passive" equilibrium. Even if one party initially shows a higher inclination toward active regulation, the final cooperation may still fail due to the other party's opportunistic behavior or "free-riding" tendencies. This reflects an imbalance in external net benefits and misaligned assessment benchmarks that impede the achievement of a cooperative equilibrium. Conversely, when the initial configuration leans toward active regulation ($x_0 > 0.5, y_0 > 0.6$), the system tends to converge toward the "double active" stable state. This finding aligns with the path dependence proposition described in Proposition 5, further confirming the hypothesis of a "window of initial trust" in the evolutionary design of intergovernmental cooperation mechanisms—namely, that early-stage institutional incentives and mutual signaling can significantly shape the long-term direction of strategic evolution.

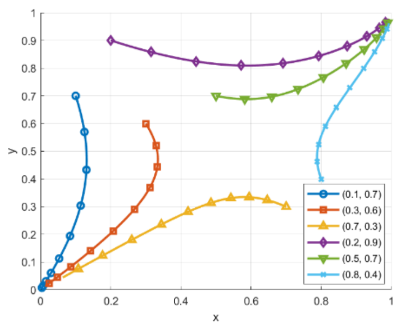

Figure 3. *Evolutionary trajectories under different initial states*

Core parameter sensitivity analysis

To further validate the effectiveness of the evolutionary game model and better reflect the sensitivity of local government strategies to institutional incentives under a competitive framework, this section focuses on three core parameters: central government's environmental performance weight (μ), the intensity of punishment for

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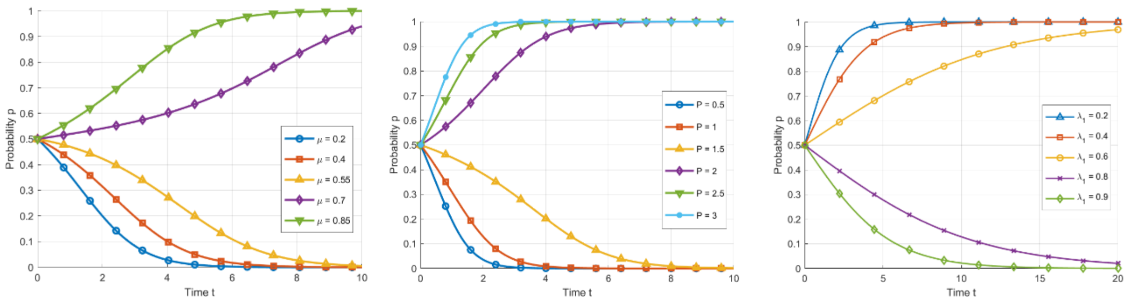
passive regulation (P), and the degree of pollution spillover (λ_1). Through numerical simulations, the sensitivity of these parameters to the evolution of intergovernmental environmental regulation strategies is assessed (*Fig. 4*). Results demonstrate that the institutional incentive structure exerts nonlinear guidance effects on the evolutionary pathways of local government regulation strategies.



(a) *Evolution trajectory of* μ (b) *Evolution trajectory of* P (c) *Evolution trajectory of* λ_1

Figure 4. *Evolutionary trajectory of core parameter changes*

First, an increase in μ enhances the motivation of local governments to adopt active regulation strategies. This mechanism functions by amplifying the weight of pollution control effectiveness in performance evaluations, thereby raising the marginal payoff of active regulation and facilitating convergence toward a "double active" (cooperative) equilibrium (validating Proposition 1). Second, P operates as a "negative incentive mechanism," whereby higher punishment intensity reduces the net returns of passive strategies and thus raises the relative advantage of active regulation (validating Proposition 2). Lastly, λ_1 captures the degree to which pollution from local government A spills over to region B. As λ_1 increases, the spillover externalities intensify the interdependence between the two regions, thereby destabilizing the cooperative incentives for active regulation and ultimately pushing the system toward a "double passive" outcome (validating Proposition 3).

Sensitivity analysis of internal and external return parameters

To further examine the impact of benefit-related parameters on the evolutionary dynamics of intergovernmental environmental regulation strategies, this section selects three key factors: the environmental treatment effectiveness of active regulation (M_1), the pollution cost externalization effect (N_1), and short-term economic incentives from passive regulation (R_1). These variables are incorporated into numerical simulations to explore their sensitivity to regulatory strategy evolution (*Figure 5*).

First, as M_1 increases ($M_1 > 0.8$), the probability of local governments adopting active regulation strategies rises, and the system gradually converges to the cooperative equilibrium point $E_4(1,1)$ (*Fig. 5d*). This reflects the fact that local governments are more likely to pursue pollution mitigation when the marginal environmental benefits are high, which enhances the comprehensive payoff of active strategies and validates Proposition 4.

Second, with increasing N_1 ($N_1 \geq 1$), the likelihood of adopting active regulation strategies rises, and the system tends to stabilize at the "double active" equilibrium (*Fig. 5e*). However, if the pollution costs caused by passive regulation continue to

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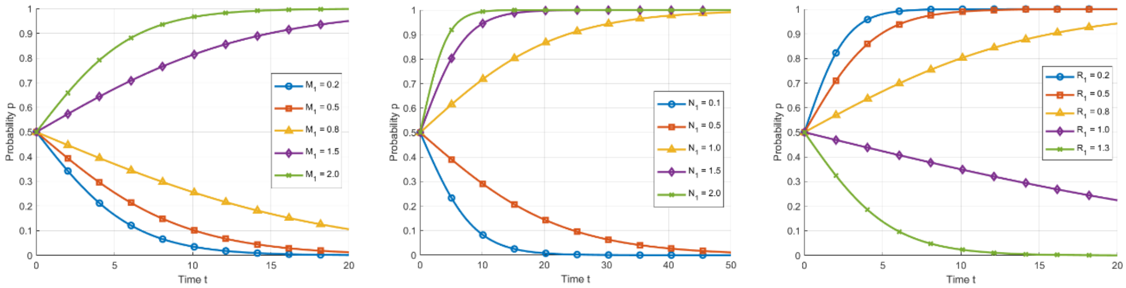
escalate—and are primarily borne by local governments themselves—then local actors are more likely to adopt proactive pollution-avoidance behavior. This leads to the selection of stricter regulatory strategies, further confirming Proposition 5.



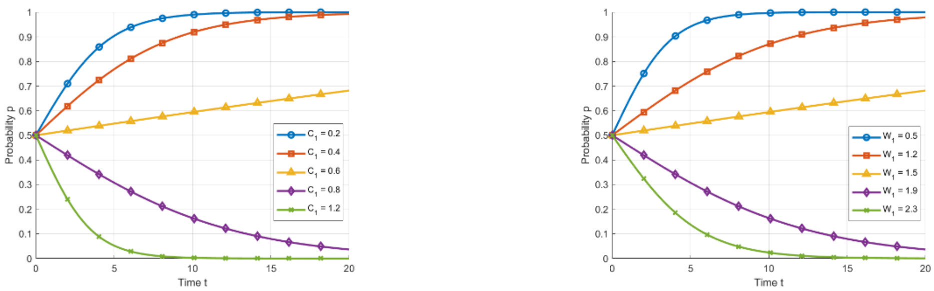
(d) Evolution trajectory of M_1 (e) Evolution trajectory of N_1 (f) Evolution trajectory of R_1

Figure 5. *The evolutionary trajectory of changes in internal and external return parameters*

Finally, as R_1 increases ($R_1 > 0.8$), the attractiveness of active regulation strategies diminishes (*Fig. 5f*). This suggests that higher short-term economic returns from passive strategies may shift local governments' preferences away from long-term environmental objectives. The result is a weakening of cooperation and a drift toward a "double passive" (non-cooperative) outcome, which supports the prediction in Proposition 8.

The interference effect of cost structure on cooperation mechanism

Although institutional incentives and benefit structures significantly affect the proactivity of intergovernmental environmental regulation, the influence of regulatory costs cannot be overlooked. In particular, the potential presence of a "cooperation failure" cost structure may hinder regulatory alignment. To investigate this, we focus on two key cost-related parameters: the active regulation cost borne by local government A (C_1), and the economic loss incurred in the event of cooperation failure (W_1). These variables are incorporated into the numerical simulations to evaluate their impact on strategy selection outcomes (*Fig. 6*), thereby further revealing the response effect of cost structures on the intergovernmental regulatory strategy choices.



(g) *Evolution trajectory of* C_1 (h) *Evolution trajectory of* W_1

Figure 6. *Evolutionary trajectory of cost structure parameter changes*

On the one hand, as the regulatory cost parameter C_1 increases, the probability that local government A adopts a proactive regulatory strategy declines significantly

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($C_1 > 0.6$) (*Fig. 6g*). The evolutionary trajectory shifts from an "optimization strategy" toward a "bottom-out strategy," eventually stabilizing in a "dual passive regulation" state. This indicates that with higher marginal regulation costs, weaker local governments lose their relative advantages in policy competition and are more likely to exit the cooperative path—thus verifying Proposition 6.

On the other hand, as the value of the loss cost parameter W_1 increases ($W_1 > 1.5$, *Fig. 6h*), the probability of choosing an active regulatory strategy also decreases. The system once again exhibits a shift from optimization toward degeneration. The parameter W_1 reflects the risk of cooperative failure, and higher values suggest that government A anticipates significant "expected net loss" in the policy game. This weakens its willingness to cooperate, ultimately leading the system to evolve toward a non-cooperative path (passive regulatory strategy), which supports Proposition 7.

Conclusions and policy implications

This study develops a multidimensional evolutionary game framework that integrates hierarchical incentives, intergovernmental competition, and strategic adaptation under heterogeneous governance capacities. From a competitive governance perspective, the study investigates the strategic interaction of environmental regulation among local governments. By analyzing five typical evolutionary scenarios, eight theoretical propositions are proposed and validated through numerical simulations across three core dimensions: institutional incentives, benefit distribution, and cost allocation. The key findings are summarized as follows:

(1) The existence of a "dual equilibrium" structure in regulatory cooperation suggests that the evolution of government behavior is significantly influenced by initial conditions and institutional signaling. When the initial strategic configuration is highly asymmetric or incentive intensity is weak, the system tends to evolve toward a non-cooperative, "loosening regulation" path—reflecting a pattern of bottom-up competition. In contrast, strong institutional incentives lead to convergence toward cooperative, proactive regulation strategies, indicating a trajectory of top-down optimization.

(2) Institutional incentives do not directly enforce proactive regulation but instead reshape marginal strategic payoffs through structural transformation. Key variables such as assessment weight, penalty intensity, and pollution spillover levels modify the relative payoffs of strategic options, thereby driving the system toward different stable equilibria: "dual proactive," "dual loosening," or "differentiated competition."

(3) The dynamic adjustment of benefit structures is essential to sustaining proactive regulatory efforts. Only when pollution externalities are effectively constrained and long-term regulatory returns are secured can governments maintain cooperative strategies under a top-down optimization framework. Otherwise, structural imbalances in benefit distribution are likely to cause the system to devolve into a bottom-up deregulation path.

(4) The elasticity of cost allocation significantly affects strategic preferences. When regulatory costs are perceived as excessive or asymmetrically distributed, the risks of cooperative failure increase. Even in the presence of adequate incentives and benefit expectations, governments may withdraw from cooperation to avoid potential losses, thus reinforcing non-cooperative, divergent regulatory behavior.

In summary, the evolution of intergovernmental regulatory strategies is not solely determined by top-down mandates but is fundamentally shaped by the endogenous interplay among incentives, benefits, and costs. Constructing an effective regulatory

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pathway requires not only strengthening vertical incentives but also improving cost-sharing mechanisms and balancing benefit distributions to guide local governments toward a cooperative and high-efficiency regulatory equilibrium.

Based on the findings derived from the theoretical framework and simulation analysis, the following policy recommendations are proposed:

(1) Strengthen the incentive system and enhance guiding effectiveness. The central government should improve multidimensional performance evaluation mechanisms and fiscal compensation systems to strengthen the credibility of environmental governance in the early stages of policy release, thereby increasing the attractiveness of proactive regulatory strategies.

(2) Promote differentiated collaborative governance and match regulatory incentives with local capacity. Given the disparities in fiscal resources and administrative capabilities across local governments, environmental governance efforts should be differentiated. Fiscal transfers and technical support should be allocated based on environmental spillover levels and governance efficiency to ensure precise policy alignment, thereby preventing weak jurisdictions from avoiding regulatory responsibility.

(3) Refine the external benefit internalization mechanism and improve long-term cooperation incentives. This can be achieved by establishing mechanisms such as ecological compensation, cross-regional trading, and shared incentives, which can strengthen intergovernmental cooperation and promote the stability of proactive environmental regulatory strategies.

(4) Optimize cost control and clarify the allocation of collaborative responsibilities. Reasonable cost-sharing and risk-compensation mechanisms should be designed to reduce the expected losses from policy failure and prevent local governments from falling into a “free-rider” mindset during environmental collaboration.

(5) Seize the strategic window of early policy intervention and mitigate adverse path dependency. In the initial phase of policy implementation, efforts should be made to improve the credibility of policy signals through incentive disclosure and strategy coordination, so as to guide local governments toward early-stage policy alignment and interjurisdictional cooperation.

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