An Evolutionary Game Analysis of Environmental Governance Strategies of Central and Local Governments under High-Pressure Environmental Inspections

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ABSTRACT High-pressure environmental inspections have reshaped the interaction between central and local governments and created new challenges for understanding the dynamic formation of environmental governance behavior. To address this issue, this study develops an evolutionary game model under bounded rationality to examine the strategic interaction between central supervision and local governance decisions. A payoff matrix incorporating governance costs, supervision costs, accountability penalties, and environmental performance benefits is constructed to capture the incentive structure of both actors. Replicator dynamics and Jacobian stability analysis are employed to identify equilibrium states and evaluate their stability conditions. Furthermore, parameter sensitivity analysis and scenario simulations are conducted to explore how institutional variables influence strategic evolution. The results indicate that stronger supervisory pressure promotes proactive environmental governance and accelerates convergence toward a collaborative equilibrium. When supervision intensity reaches 0.6, the probability of local governments adopting proactive governance rises to 0.87, the real part of the equilibrium eigenvalue remains at -0.23, and the system converges within 16 periods. In addition, accountability penalties strengthen the stability of cooperative behavior, whereas higher governance costs weaken governance incentives and slow convergence. The findings demonstrate that high-pressure environmental inspections can effectively reshape the payoff structure of environmental governance and foster a stable collaborative governance pattern between central and local governments. This study provides a dynamic analytical framework for understanding governmental behavior and offers policy insights for optimizing environmental governance mechanisms.

INDEX TERMS Evolutionary Game Theory; Central-Local Government Interaction; Environmental Governance Behavior; High-Pressure Environmental Supervision; Dynamic Strategy Evolution

I. INTRODUCTION

THE increasing focus on the development of a sustainable eco-civilization and ongoing efforts to improve environmental governance goals, has illustrated that developing local accountability for environmental protection through institutionalized environmental protection inspections is a critical element of the environmental governance system in China. Throughout the past several decades, the development model of economic growth has created a backlog in the level of pressure being placed on the environment within regions across China. With a decentralized form of government, local governments have had significant conflict between the development of economic goals and protecting the environment. The central government is now restructuring the method of governance within the Chinese government by creating a new system of direct relations for the central to local government (through increased requirements for oversight and accountability), to create a better method of fostering improving upon the environmental governance performance [1]-[2]. When government is viewed through the lens of modernizing national governments, inspections that are high-volume or resource demanding (the primary method of formal government) also impact the overall effectiveness of environmental governance, and how the framework for addressing the relationship between central and local governments and the development of a modern/public governance model, and therefore have significant theoretical and practical value for learning about how the different levels of government operate together [3].

Research has established, there are several structural barriers for the implementation of environmental governance practices. Within the context of financial decentralization and performance evaluation, local governments do not have sufficient governance incentives to ensure that they are able to meet environmental governance standards; The investment in governance activities related to environmental governance has substantial externalities and long-term implications, while short-term evaluations based on economic performance do not provide sufficient motivation for local governments to have sustainable governance behaviour; The literature on environmental federalism and political incentives has highlighted this significant issue [4]-[5]. Furthermore, while the central government strengthens constraints on local governments through supervision and accountability, information asymmetry between the central and local governments creates challenges for the central government to accurately assess the actual behaviour of local governments regarding environmental governance activities; thus creating an environment where local governments may implement environmental governance activities strategically or not at all [6]-[7]. As a result of uncertainty regarding costs and lagged benefits of environmental governance, local governments are subject to decision-making risk regarding environmental governance; therefore, their governance behaviour tends to be inconsistently phased and path dependent; resulting in substantial variations in policy implementation performance across various regions [8]-[9]. These problems highlight that the relationship between the central and local governments is not a static one; rather it is a continuing strategic game that both the central and local governments are engaged in to adjust to the various changes occurring within the relationship [10]-[11].

Different viewpoints have been used by academics to address these issues. Environmental federalism assesses how burdens are assigned to centralized and decentralized (national and local) governments within a decentralized framework of institutions and discusses structural incentives for governance based on that framework; but most of the these uses static equilibrium methods to assess and lacks the ability to measure long-term changes in strategies and how they change over time [12]-[13]. Principal-agent theory reviews restrictions to information transfer from central entities to local entities and develops incentive contracts as a means of addressing failure of governance contracts. However, principal-agent theory typically assumes complete rationality and does not explore gradual changes in behavioral responses consistent with that assumption [14]-[15]. System dynamics (SD) modelling looks at policy implementation in terms of feedback structures and adds further support for the dynamic analytical approach; however, the parameters used in this form of modelling are often derived from empirical data, which limits the ability of these models to explain the strategic choice theory as well as to reflect the game-theory nature of strategic choice [16]-[17]. Traditional game theory (GT) provides a direct analysis of strategic interdependence; however, since the outcome(s) of the GT analysis are dependent on complete rationality assumptions, GT does not provide insight into the progressive modification of strategies in actual practice [18]-[19]. This means that there are still reasonable grounds for research into the processes through which central and local governments develop stable models of governance in response to highly intensive environmental inspections.

This article develops an evolutionary game model of the central and local government under the framework of bounded rationality to respond to the fact that high-pressure environmental inspections change the incentive structure of governments but do not describe the paths by which governments develop their behavior. The central government's supervisory decisions and the local governments' governance choices are strategically abstracted in order to establish a dual-subject payoff matrix that includes the supervisory cost, governance cost, accountability penalty, and benefit of environmental performance as their payoff functions. Using this dual-subject payoff matrix, a replication dynamic equation is derived to describe the evolution of the strategy proportions over time. The equilibrium point solutions along with a Jacobian matrix analysis are used to characterize the stable state of the system. In addition, a sensitivity analysis of the parameters is used to evaluate the mechanism through which supervisory intensity and governance costs affect the convergence path of the strategies. This study describes the inherent logic of government behavioural changes given high-pressure inspection circumstances from a dynamic interaction perspective, incorporating institutional pressures into the evolutionary mechanism analytical framework and providing a theoretical framework for explaining variances in the effectiveness of policies for governing environmental resources.

II. CONSTRUCTION OF A GAME THEORY MODEL FOR THE EVOLUTION OF ENVIRONMENTAL GOVERNANCE BETWEEN CENTRAL AND LOCAL GOVERNMENTS

A. SETTING THE MAIN STRATEGIES UNDER HIGH-PRESSURE SUPERVISION

High-pressure environmental inspections have altered the incentive and constraint structure between the central and local governments in traditional environmental governance, transforming their behavior from a one-off decision-making process into a dynamic adjustment process under continuous supervisory pressure and governance cost constraints [20]-[21]. To characterize the strategic interaction in this institutional context, this section formally models the game actors, strategy space, and behavioral selection mechanism within the framework of bounded rationality, transforming the pressure of high-pressure inspections into an endogenous variable affecting the difference in strategy returns, thus allowing institutional constraints to directly enter the behavioral evolution process.

The central government bears the responsibility of supervision and accountability in the environmental governance system, with its core decision-making focused on the allocation of supervisory intensity; local governments bear the responsibility of governance implementation, with their core decision-making focused on the degree of governance investment [22]-[23]. Considering that government decisions in the actual governance process rely on experience adjustments and performance feedback, the actors' behavior is set as a group strategy proportional selection, rather than a completely rational optimal decision. The central government's strategy set is denoted as two behavioral states: intensified supervision and routine supervision; the local government's strategy set is denoted as two implementation states: active governance and passive governance, thus forming a dual-subject binary strategy interaction structure [24]-[25].

The institutional effect of high-pressure supervision enters into local government behavior and decision-making through a supervisory pressure function. Supervisory pressure is not only reflected in administrative accountability risks, but also in altering the revenue structure of local governments through political performance evaluation; therefore, it can be represented as a moderating term of supervisory intensity on the difference in governance benefits [26]-[27]. To characterize this relationship, a supervisory intensity driving function is introduced:

$$S = \alpha H - \beta C \tag{1}$$

In equation (1), S represents the level of comprehensive supervision pressure perceived by local governments; H represents the supervision intensity parameter implemented by the central government; α represents the institutional sensitivity coefficient of the transformation of supervision intensity into governance pressure; C represents the governance cost burden borne by local governments; and β represents the inhibition coefficient of cost on governance willingness. This expression reflects the hedging relationship between supervision enhancement and governance costs. High-pressure supervision changes the local strategy benefit ranking by increasing the pressure value.

Under bounded rationality, government strategy selection is not a deterministic behavior, but rather a probability distribution of strategy adoption [28]. The proportion of the central government choosing the enhanced supervision strategy is denoted as a dynamic variable, and its evolution depends on the difference in supervision benefits; the proportion of local governments choosing the positive governance strategy is determined by the net governance benefit. To transform behavioral choices into a probabilistic form, a strategy response function is introduced:

$$P = \frac{1}{1 + e^{-\lambda R}} \tag{2}$$

In equation (2), P represents the probability that the local government adopts a proactive governance strategy; R represents the difference in benefits between proactive and passive governance; and λ represents the strategy adjustment sensitivity parameter, used to characterize the intensity of the subject's response to changes in benefits under bounded rationality. This function transforms strategy selection from discrete decision-making into continuous probabilistic evolution.

The central government's decision-making objective under high-pressure supervision is reflected in the trade-off between environmental performance and supervision costs; therefore, its strategy selection depends on the net benefit of supervision. The net utility of supervision is formalized as:

$$U = \theta E - \kappa G \tag{3}$$

In equation (3), U represents the net utility of the central government implementing enhanced supervision; E represents the degree of improvement in environmental performance; θ represents the weight of environmental performance in the central governance objectives; G represents the cost of supervision implementation; and κ represents the influence coefficient of supervision costs. This expression integrates the effectiveness of ecological governance and administrative costs into the central decision-making logic.

In the process of central-local interaction, the intensity of supervision further affects the overall governance status by changing the probability of local strategies. Therefore, the governance level at the system level is defined as the result of strategy coupling:

$$L = \mu P_{lg} Q \tag{4}$$

In equation (4), L represents the overall level of environmental governance; P_{lg} represents the proportion of local governments actively engaging in governance; Q represents the proportion of central government strengthening supervision; and μ represents the strategy synergy efficiency coefficient, used to characterize the coupling degree between supervision and governance. This relationship reflects that governance performance originates from the synergy of strategies by both entities, rather than unilateral behavior.

Centralized Environmental Oversight via Modeling Process has transitioned from an institutional context to a measurable variable for the impact of behavior creating an ongoing interactive connection between decision making on the supervision of entities located centrally and their decision-making on local governments in a single structure framework. The strategic interaction structure between centrally located government and locally located governments' relationship is depicted schematically in Fig. 1.

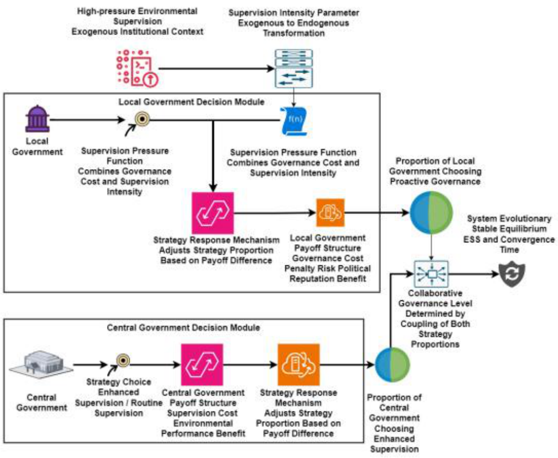

FIGURE 1. Evolutionary Game Mechanism of Central and Local Governments under High-Pressure Environmental Inspections.

Fig. 1 shows the path of supervision intensity entering the local benefit structure through the supervision pressure function, with the central and local governments as the two core nodes. The level of collaborative governance is coupled and determined by the strategy ratios of both parties. Figure 1 highlights the process by which the supervision intensity parameter is transformed from an exogenous institutional environment into an endogenous evolutionary variable, reflecting the core idea of embedding institutional constraints into the evolutionary game system in this model, and laying a structural foundation for subsequent benefit function construction and dynamic equation derivation.

B. BENEFIT FUNCTION CONSTRUCTION AND GAME MATRIX FORMATION

Under the high-pressure environmental supervision system, the strategic interaction between the central and local governments is essentially a process of interest redistribution between supervision constraints and governance inputs [29]-[30]. Once the main strategy is determined, its behavioral choices depend on the benefit differences under the combined effect of different institutional variables. Therefore, it is necessary to integrate governance costs, supervision costs, accountability penalties, and environmental performance benefits into a calculable benefit structure to achieve a formal expression of the evolutionary game model. Based on the strategy setting, this section transforms institutional pressure into benefit function parameters and establishes the game benefit matrix of the central and local governments through benefit quantification.

The decision-making objectives of local governments in environmental governance are reflected in the trade-off between governance input and comprehensive benefits [31]. Positive governance behavior brings environmental performance benefits and political evaluation improvement, while generating governance cost expenditures; negative governance behavior reduces short-term costs, but will face accountability penalties and performance losses under high-pressure supervision. To characterize the net benefits of local governments under different strategies, a local government revenue function is introduced:

$$\Pi_L = \tau V - \omega K - \phi F \tag{5}$$

In equation (5), Π_L represents the net benefit of local governments choosing proactive governance strategies; V represents the level of environmental performance benefits; τ represents the performance benefit conversion coefficient; K represents the governance cost input; ω represents the governance cost weight; F represents the intensity of accountability penalties generated under supervision; and ϕ represents the impact coefficient of penalties on local benefits. This function directly embeds institutional constraints into the local government's benefit structure, allowing supervisory pressure to influence strategy selection through penalties.

Supervisory actions taken by the central government also involve a benefit-cost trade-off. Improving supervision increases the performance of environmental governance, as well as meeting central government objectives. However, in order to improve supervision, the use of administrative resources must be expended. Thus, the benefits from the central government are expressed as follows:

$$\Pi_C = \eta M - \delta D \tag{6}$$

In equation (6), Π_C represents the benefits of the central government implementing the enhanced supervision strategy; M represents the overall improvement in environmental governance; η represents the weight of environmental performance in the central objective function; D represents the cost of supervision implementation; and δ represents the influence coefficient of supervision costs.

The systemic benefits formed by the interaction of strategies between the central and local governments depend not only on the actions of one party but also on the degree of strategy matching. Enhanced supervision and proactive governance form a synergistic state, while weakened supervision and passive governance form a low-governance state. Therefore, a strategy matching benefit function is introduced:

$$W = \gamma XY \tag{7}$$

In equation (7), W represents the additional governance benefits generated by strategic synergy; X represents the proportion of the central government's strengthened supervision strategy; Y represents the proportion of local government's proactive governance strategy; and γ represents the synergistic governance efficiency coefficient. This term reflects the systemic governance gains brought about by central-local interaction.

Based on the above benefit function, the benefits of the central and local governments under the two types of

TABLE 1. Benchmark setting of revenue parameters for central and local governments.

Parameter Symbol	Meaning	Value Range	Benchmark Value
V	Level of environmental performance benefits	0.4–1.0	0.8
K	Local governance cost	0.2–0.8	0.5
F	Accountability/punishment intensity	0.3–1.2	0.7
D	Central supervision cost	0.1–0.6	0.3
γ	Collaborative governance efficiency coefficient	0.2–0.9	0.6

strategy combinations are expressed in a matrix format, giving the evolution process a clear benefit reference structure. To ensure that subsequent simulations and stability analyses of the model have a unified parameter basis, it is necessary to numerically set the key institutional variables and form a standardized parameter system. Based on the institutional cost structure and governance incentive logic, the core parameters are benchmarked and the parameter setting results are constructed. To demonstrate the value range and economic meaning of each benefit parameter in the model, the key institutional variables are now organized as shown in Table 1.

Table 1 reflects that the model parameters are derived from the unified setting of institutional constraints and governance cost structure. Environmental performance benefits and the degree of governance improvement are used to characterize the level of governance goal achievement; governance costs and supervision costs reflect the constraints of administrative resource input; the intensity of punishment reflects the characteristics of the high-pressure environmental protection supervision system; and the synergy efficiency coefficient is used to describe the amplifying effect of the consistency of central and local strategies on overall governance performance. The setting of parameter ranges ensures the comparability of the model under different institutional scenarios and provides a unified input basis for subsequent replication dynamic equation solving and sensitivity analysis.

Under the given definition of the payoff function, the central government's strategy set is $S_C = \{Q, N\}$, and the local government's strategy set is $S_L = \{P_z, N_z\}$. Where Q represents strengthened supervision, N represents routine supervision; P_z represents active governance, and N_z represents passive governance. The standard game payoff matrix structure is expressed as:

$$G = \begin{bmatrix} (\eta M - \delta D + \gamma,\ \tau V - \omega K - \phi F + \gamma) & (\eta M - \delta D,\ -\phi F) \\ (\eta M - \delta D,\ -\phi F) & (0,\ 0) \end{bmatrix} \tag{8}$$

In equation (8), the first row of the matrix represents the combined benefits of the two strategies employed by local governments when the central government adopts strategy Q, and the second row represents the combined benefits when the central government adopts strategy N. The first term within each set of parentheses represents the central government's benefit, and the second term represents the local government's benefit. This matrix, based on institutional costs, performance benefits, and synergistic effects, forms the benchmark for the benefit structure in subsequent evolutionary dynamics system analysis.

C. REPLICATION DYNAMIC EQUATIONS AND EVOLUTIONARY STABILITY ANALYSIS

After the payoff function and game matrix are determined, the strategic interaction between the central and local governments no longer manifests as a static equilibrium problem, but rather as a dynamic adjustment process of the strategy proportion under the influence of continuous supervision pressure and payoff feedback [32]-[33]. High-pressure environmental supervision has altered the formation mechanism of strategy payoff differences, causing local government behavior to continuously adjust with changes in supervision intensity. Therefore, a dynamic evolutionary model is needed to characterize the trajectory of the strategy group proportion over time [34]-[35]. This section, based on evolutionary game theory, considers the central and local governments as boundedly rational groups, introduces a replicating dynamic equation to describe the strategy diffusion and elimination process, and identifies the long-term equilibrium state through stability judgment.

Let the proportion of the central government choosing the intensified supervision strategy be a dynamic variable, and the proportion of local governments choosing the proactive governance strategy be another dynamic variable. The rate of change of the strategy proportion is determined by the difference between the strategy payoff and the average group payoff. When the payoff of a certain strategy is higher than the average payoff, the proportion of that strategy in the group continues to rise. Based on the basic principles of evolutionary game theory, the evolutionary process of the central government's strategy is represented as:

$$\dot{x} = x(1 - x)(A - B) \tag{9}$$

In equation (9), $\dot{x}$ represents the rate of change of the proportion of the central government's intensified supervision strategy; x represents the current proportion of the intensified supervision strategy; A represents the benefit of the intensified supervision strategy; and B represents the benefit of the conventional supervision strategy. This expression reflects the mechanism by which the difference in benefits drives the adjustment of the strategy proportion. When the benefit advantage of intensified supervision expands, the intensified supervision behavior continues to spread within the group.

The strategy adjustment of local governments under the constraint of high-pressure supervision depends on the difference in governance benefits, and its replication dynamic equation is constructed as follows:

$$\dot{y} = y(1 - y)(P_b - N_b) \tag{10}$$

In equation (10), $\dot{y}$ represents the rate of change of the proportion of proactive governance strategies; y represents the proportion of local governments choosing proactive governance; P_b represents the benefits of proactive governance; and N_b represents the benefits of passive governance. This equation characterizes the behavioral evolution of local governments under the combined influence of accountability pressure and governance costs.

A two-dimensional dynamic system can be formed from the above two dynamic equations, and its equilibrium state is determined by the simultaneous zero rate of change of strategies. The system equilibrium point satisfies:

$$\Omega = (\dot{x}, \dot{y}) = (0, 0) \tag{11}$$

In equation (11), Ω represents the set of candidate stable states in the system's evolution. This condition implies that the proportions of central and local strategies no longer change, corresponding to the potential long-term governance structure.

To determine the stability of the equilibrium state under perturbation conditions, a local stability analysis of the dynamic system is required. The system's Jacobian matrix is constructed by calculating the first-order partial derivatives of the replicated dynamic equations:

$$J = \begin{bmatrix} \frac{\partial \dot{x}}{\partial x} & \frac{\partial \dot{x}}{\partial y} \\ \frac{\partial \dot{y}}{\partial x} & \frac{\partial \dot{y}}{\partial y} \end{bmatrix} \tag{12}$$

In equation (12), J represents the Jacobian matrix of the system at the equilibrium point; the matrix elements represent the marginal response relationship between the rate of change of strategies and the proportion of strategies of the two main entities. By calculating the sign of the matrix eigenvalues, it can be determined whether the equilibrium point belongs to a stable point, an unstable point, or a saddle point structure. When all real parts of the eigenvalues are negative, the system converges to an evolutionary stable strategy.

Based on the construction of the payoff function and the game matrix, it is necessary to further characterize the payoff distribution characteristics of the interaction between central and local government strategies under different institutional scenarios. The combined changes in supervision intensity and governance costs directly affect the net payoff level of local governments under different strategies, and thus affect the initial incentive structure of system evolution. To reveal the shaping effect of institutional variables on the payoff structure, under the benchmark parameter setting, a two-dimensional interval perturbation of supervision intensity and governance costs is performed to calculate the payoff difference of local governments under active governance and passive governance strategies, and this difference is used as an indicator of the strategy incentive intensity under the influence of institutional combinations. Fig. 2 shows the impact of the combined changes in supervision intensity and governance costs on the local strategy incentive intensity.

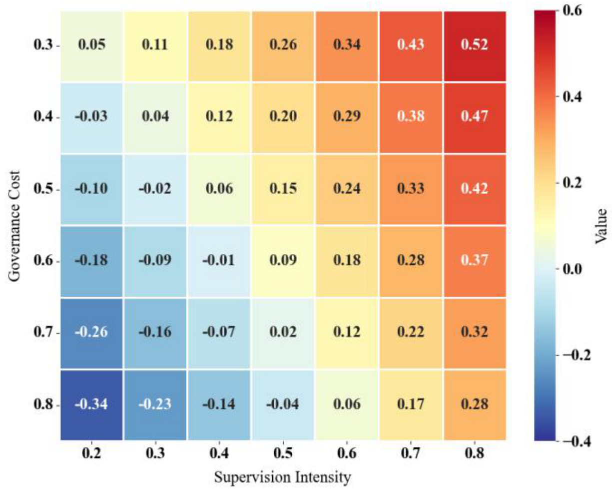

FIGURE 2. The impact of monitoring intensity and governance cost on the intensity of local policy incentives.

As shown in Fig. 2, as the monitoring intensity increases from 0.2 to 0.5, the incentive intensity significantly increases in the region where the governance cost is below 0.5, indicating that moderate to high-level monitoring constraints can effectively offset the benefit-inhibiting effect of governance costs. When the monitoring intensity exceeds 0.6, the incentive intensity remains at a high level within the range where the governance cost is below 0.7, indicating that high-intensity monitoring expands the benefit advantage range of proactive governance strategies. When the governance cost is above 0.7, the incentive intensity is generally low, reflecting that cost rigidity offsets institutional incentives, and even with increased monitoring intensity, it is difficult to completely reverse the strategy disadvantage structure. Fig. 2 visually presents the path through which institutional variables shape the basis of local strategy choices through benefit differences, providing a structural basis for understanding the direction of replication dynamic evolution.

D. PARAMETER SENSITIVITY AND INSTITUTIONAL THRESHOLD IDENTIFICATION

After determining the replication dynamic system and its stability structure, the impact of institutional variables on the evolution path needs to be identified through parameter perturbation analysis. This section treats the intensity of supervision, accountability and punishment coefficients, and governance costs in a high-pressure environmental protection inspection scenario as institutional regulatory variables. By changing the parameter values and observing the direction of change in the system's equilibrium state, it characterizes the response process of the central-local policy interaction structure to the intensity of institutional constraints, thereby identifying the critical conditions for local governments to shift from passive to active governance.

The stable state of the evolutionary system depends on the response gradient of the policy payoff difference function to the institutional parameters. When institutional variables undergo small changes, the growth trend of local government's active governance strategies is determined by the sign of the payoff difference function. To characterize the impact of institutional variable perturbations on the evolutionary direction, a policy advantage function is introduced:

$$\Delta G = \Phi(\rho) - \Psi(\rho) \tag{13}$$

In equation (13), ΔG represents the net benefit advantage of the proactive governance strategy relative to the passive governance strategy; $\Phi(\rho)$ represents the expected benefit of proactive governance under the influence of the supervision intensity parameter ρ; and $\Psi(\rho)$ represents the expected benefit of passive governance under the same institutional environment. This function reflects the change in the incentive direction of local government behavior after the high-pressure supervision system enters the benefit structure.

The identification of the institutional threshold depends on the sensitivity of the benefit advantage function to parameter changes. To measure the impact of changes in institutional variables on the evolution speed, a parameter sensitivity index is introduced:

$$S_\rho = \frac{\partial \Delta G}{\partial \rho} \tag{14}$$

In equation (14), S_ρ represents the marginal impact of changes in supervision intensity on strategic advantage; $\partial \Delta G$ represents the change in benefit advantage; and $\partial \rho$ represents the minute adjustment magnitude of supervision intensity. When this indicator is positive, increased high-pressure supervision will drive up the proportion of proactive governance strategies, and the system evolution trajectory will shift towards a collaborative governance equilibrium.

Considering the structural role of governance costs in constraining local government behavior, governance cost disturbances are introduced into the stability criterion, and a critical institutional function is constructed:

$$\Theta = \Delta G - \sigma \tag{15}$$

In equation (15), Θ represents the net institutional incentive level; σ represents the offsetting effect of incremental governance costs on the benefit advantage. When $\Theta > 0$, the positive governance strategy exhibits an expansionary trend in the replication dynamics; when $\Theta < 0$, the system reverts to the negative governance attraction domain, thus yielding the critical interval where institutional constraints exert their effect.

To further identify changes in the system's stable structure under different institutional combinations, an equilibrium response index is introduced:

$$R_c = \frac{\lambda^*}{\omega} \tag{16}$$

In equation (16), R_c represents the comprehensive response of the institutional combination to the stability of the system; λ^* represents the real part of the eigenvalue of the Jacobian matrix corresponding to the stable equilibrium point; and ω represents the policy adjustment speed parameter. This index is used to compare the differences in the convergence strength of the system under different institutional parameter configurations; the smaller the value, the stronger the equilibrium attractiveness.

Within the above analytical framework, interval perturbation calculations are performed on the supervision intensity, penalty coefficient, and governance cost, and the changes in system equilibrium type, stability characteristics, and convergence time are recorded. To present the action path of institutional variables, the results of multiple parameter combinations are uniformly organized, and the results are summarized in Table 2.

Table 2 shows the effects of institutional variables on the evolution of a system. Both increased intensity of supervision and penalties alter the real part of the system's stable eigenvalue from "+" to "-", and move the evolutionary evolutionary trajectory of a strategy from divergent to converging, ultimately reaching dominance by local government(s) through proactive governance. The increase in governance costs produces longer convergence periods and weaker attractions to stable states. These results demonstrate that institutional variables do not act linearly on strategy selection, but rather reshape the evolutionary stability domain by altering the structure of payoff differences, providing a parameter range basis for subsequent simulation analysis.

III. MODEL SIMULATION AND PARAMETER SETTING

A. SIMULATION PLATFORM AND CALCULATION METHODS

To examine the dynamic evolution of the interaction between central and local strategies under high-pressure environmental inspections. The dynamic system will be discretized and solved repeatedly using the Euler discretization technique, with a numerical simulation environment established based on the dynamic system analysis and matrix operation frameworks, and utilizing a bivariate, dynamic iterative system to simultaneously update both the supervision strategy of the central government and the governance strategy of the local governments, while maintaining satisfaction of the probabilistic constraints for each strategy proportion within each iteration cycle through all iterations.

The continuous-time replicated dynamic system is converted to an equally spaced discrete-time series from a computational perspective by recursively adjusting the strategy proportions every period at a fixed time interval (time step). Each time a calculation is performed during a cycle, the direction of the strategy adjustment for the current time period is determined from the previous period's strategy

TABLE 2. Results of the impact of central-local governance system parameters on evolutionary stability.

Supervision Intensity Level	Punishment Coefficient Level	Governance Cost Status	Equilibrium Type	Sign of Real Part of Eigenvalue	Convergence Time (Periods)
Low	Low	High	Passive Governance Equilibrium	Positive	Divergent
Medium	Low	Medium	Mixed Strategy Equilibrium	Near 0	42
Medium	Medium	Medium	Conditionally Stable Equilibrium	Negative	27
High	Medium	Low	Collaborative Governance Equilibrium	Negative	21
High	High	Low	Strongly Stable Collaborative Equilibrium	Significantly Negative	18
High	High	Medium	Collaborative Governance Equilibrium	Negative	24

proportion and return. An interval correction is then applied to the adjusted strategy proportions to ensure that they lie within the closed interval [0,1]. The time step is set to a small constant value in order to provide numerical stability and prevent strategy proportions from oscillating in the short term or exceeding bounds.

An iterative termination method is used for the dynamic system solution to identify a stable system. When the strategy proportions between subsequent periods do not experience a net change greater than a predetermined threshold, it has been established that the system is in a stable state. The convergence criteria rely on the use of the absolute difference in strategy proportion changes, in combination with a maximum iteration counter to prevent calculations entering into an infinite loop. In order to compare differences in evolutionary trajectories under differing configurations of institutional variables, a multi-scenario batch calculation program with a common algorithm structure has been designed. The multi-scenario batching calculations carry out an interval scanning of supervision intensity, penalty coefficient and governance cost parameters and store the complete set of time versus strategy proportion changes for each parameter combination as a full trajectory record of all calculations between subsequent periods.

In order to verify the consistency of the simulation repeats, the initial strategy proportions are deterministically set, and each time the dynamic system is executed (a number of times), it is done so with a variety of initial states to see how sensitive each evolutionary path is with respect to its corresponding initial conditions. The data output module will hold the central strategy proportion and the local strategy proportion increase difference, system revenue difference, as well as how many cycles it takes to achieve convergence in each time period; therefore, it is providing ongoing time series data support to facilitate the analysis of subsequent results. The overall process of the simulation centres around the main framework of central-local strategy interaction in order to keep in accordance with both the dynamic calculation results and all of the theoretical model settings, thus providing a sound basis for the numerical verification of all institutional variables' influence mechanisms.

B. PARAMETER RANGE SETTING AND INITIAL CONDITIONS

To ensure there was consistency of the simulation of the evolutionary game model with an actual global institutional environment, during the parameter setting phase for this study, the researcher used publically available policy data and governmental statistics to provide an interval-based quantification of the institutional variables based on the high-stress environment of inspection for environmental protection. The parameter of intensity of supervision was normalized, based on the parameters of the frequency of inspections, accountability coverage and the cycle of feedback from the rectification of earlier inspection results as noted in the readily available literature for the design of the Public National System of inspection for Ecological and Environmental Protection. This created a means of converting, for this study, the pressure of the institution on the inspection of the environment to a parametric intensity value in continuum.

The parameter for costs of governance utilized the raw data created from the investment into governance for environmental protection data released by the National Bureau of Statistics and was normalized to convert it to a percent of the unit of the fiscal expense for the purpose of establishing comparable governance burden across the various regions. The parameter of penal intensity created a level mapping system based on the level of responsibility for the administration of the penalty and the severity of the penalty based on the information provided in the publically available information on anticorruption/anti-ecological and environmental accountability/eco-friendly inspections of ecological and environmental regulations and laws so that the discrete accountability would be converted to a continuous numerical interval. Each of these parameters was defined by the indicated range of values defined by the official specifications of the dataset to be used in this study so that subjective decision-making during the parameter setting of the parameters would not result into structural bias.

After setting the parameter ranges, the simulation system designed institutional scenario combinations via the interval-scan method. The three constituent components of supervision intensity, governance costs, and penalty coefficients were divided into several parameter vectors with equal spacing. Each of the parameter vectors was then aggregated to form values consistent with a single evolution rule and used to calculate iteratively how institutional variable changes will affect (affect) strategy evolution path. The final model will not have parameter values estimated at a single value but will have the parameter ranges entered into an interval defined distribution. This is done to indicate and demonstrate the policy flexibility attributes associated with the high pressure supervision systems at different levels of implementation intensity.

The initial conditions are set around the assumption of bounded rationality. The central and local governments' policy ratios are provided in probabilistic terms with respect to each other and are constrained by an overall probability constraint that prevents the initial policy ratios from causing a structural bias in the direction of the system. To assess how much the initial state of the system affects the evolutionary path, the simulation program runs the dynamic system repeatedly under a combination of multiple initial probabilities while maintaining the same institutional parameters in order to create a set of comparable evolutionary trajectories. To ensure policy competition exists at the same time in the early stages of evolution, all initial policy ratios have been selected from closed intervals to allow the replication dynamic mechanism to fully unfold.

Following the setting of initial policy ratios and parameter intervals, the simulation program will write the initial state and institutional variables into the unified calculation configuration file and produce a standardised input matrix that provides a consistent data interface for the subsequent batch iterations. A detailed summary of the institutional variables and initial conditions used in the parameter configuration is presented in Table 3 to aid in understanding the overall configuration structure of the institutional variables and initial condition parameter.

TABLE 3. Simulation system parameters and initial strategy settings.

Parameter Category	Parameter Name	Data Source (Official)	Value Range	Basis for Setting
Institutional Variable	Supervision Intensity	Public documents of Central Ecological and Environmental Protection Inspections (Ministry of Ecology and Environment website, State Council Gazette) 2016–2023	0.2–0.8	Standardization of inspection frequency and coverage
Institutional Variable	Punishment Intensity	Ecological and environmental accountability case announcements (Ministry of Ecology and Environment accountability cases, Central Commission for Discipline Inspection and National Supervisory Commission bulletins) 2016–2023	0.2–0.8	Mapping of accountability level to penalty magnitude
Cost Variable	Governance Cost	China Environmental Statistical Yearbook, National Bureau of Statistics environmental pollution governance investment data 2015–2023	0.3–0.7	Proportion of governance investment in fiscal expenditure
Benefit Variable	Environmental Performance Benefit Coefficient	China Ecological and Environmental Status Bulletin, annual ecological environment quality bulletins 2016–2023	0.4–1.0	Conversion from environmental improvement performance index
Initial Condition	Central Strategy Proportion	Model initial setting	0.2–0.8	Finite rationality random distribution
Initial Condition	Local Strategy Proportion	Model initial setting	0.2–0.8	Constraint of coexistence of two strategies

Table 3 shows the sources, ranges, and numerical basis for the institutional parameters in the simulation phase; it identifies the match or correspondence of simulated model inputs to empirical policy data. The intensity of supervision and the intensity of punishment are viewed as signs of institutional risks associated with high intensity environmental inspections; the cost of governance represents the amount of resources a local government has to expend to implement environmental policies; the benefit coefficients for environmental performance represent the sources of governance incentive; and the initial strategy ratio indicates that an evolutionary process occurs under a state of bounded rationality. The simulation input values are consistent with and traceable to the same data sources and ranges of data, and will provide a durable data base to allow for the subsequent analysis of the evolutionary results.

IV. RESULTS ANALYSIS

A. ANALYSIS OF CONVERGENCE CHARACTERISTICS OF STRATEGY EVOLUTION

Using the simulation platform and surrounding parameter space, an analysis of the convergence characteristics of the evolution of the two levels of government was completed by the effect that increasing or decreasing the level of oversight has had on the dynamic development of strategy for both levels of government. By not changing the three parameters of governance costs, penalty severity, or initial strategy proportions, only the oversight parameter was adjusted incrementally to provide for a discrete iterative process with numerous scenarios of institutional pressure during the evolution of each government level. Throughout the experimental process, the continuous change of local government strategy proportions towards proactive governance strategies over the course of the evolution was recorded, while the amplitude of variation in local government strategy proportions and the time spent in the stable phase was recorded simultaneously. This analysis has been conducted to determine the mechanism of influence of the intensity of institutional constraints with respect to the rate and direction of strategy adjustments in response to scenarios of high-pressure oversight. Independent evolution paths were created at each level of oversight, and all evolution paths were aligned at a common timeline to create a common dynamic evolution sequence. Changes in strategy proportions were indicated on Fig. 3.

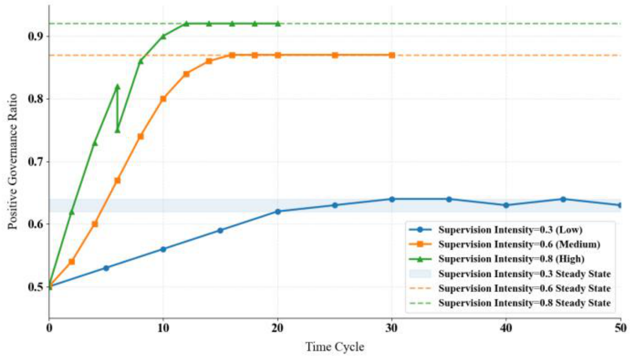

FIGURE 3. Strategy evolution trajectory under different supervision intensities.

Fig. 3 reveals that at the lower end of the supervisory intensity scale (0.3), the active proportion of local government governance has risen from approximately 0.50 to 0.62 over a slower period of time, and after the 35th period, it entered a period of slight fluctuation. Is a result of less supervisory constraints allowing local governments to develop their governance-level advantage at a slower rate than they would with greater supervision. At the supervisory level of 0.6, the proportion of active governance reached its peak level (0.87) in period 16 and has stabilized at that level with a considerably greater degree of matching speed than was experienced below 0.3. This is due to the increased supervisory accountability creating a more rapid concentration of replication through changes in the relative cost of passive governance as compared to active governance. Once the supervisory level is raised to the level 0.80, the proportion of active governance arrive the 0.90 at the period of 12 overall. However, within the early portion of this period, the active proportion dropped over the period of early time by approximately 0.07 due to the use of sudden high intensity-supervision increasing the frequency of strategy adjustments and causing a periodic over-correction. Additionally, the changing response time for the strategies, pre- versus post-supervisory level adjustments, indicate that the increase in institutional pressures directly compresses the cycle period of strategy games and caused shifts in the process of system evolution from slow coordination to a relatively quicker and stable state.

B. CRITICAL PENALTY THRESHOLD IDENTIFICATION AND ANALYSIS

Under the established simulation environment and parameter range settings, the critical penalty threshold identification and analysis focuses on the impact of accountability penalty intensity on the transformation process of local government strategy choices. By maintaining the supervision intensity and governance cost parameters at a unified baseline level, and only setting the penalty coefficient to continuously increase, the evolutionary system undergoes multiple rounds of dynamic iterative calculations under different institutional constraint intensities. During the experiment, the temporal evolution trajectory of the proportion of proactive governance strategies of local governments is continuously recorded, and the turning point when the strategy proportion shifts from a downward trend to an upward trend is simultaneously tracked to characterize the impact of the penalty mechanism on the path of benefit structure adjustment. Different penalty levels correspond to independent evolutionary processes, and all trajectories are standardized at a unified time scale. The evolutionary path of the transformation of local government behavior strategies from passive governance to proactive governance obtained through this process is shown in Fig. 4.

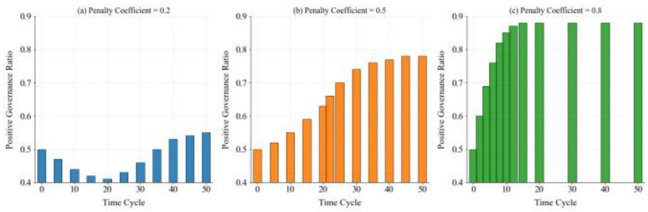

FIGURE 4. Strategy inflection trajectory under changes in penalty intensity. Fig. 4(a) Penalty coefficient -0.2. Fig. 4(b) Penalty coefficient -0.5. Fig. 4(c) Penalty coefficient -0.8.

As displayed in Fig. 4(a), at the 0.2 penalty coefficient, active governance has decreased from 0.50 to 0.41, and is on a slow upward trend to reach 0.55 at the end of the period (50). The low penalty cost was less than the cost of additional governance, which allowed local governments to continue enjoying the advantages of passive governance during the onset of the period. Fig. 4(b) shows that with an increase to a 0.5 penalty coefficient, that there is a significant turning point in period 22, after which there is a steady increase to 0.78 for the strategy proportion. The higher level of penalty pressure has provided a new level of incentive to local governments to transition to active governance during the period of replicating strategies. In Fig. 4(c), the penalty coefficient of 0.8 resulted in active governance being above 0.85 at the end of period 10, and this value has remained stable. The high accountability level created a higher probability of incurring losses when utilizing passive governance, which has accelerated the rate at which local governments adjusted their strategies relative to one another and has reduced the variability in the trajectory of those strategies. On the whole, with the penalty coefficient of 0.2, the system was only adjusted after period 20, while at the 0.5 and 0.8 penalty coefficients, the strategy evolution of local governments was in a monotonic increasing trend. The institutional penalties on each strategy created a new payoff comparison, transitioning the system from a lagged adjustment to a rapid behaviour transition.

C. ANALYSIS OF CHANGES IN SYSTEM STABILITY STRUCTURE

To examine the changes in the system's stable structure after the introduction of the high-pressure environmental protection supervision mechanism, under a given simulation environment and parameter range setting, the central government's supervision intensity parameter was adjusted in stages, and multiple sets of dynamic evolution calculations were conducted under a unified initial strategy ratio. During the experiment, the governance cost and supervision cost parameters were kept within the baseline range, and only the supervision intensity level was changed to form different institutional scenarios. By continuously recording the changes in the system equilibrium point position and the eigenvalues of the Jacobian matrix, the evolution of the system from multiple equilibrium states to a single stable structure under different supervision constraints was compared. Simultaneously, the trend of the change in the real part of the stable eigenvalues during the strategy ratio convergence phase was extracted to characterize the dynamic adjustment process of system stability, thus obtaining the stable structure evolution results under different supervision intensity scenarios, as shown in Fig. 5.

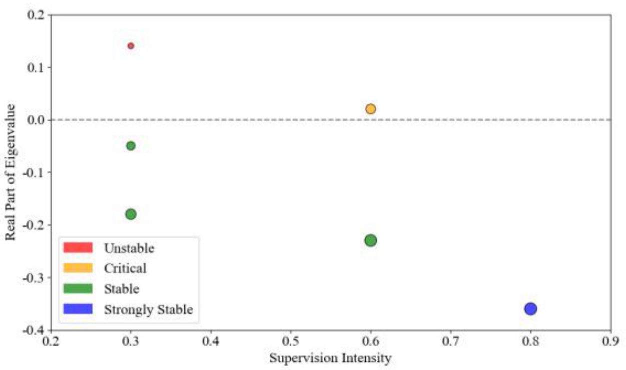

FIGURE 5. Evolution of system stability structure under varying supervision intensity.

As noted in Fig. 5, three equilibrium points (with real eigenvalues equal to 0.14, -0.05 and -0.18) occur with a monitoring intensity level of 0.3. There are positive eigenvalues with real parts among some eigenvalues, indicating that strategies will diverge from one another over time due to evolutionary processes. Because of the relatively small incentives created by sufficient monitoring to bring people together when compared to cost savings through passive forms of governance, there is a multi-regional attractive structure of payoffs. The equilibrium critical point corresponding to an increase in monitoring from 0.3 to 0.6 has an associated eigenvalue of 0.02. Therefore, by changing the slope of the median pay-off curve through increasing the monitoring pressures, the size of regions of stability around each equilibrium point will gradually decrease. Finally, as monitoring reaches the level of 8.0, there will be only one very stable equilibrium, related to a historical low of -0.36 for the eigenvalue. This will create an increase in the size of the negative feedback loops from previous strategies to the extent that the rate of regression is significantly influenced by the departure from equilibrium. The competitive multi-equilibrium structure evolves into a unified constraint on payoffs. The overall stability structure at the original equilibrium of the system will be decentralized to the newly created centralized new equilibrium.

D. ANALYSIS OF THE MARGINAL EFFECT OF MONITORING INTENSITY

Under the given simulation platform and parameter range settings, to characterize the nonlinear characteristics of local government governance strategy responses during changes in monitoring intensity, continuous gradient perturbations were applied to the monitoring intensity parameter, and multiple rounds of dynamic evolution calculations were conducted under uniform initial strategy proportion and governance cost parameter levels. During the experiment, the steady-state level of the proportion of proactive governance strategies by local governments was recorded under each scenario by gradually increasing the monitoring intensity value. Simultaneously, the rate of change of the strategy proportion and the slope of the steady-state interval were extracted to identify the stage-specific differences in the magnitude of strategy responses during periods of increased monitoring pressure. Furthermore, the marginal change process of the strategy proportion growth trend was observed through multi-scenario trajectory comparison, thus forming the functional relationship between monitoring intensity and the proportion of governance behavior, as shown in Fig. 6.

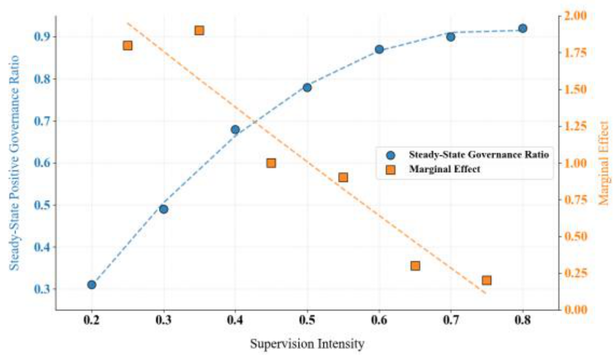

FIGURE 6. Changes in the marginal effect of monitoring intensity.

Fig. 6 shows, as the supervision intensity increased from 0.2 to 0.4, the rate of proactive governance by local governments increased from 0.31 to 0.68. In this phase, the anticipated benefits of punishment through central oversight substantially exceed the savings from passive governance, which has considerably widened the slope of the benefit difference curve. As the intensity of supervision goes up to 0.6, the percentage of proactive governance reaches 0.87, but the increase in percent is decreasing. This is due to the fact that the majority of decision makers have already finished adjusting their strategies, and that the remaining entities using passive governance are less likely to respond to changes in benefits. As the intensity of supervision reaches 0.8, the proportion increases from 0.87 to 0.92. The marginal rate of change has dropped to 0.05. The incremental effect of strengthening the supervision system on the value of benefit is gradually reduced by the rigidity of governance cost and the strategic space of governance is approaching saturation. The system also has a distinct diminishing marginal returns characteristic; this shows that the impact of supervision intensity on the governing behaviour of local governments is limited by a threshold range.

E. ANALYSIS OF GOVERNANCE EFFICIENCY AND CONVERGENCE TIME

Under a unified simulation platform and parameter range, to examine the impact of different institutional combinations on the system's dynamic adjustment efficiency, multiple scenarios were set for monitoring intensity, penalty coefficient, and governance cost parameters. Repeated iterative calculations were performed with the same initial policy ratio, recording the time period during which the system evolved from its initial state to stable equilibrium. During the experiment, the stabilization of the policy ratio was used as the convergence criterion. By statistically analyzing the time length of the evolution trajectory under different parameter combinations, the differences in convergence speed caused by changes in institutional variables were compared. Simultaneously, the characteristics of the policy adjustment rate change before the stable phase were extracted to characterize the correspondence between the strength of the governance system and the system's adjustment efficiency. The resulting system convergence time distribution under different institutional scenarios is shown in Fig. 7.

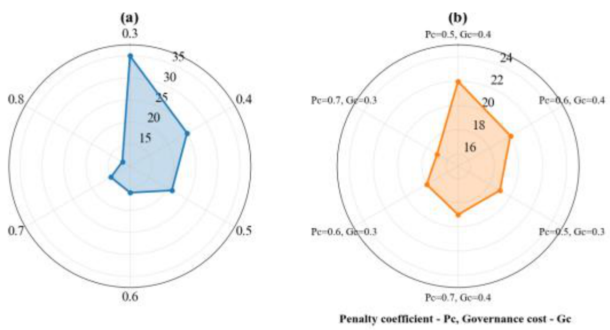

FIGURE 7. Comparison of system convergence times under different institutional scenarios. Fig. 7(a) Changes in convergence time under different levels of supervision. Fig. 7(b) Distribution of convergence time under the combination of penalty coefficient and governance cost.

The data in Fig. 7(a) shows that when the supervision intensity increases from 0.3 to 0.6, the system convergence time shortens from 35 periods to 16 periods, with a time difference of 19 periods. This is because the difference in strategic benefits for local governments widens rapidly after the increase in supervision pressure, and the direction of strategy updates tends to be consistent, reducing the game oscillations during repeated adjustments. When the supervision intensity continues to increase to 0.8, the convergence time is only further shortened to 12 periods, because most subjects have already completed the strategy shift in advance, and the driving effect of additional supervision input on the speed of strategy adjustment weakens. As shown in Fig. 7(b), the convergence time is 22 periods under the condition that the penalty coefficient is 0.5 and the governance cost is 0.4. However, when the penalty coefficient increases to 0.7 and the governance cost decreases to 0.3, the convergence time is shortened to 17 periods. The enhanced institutional incentive changes the stable direction of the benefit structure, causing the strategy selection to quickly concentrate in the advantageous strategy area, and the system adjustment path is significantly compressed, indicating that the intensity of the institutional combination has a significant impact on governance efficiency.

V. CONCLUSION

This article focuses on the dynamic formation mechanism of environmental governance behavior of central and local governments under the context of high-pressure environmental protection inspections. Using a bounded rationality model and evolutionary game-theoretic concepts, it develops a strategy interaction model that contains two players: the central government and the local government. Each player's strategic choices can influence the payoffs of both players based on outcome variables, including governance costs, supervisory costs, and penalties for violations as well as an expected value from improving environmental quality. To explore these interactions, construct an evolutionary game-theoretical strategic interaction model and obtain a corresponding game matrix. Using these data, derive the replication dynamics equation for this model. We also analyze the evolutionarily stable strategy (ESS) of the two-player interaction system and identify the interactions among the institutional variables which influence the evolution path of their strategies through simulations of parameter sensitivity and scenarios. Experimental results show that when the supervision intensity is 0.6, the proportion of proactive governance strategies by local governments stabilizes at 0.87, and the system enters a stable state in period 16, with a stable equilibrium eigenvalue of -0.23. This indicates that high-pressure supervision constraints can change the payoff structure and form a stable collaborative governance equilibrium. As the supervision intensity increases from 0.3 to 0.8, the strategy convergence period shortens from 35 to 12, and the system's stable structure evolves from multiple equilibria to a single stable equilibrium. According to studies, institutional pressures guide strategizing replication since they change the ways organisations perceive benefit differences, leading to synergy between central oversight and local governing behaviour. This study provides a dynamic analytical framework to explain the differences in governance performance under the background of high-pressure environmental protection supervision. It has important theoretical support and decision-making analysis value in the research on the optimization of multi-level government governance mechanisms, the evaluation of the effectiveness of environmental policy implementation and the configuration of institutional strength.

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