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Research article

A system dynamics model integrated evolutionary game theory and hybrid appraisal mechanisms for industrial pollution control

Fulei Shi[1], Zisha Zhou[1], Jianzhang Wang[2], Chuansheng Wang[1] and Feng Gu[3,*]

1 School of Management and Engineering, Capital University of Economics and Business, Beijing 100070, China
2 School of Business, Nanfang College, Guangzhou 510970, China
3 Department of Computer Science, College of Staten Island, City University of New York, Staten Island, NY 10314, USA

* **Correspondence:** Email: Feng.Gu@csi.cuny.edu.

Abstract: Effectively controlling industrial pollution is a critical global challenge, yet the strategic interaction between local and central governments often leads to unstable or unpredictable policy enforcement, creating significant difficulties for long-term environmental governance. In this study, we developed an evolutionary game model within a system dynamics (SD) framework to analyze the strategic behaviors of local and central governments. We proposed and compared three mechanisms, the assessment mechanism for ecological progress (AMFEP), the ecological governance supervision and punishment mechanism (EGSPM), and a hybrid model combining both, to stabilize the evolutionary path. Simulation results demonstrated that while the basic model and individual mechanisms often failed to converge, the hybrid model successfully drove the system to a stable equilibrium, increasing the probability of local governments implementing environmental regulation strategies from 0.2 to 0.167. This finding indicated that a combined appraisal mechanism is significantly more effective in guiding local governments toward proactive environmental enforcement while central governments maintain a lighter supervisory role, offering a robust and practical policy tool for sustainable industrial pollution management.

Keywords: evolutionary game; industrial pollution; system dynamics model; assessment mechanisms

1. Introduction

Rapid technological advancement and economic growth have been accompanied by alarming levels of industrial pollution and environmental degradation worldwide in recent years. Industrial pollution causes significant damages to the environment in multiple ways [1]. Moreover, industrial pollution has caused many serious health issues [2,3]. Ecological studies have shown that the regions exposed to industrial pollution exhibit an estimated 17% excess cancer mortality compared with unexposed areas [2]. Therefore, the effective control of industrial pollution is urgent and critical.

Moreover, the issue of industrial pollution has drawn widespread attention from scholars. Some focus on policymaking to address this issue, while others propose policies to solve industrial pollution problems [4–6]. For example, some researchers have focused on developing policies to address differences in environmental enforcements, attempting to explain the temporal and regional variations in pollution violations and penalties [4]. Others have proposed some novel methods to deal with these problems, including statistical approaches, control theory approaches, modeling and simulation approaches, and game theory approaches. Statistical approaches study the relationship between industrial pollution and other factors [7–11]. Control theory is an important tool in modern engineering for studying dynamical systems and their state transitions. It has also been used to address industrial pollution [12–15]. Moreover, many industrial pollution problems are modeled as systems to help make policies, and the above approaches treat the industrial pollution problem as a whole system and study its states and behaviors. Game theory addresses the optimal decision making of competing players in a strategic setting [16–21]. However, the above research efforts are mainly based on classical game theory, the players in the classical game theory will behave rationally, and they do not consider the evolutionary context.

Evolutionary game theory is a dynamic framework that studies the behavior of agents engaging in repeated interactions in a strategic setting [22]. It originates from evolutionary processes in biology and has since been applied to many fields [23–26]. It is worth noting that many scholars believe that this theory can effectively solve the problem of industrial pollution [27–29]. However, while many scholars try to find equilibrium points, they mainly do so by solving equations to obtain equilibria through static analysis. System dynamics (SD) looks for solutions by studying causal relationships and dynamics of the incomplete information, emphasizing dynamic processes [30]. Therefore, researchers have begun to integrate SD into evolutionary game models to address problems [30–32]. In our work, we apply SD to industrial pollution problems within an evolutionary context.

Most literature emphasizes the game between local governments and enterprises in studying industrial pollution problems. However, many laws, regulations, and policies are mainly formulated by the central government [33]. Therefore, research on the evolutionary process between local and central governments is highly important for industrial pollution management. In this paper, we develop different evolutionary theory models with various mechanisms between the local government and the central government. Our contributions are summarized below. First, we develop an evolutionary theory model between the local government and the central government. Second, we apply two appraisal mechanisms, the assessment mechanism for ecological progress (AMFEP) and the ecological governance supervision and punishment mechanism (EGSPM), to the basic model to overcome the weakness of the basic model. Third, to further improve the convergence of the evolution path, we propose the hybrid model combining AMFEP and EGSPM. Finally, we implement the above models within a SD model and illustrate the simulation results.

The rest of this paper is organized as follows: In Section 2, we describe the related work. In Section 3, we describe the basic model. In Section 4, the model under AMFEP is presented. In Section 5, we provide the model under EGSPM. In Section 6, we illustrate the hybrid evolutionary game model that combines AMFEP and EGSPM. In Section 7, we provide the sensitivity analysis. In Section 8, we discuss the related issues in the proposed models. Finally, in Section 9, we conclude the paper.

2. Related work

The central government is expected to vigorously strengthen pollution prevention and environmental protection going forward to achieve sustainable development [33]. Environmental pollution remains a wide-reaching problem.

Research combining system dynamics models with evolutionary game theory has received widespread attention in recent years and has been applied to various fields [34–36]. For example, Chaerul et al. [34] developed a system dynamics model using the Stella® software package for hospital waste management to clarify the interactions between factors within the system. Dyson and Chang [35] presented a novel system dynamics-based method for predicting solid waste generation in rapidly growing cities with limited data samples, using San Antonio, Texas as a case study. Vlachos et al. [36] developed an efficient planning strategy for capacity planning of remanufacturing facilities in the reverse supply chain, considering not only economic factors but also environmental concerns.

SD provides an effective approach to simulation within evolutionary game theory. Some scholars have begun to integrate SD into evolutionary game models to address industrial pollution [30–32,37,38]. For example, to address the complexity of environmental pollution control, Wang et al. [30] constructed a system dynamics model to deeply analyze the strategic interactions between the government and polluting enterprises during the game process. Their stability tests and system dynamics simulations showed that a static penalty mechanism prevents the system from reaching an evolutionary stable state. Therefore, the model introduces dynamic penalty clauses, which not only facilitates the achievement of evolutionary equilibrium but also significantly improves the effectiveness of environmental governance. Tian et al. [31] proposed a system dynamics model to explore how subsidy policies can promote the adoption of green supply chain management. Within an evolutionary game theory framework, the game relationships among the three major stakeholders, government, businesses, and consumers, are clarified. Furthermore, using automotive manufacturing industry as an application scenario, the complete dynamic process of green supply chain management from its introduction to its widespread adoption is simulated. Guo et al. [32] constructed a system dynamics model to characterize the complex and dynamic interrelationships among the three stakeholders: owners, supervising engineers, and construction contractors. Winz et al. [37] argued that system dynamics, when incorporating stakeholder participation, provides an effective methodological foundation for addressing environmental issues. By reviewing the theoretical and applied evolution of this field over the past 50 years, and combining a literature review with case studies, we further identify and discuss best practice patterns and typical misconceptions in the application of system dynamics simulation.

Moreover, the aforementioned studies predominantly focus on horizontal games (government-enterprise) or tripartite stakeholder interactions, largely overlooking the vertical strategic interaction between the central and local governments; a critical institutional feature in the environmental governance system. Local governments act as the primary executors of environmental regulations (ER), while the central government serves as the supervisor and policy designer. Their conflicting objectives (economic growth vs. ecological protection) often lead to strategic non-compliance and collusive behaviors [39,40]. Empirical studies have highlighted the effectiveness of target-based assessment systems in shaping local officials' environmental behavior. For instance, the inclusion of "ecological progress" indicators in cadre performance evaluations has been shown to significantly reduce pollution emissions, though its effectiveness is highly contingent on the stringency of monitoring and punishment [41,42]. In summary, the researchers constructed the game model between the government and the enterprise instead of the local and global governments, ignored the actual institutional arrangement in environmental governance, and used the static game theory analysis. Therefore, we model the relationship between the local and central governments using different assessment mechanisms and analyze the convergence path using the evolutionary game theory.

3. Basic evolutionary game model

3.1. Research assumptions

This game model is based on the following three assumptions: First, the participants are the local government and the central government, and the strategies they adopt are not optimal at the beginning when they are faced with incomplete information. Second, to simplify the analysis, we define that the central government's strategies are supervise and not supervise. The central government with the supervise strategy often prefers a better ecological environment and higher expected social welfare. Therefore, they will supervise the local government to see whether the local government carries out environmental regulations (ER). The local government's strategies are carry out ER and not carry out ER. Third, let x represent the probability of the local government with force ER, and let y represent the probability of the central government with supervise strategy $x, y \in [0,1], 1-x, 1-y \in [0,1]$.

3.2. Parameters settings

The local government with not force ER does not need to pay any cost for environmental regulations. On the contrary, the cost of local government with force ER is ξ_2. The central government with the not supervise strategy does not need to pay any cost for supervising, and the cost with the supervise strategy is ξ_1. Moreover, local governments with not force ER will be punished by the central government with the supervise strategy, and the penalty value is φ.

All parameters are summarized in Table 1. The payoff matrix between the local government and the central government is presented in Table 2.

Table 1. All parameters.

Parameters	Definitions	Value range
ξ_1	The cost of supervise strategy	$\xi_1 > 0$
ξ_2	The cost of ER strategy	$\xi_2 > 0$
φ	The penalty value of the central government to the local government	$\varphi > 0$
x	The probability of ER strategy	$0 \le x \le 1$
y	The probability of supervise strategy	$0 \le y \le 1$

Table 2. The payoff matrix.

The local government	The central government	
	Supervise (y)	No supervise $(1-y)$
Carry out ER (x)	$(-\xi_2,-\xi_1)$	$(-\xi_2,0)$
Not carry out ER $(1-x)$	$(-\varphi,-\xi_1+\varphi)$	$(0,0)$

3.3. The evolutionary game model

First, the expected return of the ER strategy is f_x, defined in Eq (1).

$$f_x = y(-\xi_2) + (1-y)(-\xi_2)\,. \tag{1}$$

Second, the expected return of not force ER is f_{1-x}, as shown in Eq (2).

$$f_{1-x} = y(-\varphi) + 0 \times (1-y)\,. \tag{2}$$

Besides, $\overline{f_1}$ is the average benefit of the local government, as shown in Eq (3).

$$\overline{f_1} = xf_x + (1-x)f_{1-x} = -x\xi_2 - y\varphi + xy\varphi\,. \tag{3}$$

Then, according to Eqs (1)–(3), the replicated dynamic equation is $f(x)$, as shown in Eq (4).

$$f(x) = \frac{dx}{dt} = x(f_x - \overline{f_1}) = x(-\xi_2 + x\xi_2 + y\varphi - xy\varphi) = x(1-x)(-\xi_2 + y\varphi)\,. \tag{4}$$

Moreover, the expected return of the supervise strategy is f_y, as shown in Eq (5):

$$f_y = x(-\xi_1) + (1-x)(-\xi_1 + \varphi)\,. \tag{5}$$

The expected return of the not-supervise strategy is f_{1-y}, as shown in Eq (6):

$$f_{1-y} = x \times 0 + (1-x) \times 0 = 0\,. \tag{6}$$

Besides, the average benefit of the central government is $\overline{f_2}$, as shown in Eq (7):

$$\overline{f_2} = yf_y + (1-y)f_{1-y} = y(-\xi_1 + \varphi - x\varphi)\,. \tag{7}$$

Furthermore, from Eqs (5)–(7), the replicated dynamic equation is $f(y)$, as shown in Eq (8).

$$f(y) = \frac{dy}{dt} = y(f_y - \overline{f_2}) = y(-\xi_1 + \varphi - x\varphi + y\xi_1 - y\varphi + xy\varphi) = y(1-y)(-\xi_1 + (1-x)\varphi)\,. \tag{8}$$

Thus, according to Eqs (4) and (8), we get Eq (9).

$$\begin{cases} f(x) = \dfrac{dx}{dt} = x(1-x)(-\xi_2 + y\varphi), \\ f(y) = \dfrac{dy}{dt} = y(1-y)(-\xi_1 + (1-x)\varphi). \end{cases} \tag{9}$$

3.4. The Jacobian matrix partial stability analysis

The corresponding Jacobian matrix is J [43], as shown in Eq (10).

$$J=\begin{bmatrix}(1-2x)(-\xi_2+y\varphi) & x(1-x)\varphi \\ -y(1-y)\varphi & (1-2y)(-\xi_1+(1-x)\varphi)\end{bmatrix} \tag{10}$$

Then, we have Eqs (11) and (12).

$$\det J=(1-2x)(-\xi_2+y\varphi)(1-2y)(-\xi_1+(1-x)\varphi)+xy(1-x)(1-y)\varphi^2 . \tag{11}$$

$$trJ=(1-2x)(-\xi_2+y\varphi)+(1-2y)(-\xi_1+(1-x)\varphi) . \tag{12}$$

Let $f(x)=0, f(y)=0$. Then, the possible equilibrium points are: $E_1(0,0)$, $E_2(0,1)$, $E_3(1,0)$, $E_4(1,1)$, and $E_5(x^*,y^*)$, with $x^*=\frac{\varphi-\xi_1}{\varphi}$, $y^*=\frac{\xi_2}{\varphi}$.

Then, we have Eqs (13) and (14).

$$\begin{aligned}\textstyle\int_1: \det J|_{(x^*,y^*)} &= (1-2x^*)(-\xi_2+y^*\varphi)(1-2y^*)(-\xi_1+(1-x^*)\varphi)+x^*y^*(1-x^*)(1-y^*)\varphi^2 \\ &=(1-2\frac{\varphi-\xi_1}{\varphi})(-\xi_2+\frac{\xi_2}{\varphi}\varphi)(1-2\frac{\xi_2}{\varphi})(-\xi_1+(1-\frac{\varphi-\xi_1}{\varphi})\varphi) \\ &\quad+\frac{\varphi-\xi_1}{\varphi}\frac{\xi_2}{\varphi}(1-\frac{\varphi-\xi_1}{\varphi})(1-\frac{\xi_2}{\varphi})\varphi^2 \\ &=\frac{(\varphi-\xi_1)(\varphi-\xi_2)\xi_1\xi_2}{\varphi^2},\end{aligned} \tag{13}$$

$$\textstyle\int_2: trJ|_{(x^*,y^*)}=(1-2x^*)(-\xi_2+y^*\varphi)+(1-2y^*)(-\xi_1+(1-x^*)\varphi)=0. \tag{14}$$

Then, $\det J$ and trJ are given in Table 3.

Table 3. The values of $\det J$ and trJ.

Equilibrium point	$\det J$ or trJ	Expression
$E_1(0,0)$	$\det J$	$-\xi_2(-\xi_1+\varphi)$
	trJ	$-\xi_2+(-\xi_1+\varphi)$
$E_2(0,1)$	$\det J$	$(-\xi_2+\varphi)(-1)(-\xi_1+\varphi)$
	trJ	$(-\xi_2+\varphi)+(-1)(-\xi_1+\varphi)$
$E_3(1,0)$	$\det J$	$-(-\xi_2)(-\xi_1)$
	trJ	$-(-\xi_2)+(-\xi_1)$
$E_4(1,1)$	$\det J$	$-(-\xi_2+\varphi)(-1)(-\xi_1)$
	trJ	$-(-\xi_2+\varphi)+(-1)(-\xi_1)$
$E_5(x^*,y^*)$	$\det J$	$\frac{(\varphi-\xi_1)(\varphi-\xi_2)\xi_1\xi_2}{\varphi^2}$
	trJ	0

According to [43], if $\det J>0, trJ<0$, the corresponding equilibrium point is the 'Evolutionary Stability Strategy' (ESS).

Case 1: If $\xi_1<\varphi<\xi_2$, the evolutionary stability is presented in Table 4.

Table 4. Case 1.

Equilibrium point	$\det J$	trJ	Results
$E_1(0,0)$	−	±	Saddle point
$E_2(0,1)$	+	−	ESS
$E_3(1,0)$	−	±	Saddle point
$E_4(1,1)$	+	+	Unstable point
$E_5(x^*,y^*)$	−	0	Central point

Case 2: If $\xi_2 < \varphi < \xi_1$, the evolutionary stability is presented in Table 5.

Table 5. Case 2.

Equilibrium point	$\det J$	trJ	Results
$E_1(0,0)$	+	−	ESS
$E_2(0,1)$	+	+	Unstable point
$E_3(1,0)$	−	±	Saddle point
$E_4(1,1)$	−	±	Saddle point
$E_5(x^*,y^*)$	−	0	Central point

Case 3: If $\varphi < \min(\xi_1, \xi_2)$, the evolutionary stability is presented in Table 6.

Table 6. Case 3.

Equilibrium point	$\det J$	trJ	Results
$E_1(0,0)$	+	−	ESS
$E_2(0,1)$	−	±	Saddle point
$E_3(1,0)$	−	±	Saddle point
$E_4(1,1)$	+	+	Unstable point
$E_5(x^*,y^*)$	+	0	Central point

Case 4: If $\varphi > \max(\xi_1, \xi_2)$, the evolutionary stability is presented in Table 7.

Table 7. Case 4.

Equilibrium point	$\det J$	trJ	Results
$E_1(0,0)$	−	±	Saddle point
$E_2(0,1)$	−	±	Saddle point
$E_3(1,0)$	−	±	Saddle point
$E_4(1,1)$	−	±	Saddle point
$E_5(x^*,y^*)$	+	0	Central point

In Case l, if $\xi_1 < \varphi < \xi_2$, there is an ESS point at $E_2(0,1)$. In this case, the local government will adopt not force ER, and the central government will adopt the supervise strategy. There is only one ESS point at $E_1(0,0)$ in Cases 2 and 3. This means that the local government will adopt not force ER, and the central government will adopt the not supervise strategy. In Case 4, where $\varphi > \max(\xi_1, \xi_2)$, the

Jacobian at $E_5(x^*, y^*)$ yields $\det J > 0$ and $trJ = 0$. This indicates that $E_5(x^*, y^*)$ is a center in the linearized sense, not a hyperbolic equilibrium. For a two-dimensional nonlinear replicator dynamics model, a center implies the existence of a family of closed orbits surrounding the equilibrium and conservative oscillations, provided that the system is Hamiltonian or has a first integral in the neighborhood. In our parameter regime, the replicator equation (Eq (9)) exhibits exactly such a center-type behavior: The trajectories are closed curves in the phase plane, leading to persistent periodic fluctuations in probabilities $x(t)$ and $y(t)$. Unlike a stable focus or a limit cycle, the amplitude of these oscillations is determined by the initial conditions, and the system never converges to a steady state. This is a direct consequence of the zero trace of the Jacobian at the interior equilibrium, which signals the absence of any dissipative force that could drive the system toward an ESS. Consequently, from the perspective of evolutionary game theory, the center case does not provide a robust long-term prediction, because any infinitesimal perturbation or parameter drift would destroy the closed orbits and lead to either convergence to a boundary ESS or the emergence of more complex dynamics. Thus, while this mathematical structure is interesting, it is undesirable for the policy guidance because it implies that the strategic interaction between the two parties will never form a predictable pattern.

To complement the Jacobian matrix stability analysis and provide an intuitive visualization of the evolutionary dynamics, we construct phase plane diagrams for the four cases identified in Section 3.4. These diagrams depict the vector field of the replicator dynamics system defined by Eq (9), where the horizontal axis represents the probability of local governments implementing ER strategies, and the vertical axis represents the probability of the central government adopting supervision strategies.

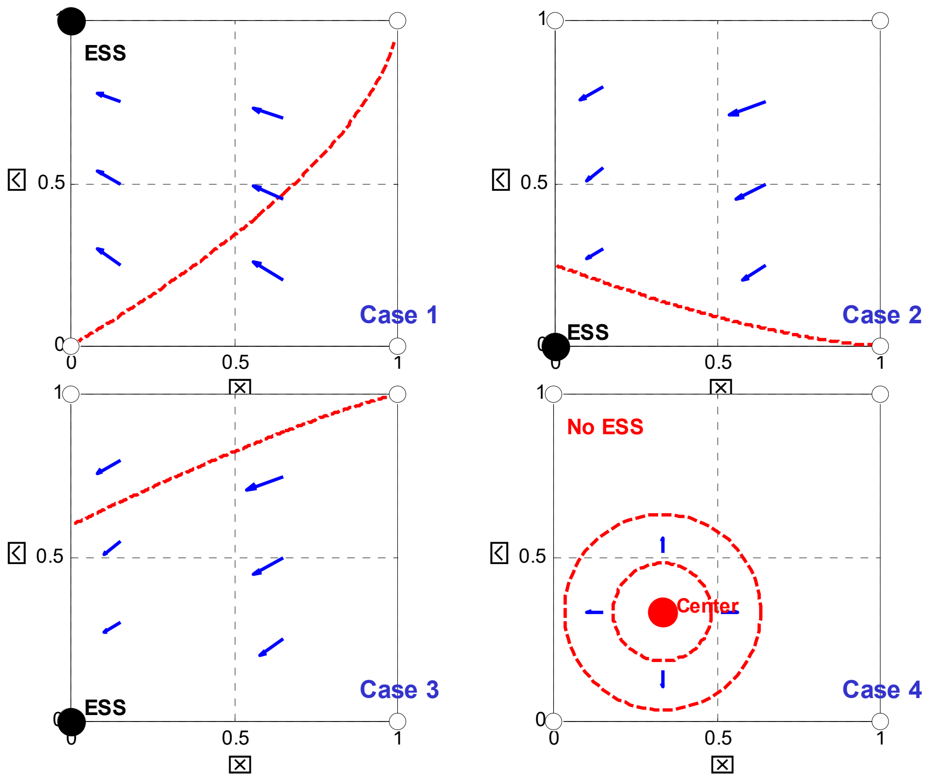

Figure 1. The phase portraits for Cases 1–4.

Figure 1 illustrates the phase portraits for Cases 1–4, with the corresponding parameter configurations listed in Table 8. In these diagrams, the direction and length of the arrows indicate the instantaneous velocity and direction of evolution from any given initial state, while the solid circles mark the equilibrium points, classified as stable nodes (ESS), saddle points, unstable nodes, or centers based on the Jacobian analysis. The phase plane analysis not only corroborates the analytical results from the Jacobian matrix but also provides a global perspective on the system's dynamic behavior, revealing how the evolutionary paths depend on initial conditions and parameter configurations. This visualization is particularly valuable for understanding the structural instability of the center case and the rationale for introducing external appraisal mechanisms to eliminate such oscillations.

3.5. The evolutionary game in a system dynamics model

The basic evolutionary game in a system dynamics model is presented in Figure 2.

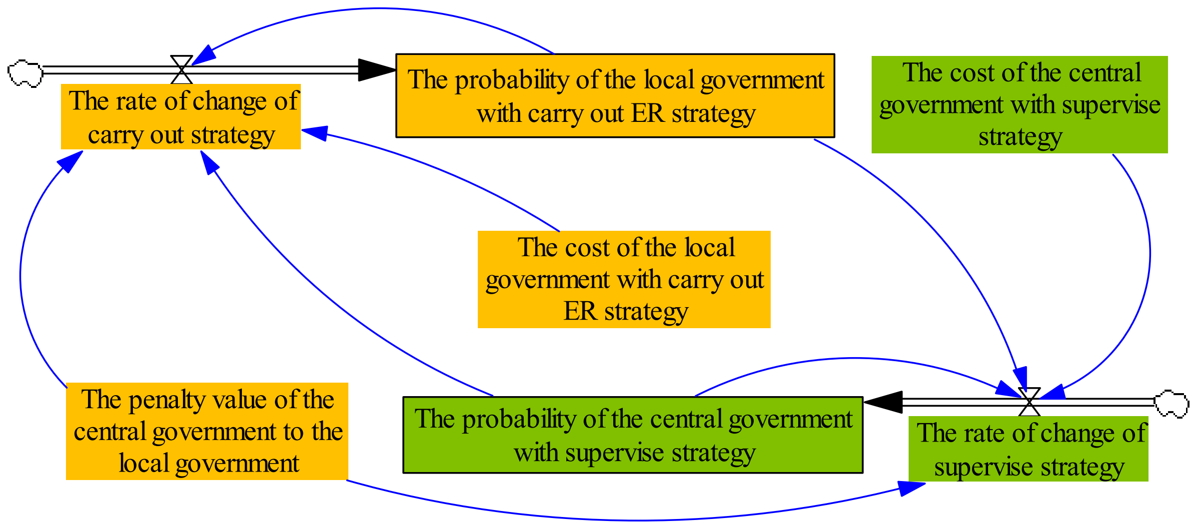

Figure 2. SD model of the evolutionary game for industrial pollution.

The parameters are shown in Table 8 [44,45]. In Case 1, $\xi_1 < \varphi < \xi_2$, the initial values are $\xi_1 = 1, \xi_2 = 3, \varphi = 2$. In Case 2, the qualification is $\xi_2 < \varphi < \xi_1$. In this situation, the initial values are $\xi_1 = 3, \xi_2 = 1, \varphi = 2$. In Case 3, the qualification is $\varphi < \min(\xi_1, \xi_2)$. In this situation, the initial values are $\xi_1 = 2, \xi_2 = 3, \varphi = 1$. Finally, in Case 4, the qualification is $\varphi > \max(\xi_1, \xi_2)$. In this situation, the initial values are $\xi_1 = 1, \xi_2 = 2, \varphi = 3$.

Table 8. The parameters.

Parameters and meanings in SD model	Case 1	Case 2	Case 3	Case 4
(ξ_1) The cost of 'supervise strategy'	1	3	2	1
(ξ_2) The cost of 'force ER'	3	1	3	2
(φ) The penalty value	2	2	1	3

3.6. Simulation analysis of the basic model

In this section, according to the above assumptions, some simulation analyses are given to illustrate the results.

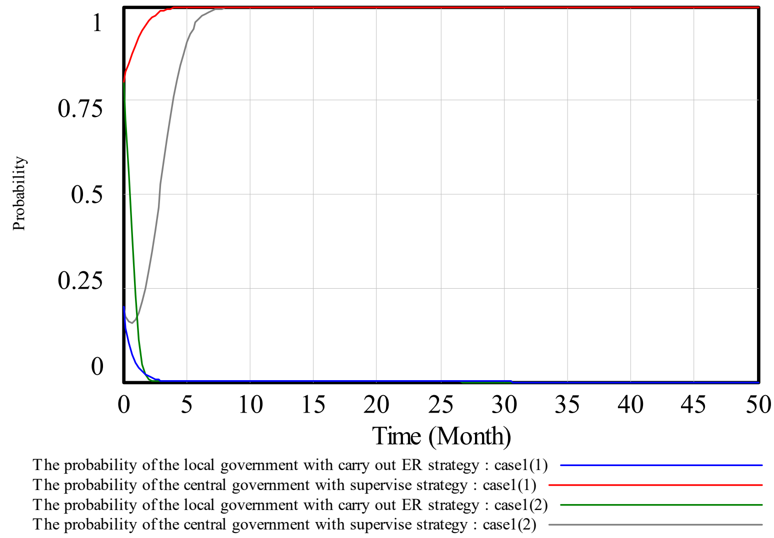

Figure 3. Simulation results in Case 1. Case 1(1): $x_t(0)=0.2$, $y_t(0)=0.8$. Case 1(2): $x_t(0)=0.8$, $y_t(0)=0.2$.

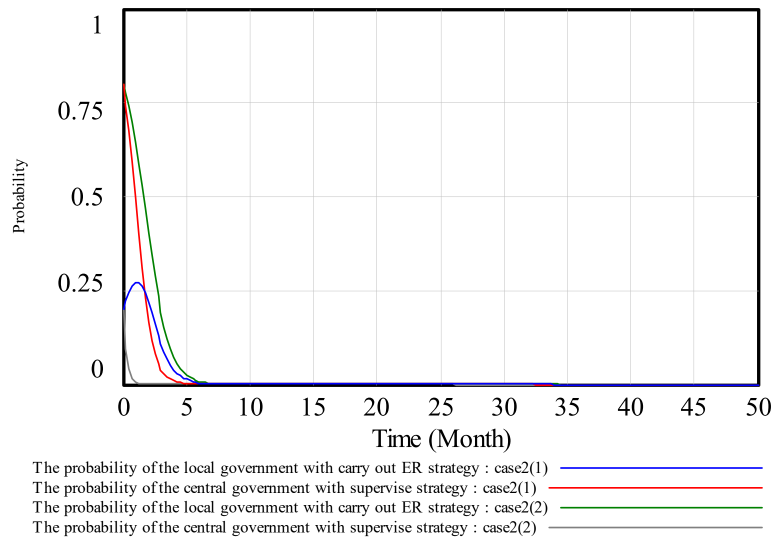

Figure 4. Simulation results in Case 2. Case 2(1): $x_t(0)=0.2$, $y_t(0)=0.8$. Case 2(2): $x_t(0)=0.8$, $y_t(0)=0.2$.

In Case 1, we set $\xi_1=1, \xi_2=3, \varphi=2$ and (x, y) as (0.2, 0.8) and, (0.8, 0.2), respectively. Figure 3 shows the simulation result, and the strategy between the two agents converges to (0,1). This means the local government tends to show weak willingness to force ER, while the central government tends to show strong willingness to supervise. This situation is mainly caused by $\xi_1<\varphi<\xi_2$, in which the value of the cost of the local government with force ER is bigger than that of the penalty value of the central government to the local government. Consequently, the local government prefers to bear the penalty rather than implement the ER strategy.

Similar to the analysis of Case 1, in Cases 2 and 3, we can get the simulation analysis in Figures 4 and 5. The strategy between the two players converges to (0,0), meaning that the local government tends to choose not force ER, while the central government tends to adopt the not supervise strategy. This situation in Cases 2 and 3 is mainly caused by $\varphi < \xi_2$. This means that the cost of the central government with the supervise strategy is higher than the earnings. Thus, the central government will adopt the not supervise strategy. Then, the local government will not force ER.

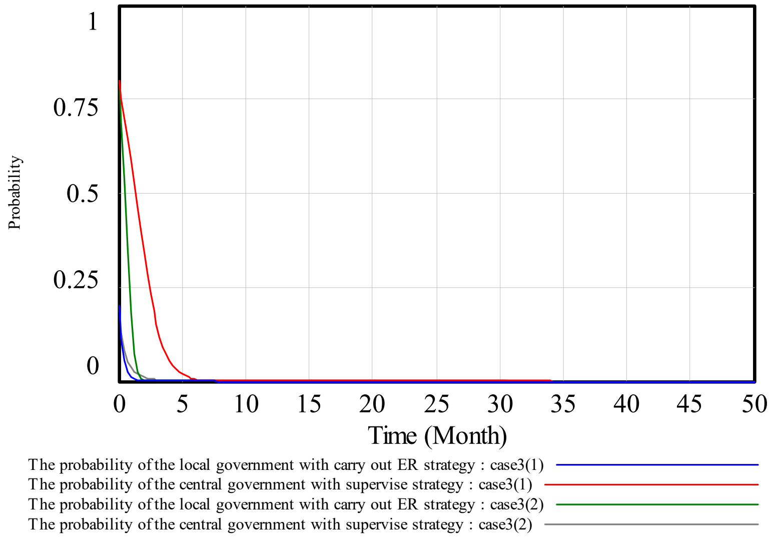

Figure 5. Simulation results in Case 3. Case 3(1): $x_t(0) = 0.2$, $y_t(0) = 0.8$. Case 3(2): $x_t(0) = 0.8$, $y_t(0) = 0.2$.

In Case 4, we can get the simulation analysis in Figure 6. From Figure 6, we can see that no matter what the initial state is, there are no certain strategies reached between the local government and the central government. Besides, the strategy between the local government and the central government presents the periodic oscillation. In the real situation of the industrial pollution management, it is difficult for the central government to show strong willingness to supervise, and it is also difficult for the local government to show strong willingness to force ER. Moreover, the central oscillations observed in Case 4 are not merely mathematical constructs; they have a plausible counterpart at the policy level. In many environmental governance systems, central and local governments often exhibit a cyclical pattern of tightening and loosening in regulatory enforcement. For example, after a major environmental incident, the central government may temporarily strengthen regulations, thereby increasing the expected penalties for local violations. In response, local governments will increase their environmental oversight. As local environmental quality improves, the central government's sense of urgency decreases, and regulatory efforts gradually loosen. This, in turn, reduces the incentive for local governments to maintain high-cost environmental oversight, leading to the environmental degradation and triggering central regulations again, and thus completing a policy cycle. However, while such cycles may reflect reality in the short term, they are undesirable from a normative perspective because they imply the persistent policy instability and unpredictability in the local implementation, making the long-term environmental planning difficult. Therefore, eliminating these oscillations through institutional mechanisms is a meaningful policy objective. Thus, it is more meaningful for the central government to adopt some appraisal mechanisms to the local government. Then, we present different kinds of new appraisal mechanisms to deal with the situation in Case 4.

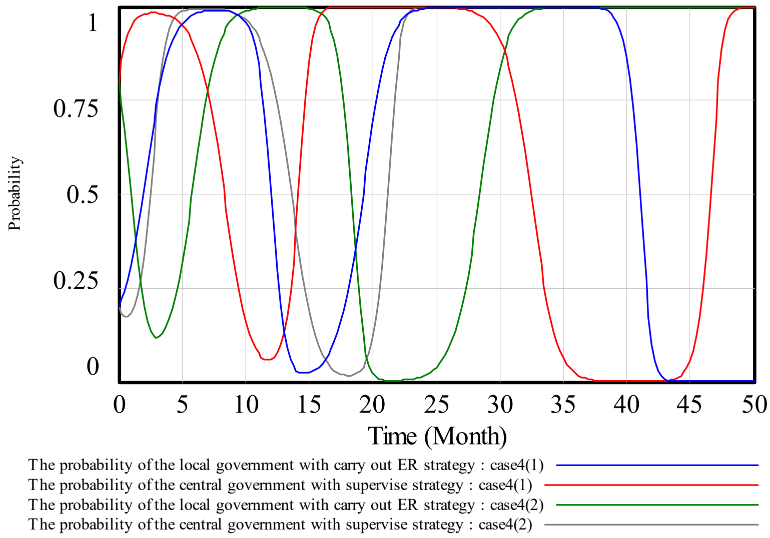

Figure 6. Simulation results in Case 4. Case 4(1): $x_t(0) = 0.2$, $y_t(0) = 0.8$. Case 4(2): $x_t(0) = 0.8$, $y_t(0) = 0.2$.

3.7. Sensitivity analysis of the initial value

As illustrated in Section 3.6, we take the value (0.2, 0.8), (0.8, 0.2) as the initial probability of (x, y). We know that the choice of initial probability does not affect the final convergence state. However, the game players in this model are different [45]. Therefore, we continue with the sensitivity analysis of the initial values. We test different initial values, covering at least four quadrants, with values C1: (0.2, 0.2), C2: (0.2, 0.8), C3: (0.8, 0.2), and C4: (0.8, 0.8) as the initial probability of (x, y). Here, we use only Case 4 as an example for sensitivity testing. The sensitivity analysis result in Case 2 is shown in Figures 7 and 8. By comparing Figures 6–8, it can be seen that all three figures show that the two game players exhibit an oscillating state, and changing the initial values will not affect the final equilibrium state of the two game players.

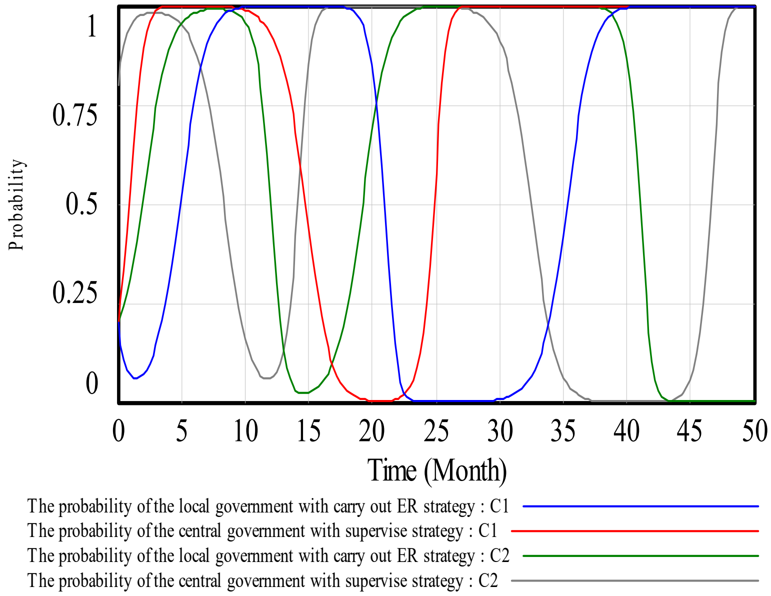

Figure 7. The sensitivity analysis result in Case 2 (C1: $x_t(0) = 0.2$, $y_t(0) = 0.2$. C2: $x_t(0) = 0.2$, $y_t(0) = 0.8$).

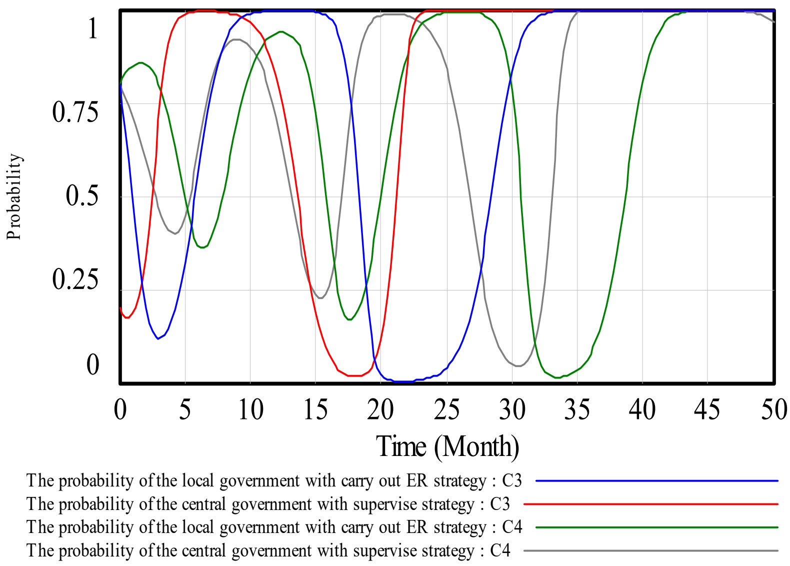

Figure 8. The sensitivity analysis result in Case 2 (C3: $x_t(0) = 0.8$, $y_t(0) = 0.2$; C4: $x_t(0) = 0.8$, $y_t(0) = 0.8$).

4. The effect of assessment mechanism for ecological progress to the stability of the model

4.1. The evolutionary game under the AMFEP

In this section, a new evolutionary game in a system dynamics model that considers the assessment mechanism for ecological progress is established. Here, we present an assessment mechanism for ecological progress between the local government and the central government.

Definition 1. The assessment mechanism for ecological progress: The central government will present an assessment on the local government according to their local environmental quality, and we call this mechanism to assessment mechanism for ecological progress (AMFEP). Thus, under this mechanism, the central government's efforts will have an influence on the local government. Therefore, whether the local government carries out ER or a strategy or not, the local environmental quality will be influenced. To illustrate this, in this mechanism, the local environmental quality production function is presented as shown in Eq (15).

$$Y = A_c y^p . \tag{15}$$

In Eq (15), Y is the local environmental quality, and y is the central government's efforts as well as the probability of the central government with supervise strategy. Additionally, p is the elastic coefficient of the central government's effort to the local environmental quality, $0 < p < 1$. A_c stands for the contribution of the central government to the local environmental quality, $A_c > 0$. Equation (15) adopts the Cobb-Douglas production function, which is widely used in environmental economics to simulate the combined contribution of government efforts and external inputs to environmental quality [46,47]. This setting implies diminishing marginal returns to central government efforts, reflecting a realistic assumption that initial regulatory efforts can lead to significant environmental improvements, while subsequent efforts gradually diminish in effectiveness due to technological limitations. The multiplicative form also reflects the complementary relationship between central government efforts and their baseline contributions to the local environmental quality. While other linear or exponential forms could be explored, the Cobb-Douglas function provides an easily manageable and empirically supported starting point, consistent with standard production theory approaches in regulatory governance [48]. By taking the Y derivative with y, the marginal utility of the central government's effort on the local environmental quality improvement is given by Eq (16).

$$\frac{dY}{dy} = pA_c y^{p-1} . \tag{16}$$

Table 9. The payoff matrix under the AMFEP.

The local government	The central government	
	Supervise (y)	No supervise $(1-y)$
Carry out ER (x)	$(-\xi_2 + pA_c y^{p-1}, -\xi_1 + pA_c y^{p-1})$	$(-\xi_2, 0)$
Not carry out ER $(1-x)$	$(-\varphi, -\xi_1 + \varphi)$	$(0,0)$

Based on the above analysis, a new payoff matrix under the AMFEP is shown in Table 9.

Based on the new payoff matrix under the AMFEP, we can establish the new evolutionary game model. Then, a new dynamic system combined by the replicated dynamic equation of the local government and the central government is given by Eq (17).

$$\begin{cases} f(x) = \dfrac{dx}{dt} = x(1-x)(-\xi_2 + y\varphi + pA_c y^p), \\ f(y) = \dfrac{dy}{dt} = y(1-y)(-\xi_1 + (1-x)\varphi + xpA_c y^{p-1}). \end{cases} \tag{17}$$

4.2. The evolutionary game under the AMFEP in a system dynamics model

In this section, the evolutionary game in a system dynamics model under the AMFEP is presented in Figure 9.

As can be seen from Figure 9, the SD model mostly consists of two flow variables, two rate-changing variables, and five external variables. To intuitively observe the dynamic change between the basic model and the AMFEP, the Vensim PLE system simulation tool [30] is used under Case 4. In this model, we set the initial values as INITIAL-TIME = 0, FINAL-TIME = 50, and TIME-STEP = 0.25. The unit for time is month and the integration type is Euler.

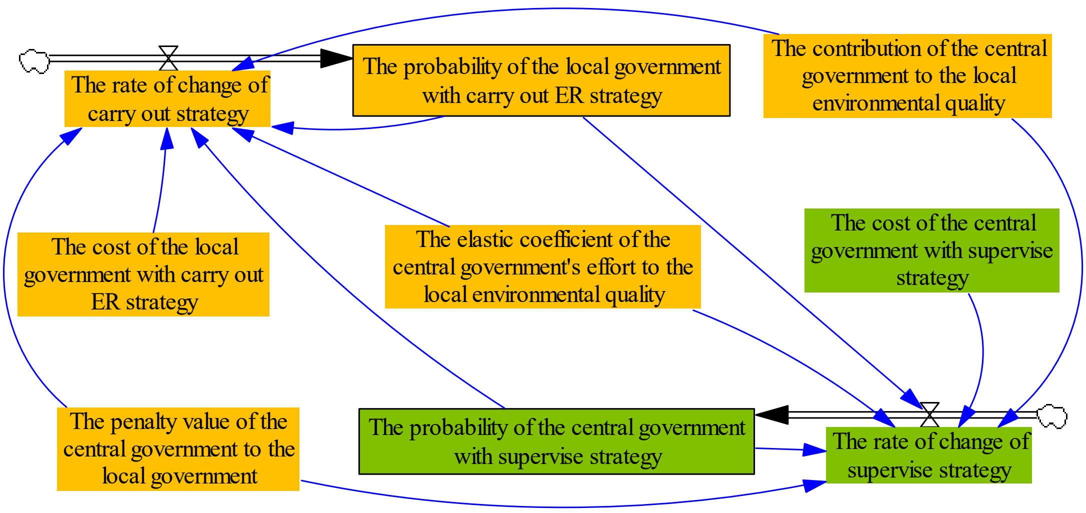

Figure 9. SD model of the evolutionary game under AMFEP for industrial pollution.

4.3. Simulation analysis of the AMFEP model

In this section, according to the above assumptions, some simulation analyses are given to illustrate the results. According to Case 4 in Section 2, the initial values are $\xi_1 = 1, \xi_2 = 2, \varphi = 3$. To simplify the analysis, we assume that p is a constant. According to the work proposed by Friedman [43], we assume that $p = 0.1$. In addition, the initial value of the contribution of the central government to the local environmental quality is small, so we let $A_c = 2$. To simplify the analysis, we present one combination of the probability. Then, one initial state of (x, y) is simulated with different probabilities: (0.2, 0.8). This initial state stands for the strategies selected by the local government and the central government, which have a weak willingness to force ER and strong willingness to supervise. The simulation analysis is presented in Figure 10. Then, we assume that $p = 0.1, A_c = 4, x = 0.2, y = 0.8$. The simulation analysis is presented in Figure 11. Furthermore, we assume that $p = 0.1, A_c = 8, x = 0.2, y = 0.8$. The simulation analysis is presented in Figure 12.

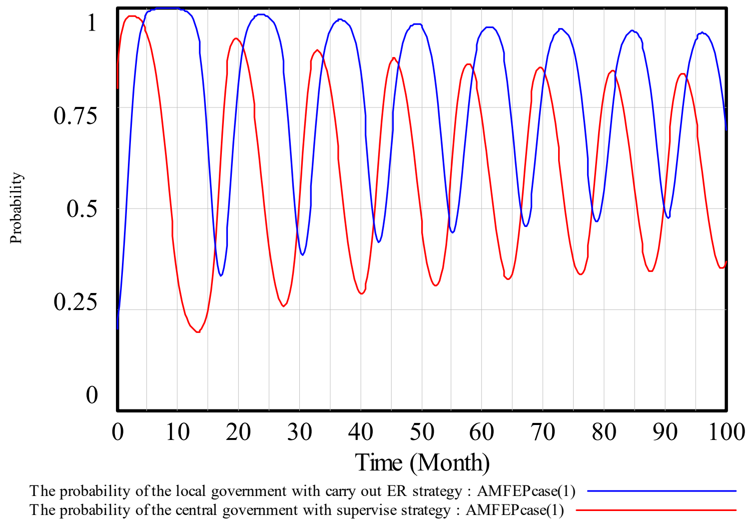

Figure 10. Simulation results in Case 4: $x_t(0) = 0.2, y_t(0) = 0.8, p = 0.1, A_c = 2$.

Compared with Figures 8 and 10, the strategy between the two players is also uncertain and it presents periodic oscillation. However, the frequency of shocks has increased, suggesting the intensity of the central government regulation has increased. Moreover, when the value A_c increases, from Figure 11, we can see that the strategy between the local government and the central government is certain, and it converges to a stable value. The value of the probability of the local government with force ER is 0.86. When we keep increasing the value A_c, the strategy between the local government and the central government will converge to a more stable status. The value of the probability of the local government with force ER is 1.

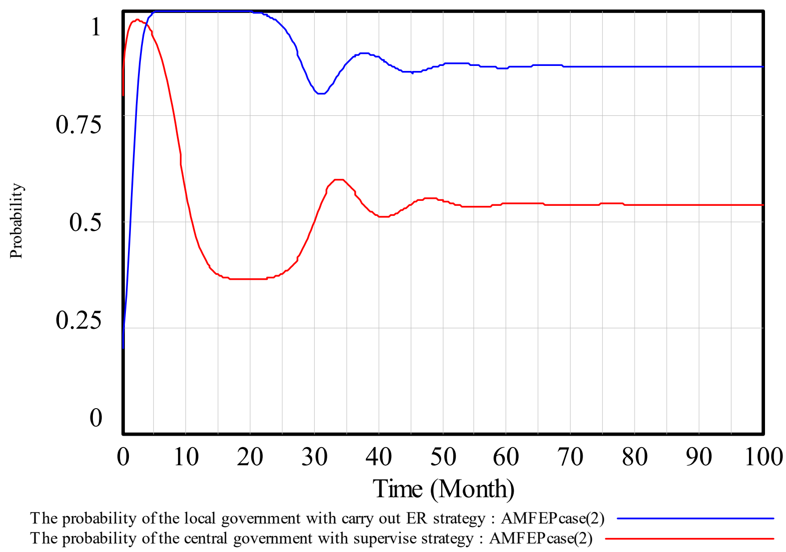

Figure 11. Simulation results in Case 4: $x_t(0) = 0.2, y_t(0) = 0.8, p = 0.1, A_c = 4$.

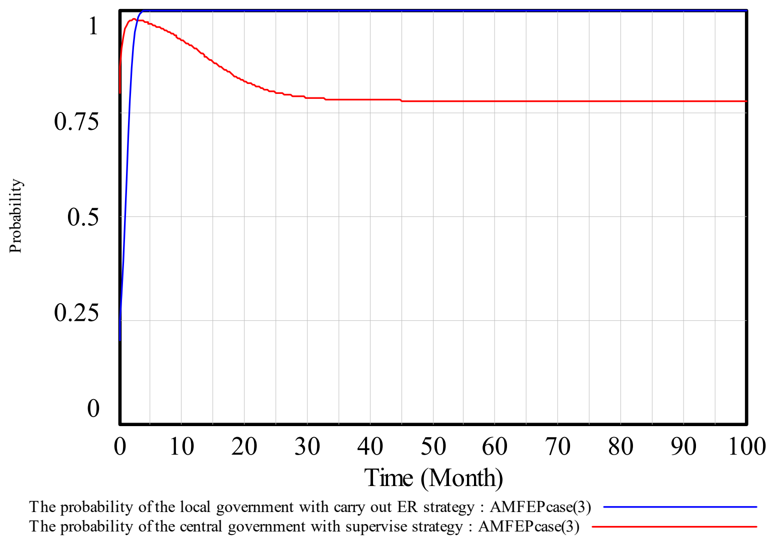

Figure 12. Simulation results in Case 4: $x_t(0) = 0.2, y_t(0) = 0.8, p = 0.1, A_c = 8$.

4.4. Stability analysis of the AMFEP mechanism

Under the AMFEP mechanism, the central government's supervision effort y positively influences the local government's utility by improving the local environmental quality $Y = A_c y^p$. This influence is incorporated into the local government's payoff function, thereby modifying its replicator dynamic equation.

Comparing the local government's replicator dynamic equation in the basic model (Eq (4)) with that under AMFEP (Eq (17)), a key change emerges: The net benefit for the local government choosing the "implement ER" strategy changes from $(-\xi_2 + y\varphi)$ to $(-\xi_2 + y\varphi + pA_c y^p)$. Here, $pA_c y^p > 0$ serves as an additional positive utility term, which directly increases the marginal benefit of choosing the "implement ER" strategy.

From a systemic perspective, this positive utility term acts as a "stabilizing" factor. When the system deviates from the desired equilibrium, for instance, when y increases, the local government's implementation willingness x receives stronger positive feedback, thereby suppressing the system's original periodic fluctuations. Numerical simulations (see Figures 8–10) demonstrate that the system converges to a stable focus only when this positive utility is sufficiently large (when A_c is large enough). This reveals that the effectiveness of AMFEP depends on the central government's substantive contribution capacity to local environmental quality (A_c).

Therefore, the new evolutionary game model of AMFEP is more conductive when the value A_c is large. However, it will get a weak effect when the value A_c is small.

5. The ecological governance supervision and punishment mechanism to the stability of the model

5.1. The evolutionary game under the EGSPM

In this section, a new evolutionary game in a system dynamics model, which considered the ecological governance supervision and punishment mechanism, is established.

Definition 2. The ecological governance supervision and punishment mechanism: This mechanism indicated that the central government would adopt a self-examination mechanism. Under this mechanism, if the central government does not supervise and the local government does not force ER, the central government will be punished. However, the central government is the highest authority, so we regard this punishment as the loss of the social welfare. Then, we call this mechanism to the ecological governance supervision and punishment mechanism (EGSPM). To illustrate, in this mechanism, the loss of the social welfare function is presented by Eq (18).

$$Y_2 = A_s(1-y)^q . \tag{18}$$

In Eq (18), Y_2 is the loss of the social welfare, and q is the punish coefficient, $q > 1$. A_s stands for the maximum penalty, $A_s > 0$. A quadratic loss function is chosen to reflect the escalating social costs of the regulatory failure. The marginal welfare loss increases with the frequency of central government negligence (non-regulation). The quadratic form shows that when the intensity of regulation is below a certain threshold, the social damage will increase at an increasing rate, which is consistent with the concept of the tipping point of environmental degradation [49]. The maximum penalty term, as the upper limit, represents the worst-case welfare loss in the absence of regulation. We choose this function due to the theoretical considerations on regulatory enforcement [50], as well as practical considerations of environmental policy, where the central government needs to bear the political and reputational costs of the ecological failure. Similar to the analysis in Section 3, a new payoff matrix under the EGSPM is shown in Table 10.

Table 10. The payoff matrix under the EGSPM.

	The central government	
The local government	Supervise (y)	No supervise $(1-y)$
Carry out ER (x)	$(-\xi_2, -\xi_1)$	$(-\xi_2, 0)$
Not carry out ER $(1-x)$	$(-\varphi, -\xi_1+\varphi)$	$(0, -qA_s(1-y)^{q-1})$

Under the new payoff matrix of EGSPM, a new replicated dynamics equation is given by Eq (19).

$$\begin{cases} f(x) = \dfrac{dx}{dt} = x(1-x)(-\xi_2 + y\varphi), \\ f(y) = \dfrac{dy}{dt} = y(1-y)(-\xi_1 + (1-x)(\varphi + qA_s(1-y)^{q-1})). \end{cases} \tag{19}$$

5.2. The evolutionary game under the EGSPM in a system dynamics model

A system dynamics model of EGSPM is presented in Figure 13.

In this model, we set the values as INITIAL-TIME = 0, FINAL-TIME = 50, and TIME-STEP = 0.25. The unit for time is month, and the integration type is Euler.

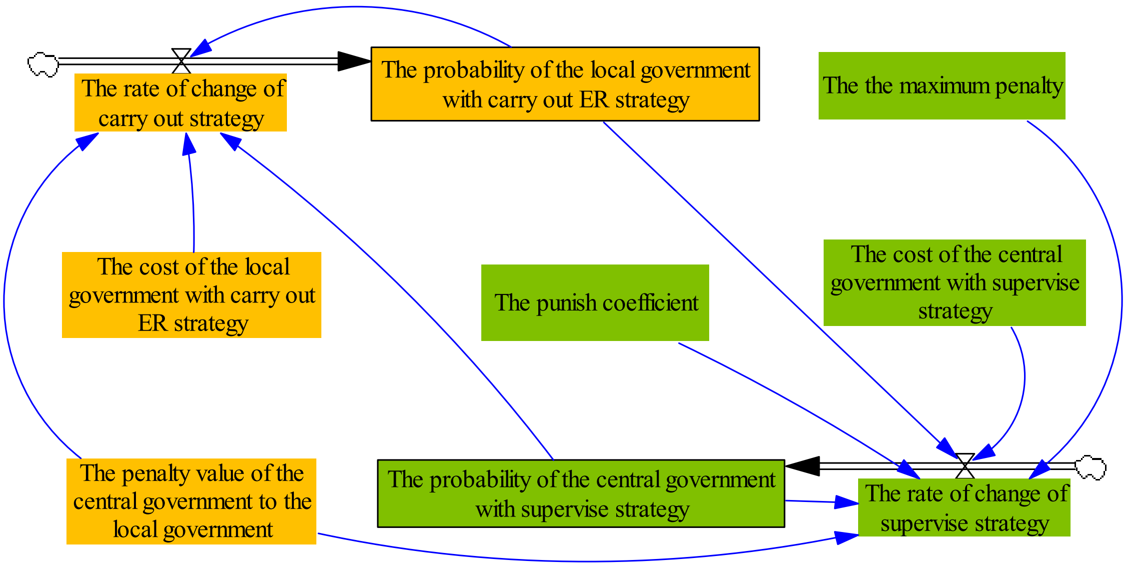

Figure 13. SD model of EGSPM for industrial pollution.

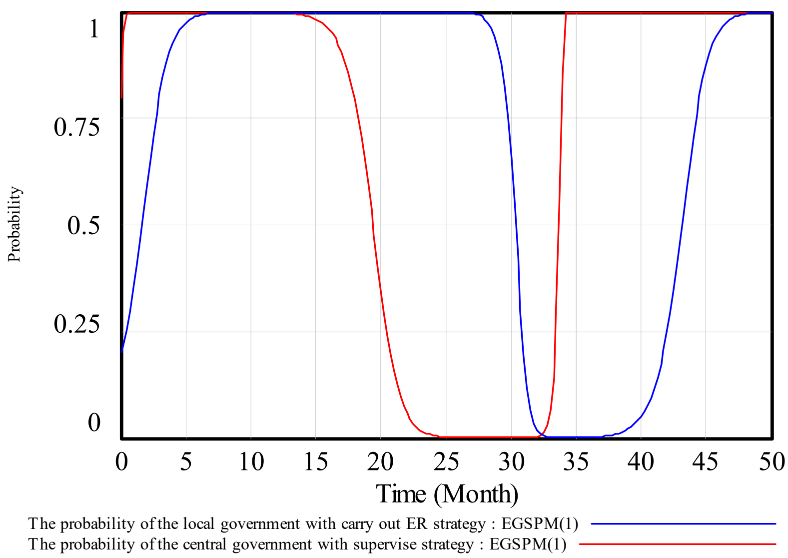

Figure 14. Simulation results in Case 4. Case 4(1): $x_t(0)=0.2, y_t(0)=0.8, q=1, A_s=3$.

5.3. Simulation analysis of the EGSPM model

In this section, based on the above assumptions, we conduct simulation analyses to illustrate the results. Following Case 4 in Section 2, the initial values are $\xi_1=1, \xi_2=2, \varphi=3$. To simplify the analysis, we examine the influence of the value q to the stability to the model. Thus, we assume that A_s is a constant. Then, let $A_s=3$. Similar to the condition in Section 4, we present one combination of the probability. Then, one initial state of (x, y) is (0.2, 0.8). In addition, we let $q=1, A_s=3, x=0.2, y=0.8$, as shown in Figure 14. Then, we assume that $q=1.5, A_s=3$, $x=0.2, y=0.8$, as presented in Figure 15. Then, we assume that $q=2, A_s=3, x=0.2, y=0.8$, as shown in Figure 16. Moreover, we assume that $q=3, A_s=3, x=0.2, y=0.8$, as presented in Figure 17. From Figures 14–17, the strategy between the local government and the central government tends to converge to a stable value while the value of q

is increasing. However, when the value of $q \le 3$, it cannot tend to converge to a stable value. Thus, in this situation, the model under the EGSPM is better than the basic model when the value of $q \ge 3$. However, it will also get a weak effect when the value of $q \le 3$.

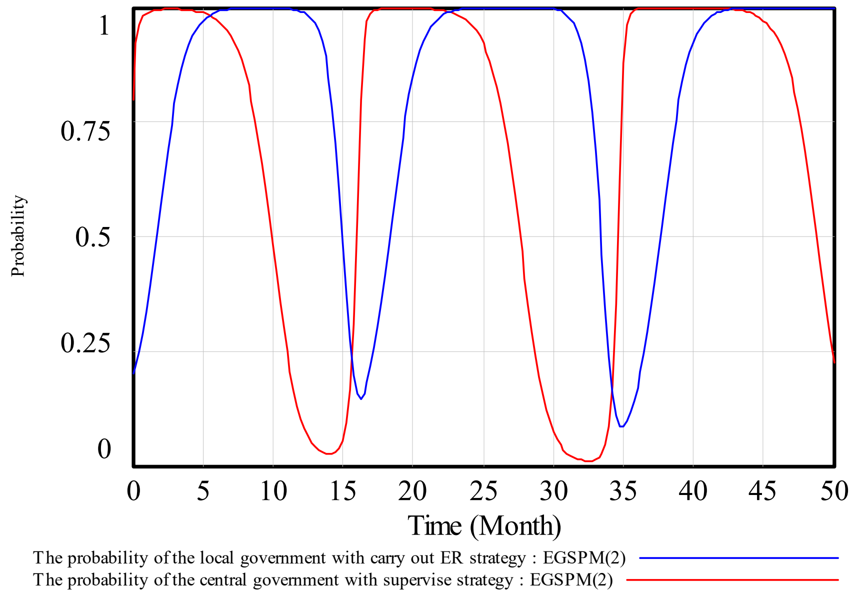

Figure 15. Simulation results in Case 4. Case 4(1): $x_t(0) = 0.2, y_t(0) = 0.8, q = 1.5, A_s = 3$.

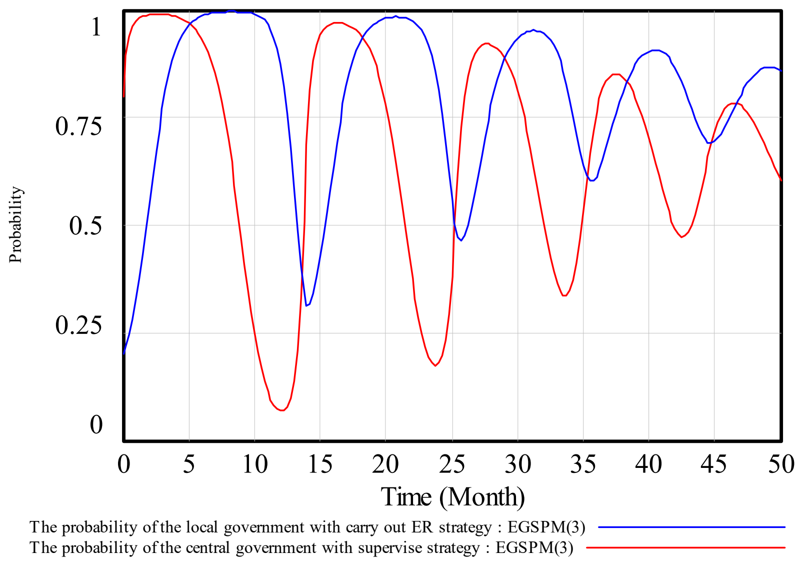

Figure 16. Simulation results in Case 4. Case 4(1): $x_t(0) = 0.2, y_t(0) = 0.8, q = 2, A_s = 3$.

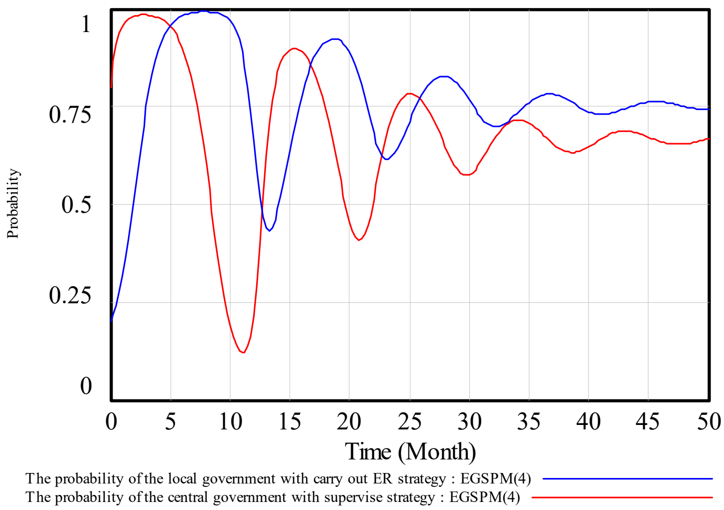

Figure 17. Simulation results in Case 4. Case 4(1): $x_t(0)=0.2, y_t(0)=0.8, q=3, A_s=3$.

5.4. Simulation analysis of the EGSPM model

The EGSPM mechanism introduces a "self-accountability" pressure on the central government. If the central government does not supervise $1-y$, and the local government does not implement ER $1-x$, the central government incurs a social welfare loss $Y_2 = A_s(1-y)^q$. This loss is incorporated into the central government's payoff for the "non-supervision" strategy (becoming $-qA_s(1-y)^{q-1}$).

This mechanism fundamentally operates as an "opportunity cost penalty". It alters the central government's decision-making reference point. In the basic model, the payoff for non-supervision is zero. Hence, whenever the supervision cost exceeds the potential penalty revenue, the central government tends not to supervise. The EGSPM attaches a negative utility to the "non-supervision" strategy, thereby effectively raising the relative benefit of supervision. When the probability of the local government not implementing ER $1-x$ increases, the potential welfare loss that the central government would bear for non-supervision also increases, compelling the central government to raise its supervision willingness to avoid risks.

6. The system dynamics model combining AMFEP and EGSPM

6.1. The hybrid evolutionary game combining AMFEP and EGSPM

Table 11. The new payoff matrix.

The local government	The central government	
	Supervise (y)	No supervise $(1-y)$
Carry out ER (x)	$\left(-\xi_2 + pA_c y^{p-1}, -\xi_1 pA_c y^{p-1}\right)$	$(-\xi_2, 0)$
Not carry out ER $(1-x)$	$\left(-\varphi, -\xi_1 + \varphi\right)$	$(0, \ -qA_s(1-y)^{q-1})$

Here, a new system dynamics model that combines AMFEP and EGSPM is established. Similar to the analysis in Sections 3 and 4, a new payoff matrix is shown in Table 11.

Here, a new replicated dynamics is given by Eq (20).

$$\begin{cases} f(x) = \dfrac{dx}{dt} = x(1-x)(-\xi_2 + y\varphi + pA_c y^p), \\ f(y) = \dfrac{dy}{dt} = y(1-y)(-\xi_1 + (1-x)(\varphi + qA_s(1-y)^{q-1}) + xpA_c y^{p-1}). \end{cases} \tag{20}$$

6.2. The evolutionary game combining AMFEP and EGSPM in a system dynamics model

Here, a system model combing AMFEP and EGSPM is presented in Figure 18.

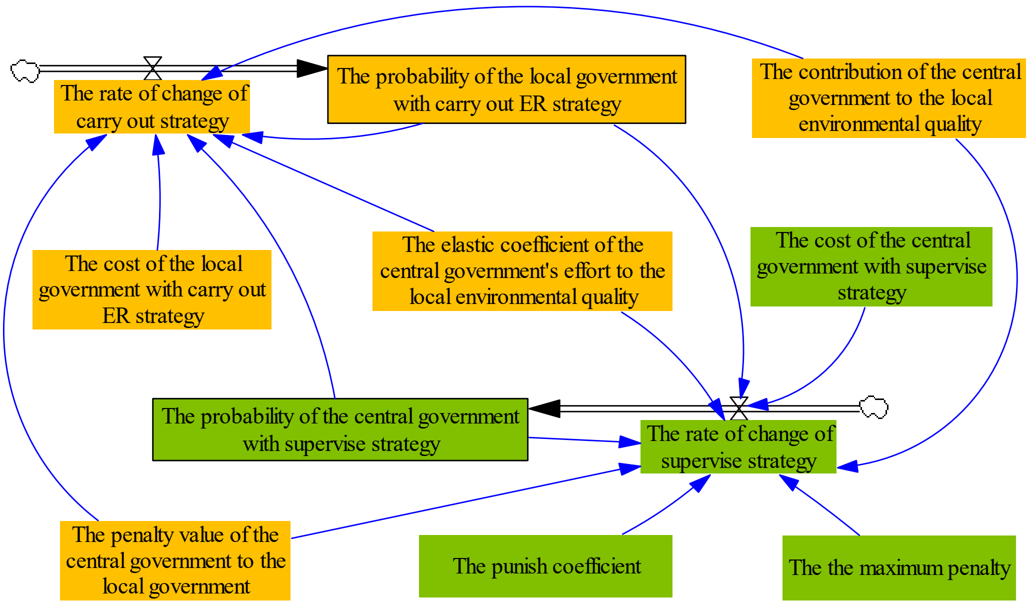

Figure 18. SD model of the evolutionary game combing AMFEP and EGSPM for industrial pollution.

In this model, we set the initial value as INITIAL-TIME = 0, FINAL-TIME = 100, and TIME-STEP = 0.25. The units for time and the integration type are set as previously.

6.3. Simulation analysis of the hybrid model

In this section, according to the above assumptions, some simulation analyses are given to illustrate the results. Following Case 4 in Section 2, the initial values are $\xi_1 = 1, \xi_2 = 2, \varphi = 3$. To observe the advantage of our new model compared with the former model, we need to examine the weak case in the former model under the case that $p = 0.1, A_c = 2, x = 0.2, y = 0.8, q = 1, A_s = 3$, as shown in Figure 19. Compared with the previous model, we can see that the strategy between the local government and the central government converges to a better value, and the value of the probability of the local government with the ER strategy is 0.167. Finally, the local government is more likely to carry out the ER strategy, while the central government tends to show weak willingness to supervise. This is more conducive than the former model, so the mechanism we establish with combining AMFEP and EGSPM is a more effective way to guide the central government to implementation policies in the real world.

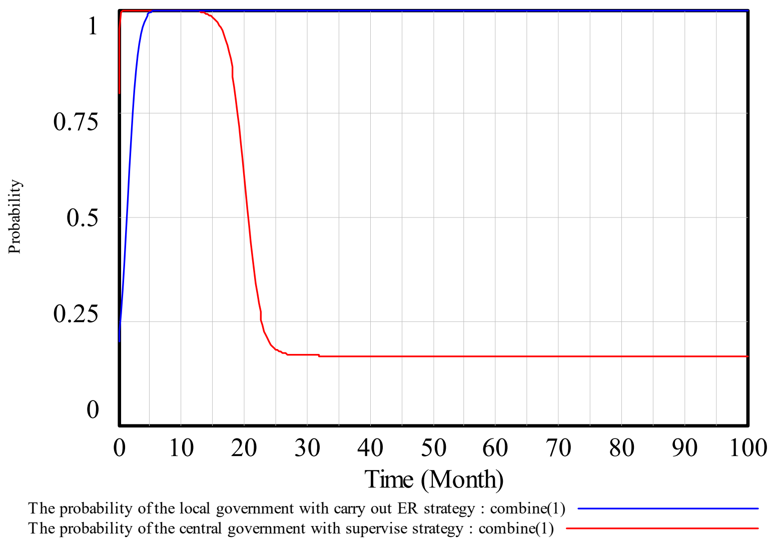

Figure 19. Simulation results in Case 4. Case 4(1): $p = 0.1, A_c = 2$ $x_t(0) = 0.2, y_t(0) = 0.8, q = 1, A_s = 3$.

6.4. Synergistic gains of the hybrid model and stability summary

The hybrid model (Eq (20)) simultaneously incorporates the gain mechanisms described above: the "benefit compensation" of AMFEP and the "opportunity cost penalty" of EGSPM. This means that the local government's implementation willingness x is simultaneously influenced by positive incentives (from $pA_c y^p$) and negative incentives (from the coupling of potential penalty φ and central supervision willingness). Moreover, the central government's supervision willingness y is also driven by the pressure from the local inaction and the indirect benefits from its own supervisory contributions.

The two mechanisms complement each other. When parameters A_c and q are in their respective "weak-effect" ranges, where each mechanism alone fails to drive convergence, the hybrid model provides the sufficient damping and driving force to the system through dual channels, ensuring the evolutionary path converges to a stable non-zero equilibrium under the broadest possible parameter conditions. As shown in Figure 19, even under parameter combinations where AMFEP and EGSPM individually fail, the hybrid model achieves the effective convergence. This confirms the theoretical superiority and robustness of the hybrid mechanism, offering policymakers a more reliable theoretical tool.

7. Sensitivity analysis

To verify the effectiveness and robustness of the hybrid model under different policy environments, in this section, we conduct sensitivity analysis on three core parameters: penalty intensity (φ), elasticity coefficient of environmental efforts (p), and central government contribution (A_c). The simulations are based on the replicator dynamic equations of the hybrid model (Eq (20)), with Case 4 as the baseline scenario ($\xi_1 = 1, \xi_2 = 2, \varphi = 3$, $p = 0.1, A_c = 2, x = 0.2, y = 0.8, q = 1, A_s = 3$). The initial probabilities are set to $(x, y) = (0.2, 0.8)$. Three levels, low, medium, and high, are assigned to each parameter to comprehensively reflect their impacts on the system's evolutionary paths.

7.1. Sensitivity analysis of penalty intensity (φ)

Figure 20 illustrates the evolutionary trajectories of the probability x that local governments adopt environmental regulation strategies for penalty intensity φ values of $\varphi = 2$ (curve a), $\varphi = 3$ (curve b), and $\varphi = 5$ (curve c), respectively. These results indicate that increasing penalty intensity significantly enhances the local governments' willingness to regulate while accelerating the convergence speed, thereby validating the effectiveness of the punishment mechanism within the hybrid model.

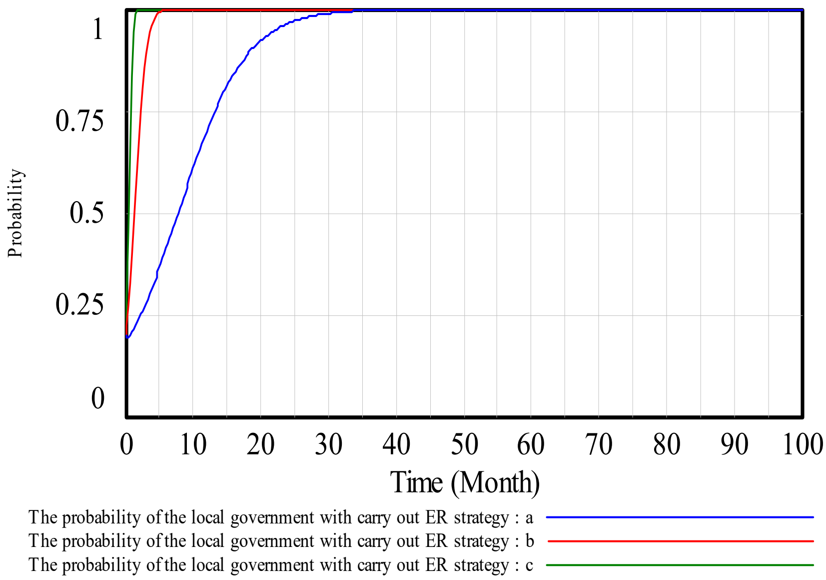

Figure 20. Sensitivity analysis of penalty intensity. d: $p = 2$, e: $p = 3$, and f: $p = 5$.

7.2. Sensitivity analysis of elasticity coefficient (p)

Figure 21 presents the evolutionary paths for the elasticity coefficient p at values of $p = 0.1$ (curve d), $p = 0.2$ (curve e), and $p = 0.3$ (curve f), respectively. The results demonstrate that an increase in the elasticity coefficient monotonically enhances the local governments' regulatory willingness. That is, the more significant the marginal improvement in local environmental quality resulting from central government regulatory efforts is, the stronger the incentive for local governments to implement environmental regulation strategies.

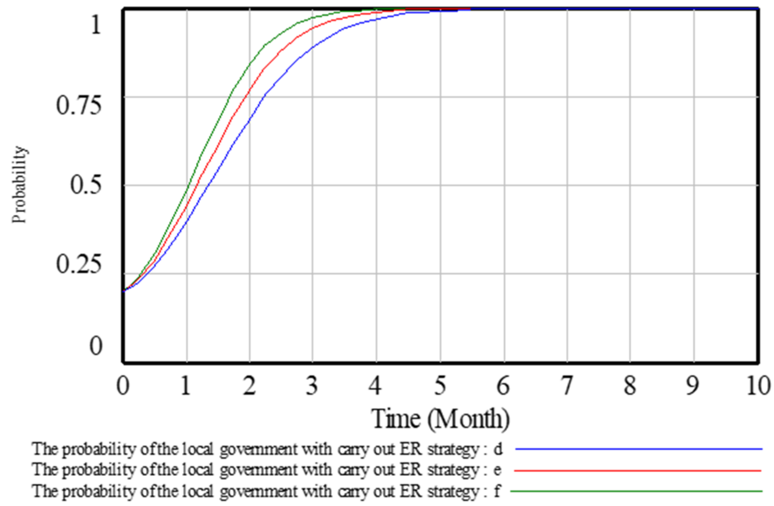

Figure 21. Sensitivity analysis of the elasticity coefficient. d: p =0.1, e: p =0.2, and f: p =0.3.

7.3. Sensitivity analysis of central government contributions (A_c)

Figure 22 shows the evolutionary paths for the central government contribution A_c at values of A_c = 2 (curve g), A_c = 3 (curve h), and A_c = 6 (curve I), respectively. This parameter exerts the most significant influence on the system's steady-state value, indicating that the central government's substantive investment in environmental quality improvement is a key driver for enhancing local governments' regulatory willingness and a decisive factor for the hybrid model to achieve optimal performance.

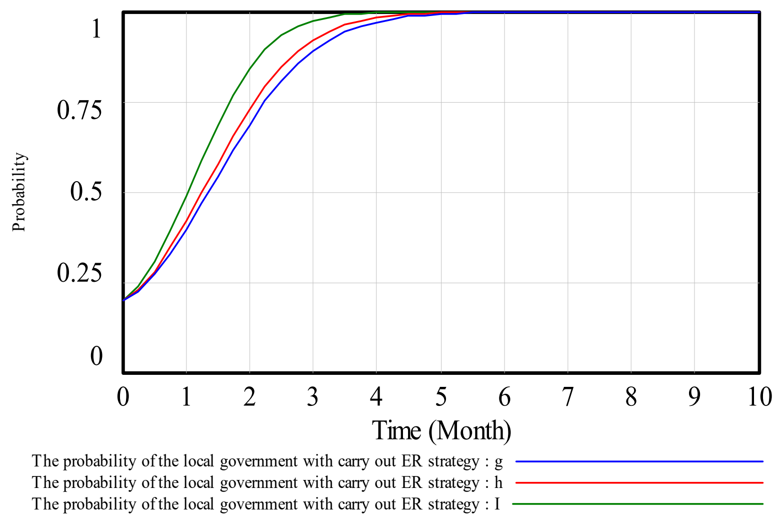

Figure 22. Sensitivity analysis of central government contributions. g: A_c = 2, h: A_c = 3, and I: A_c = 6.

In summary, the hybrid model achieves system convergence across many variations in all three parameters, with steady-state values monotonically increasing as parameter values rise. This verifies that the hybrid model possesses good adaptability and robustness under different policy contexts. When the penalty intensity, elasticity coefficient, or central government contribution is at a relatively low level, the system converges, but at a slower speed and to a lower steady-state value. This finding suggests that policymakers should ensure these key parameters are maintained at reasonable levels in practice to guarantee the effective implementation of environmental governance policies.

8. Discussion

We propose a system dynamics model that incorporates different appraisal mechanisms. Here, it is crucial to clarify why the periodic oscillations in Case 4 should be "eliminated", rather than considered a possible equilibrium outcome. In classical evolutionary game theory, the center is structurally unstable: It requires precise parametric conditions and cannot withstand minor perturbations. In practice, policy parameters (e.g., monitoring costs and penalty levels) are not static; they evolve with economic cycles, political priorities, and media attention. Therefore, central dynamics can rapidly transform into damped oscillations (convergence) or divergent spirals (collapse into boundary ESS), neither of which can be reliably predicted by models. More importantly, from a policymaking perspective, the sustainable environmental governance demands convergent behavior; either a tendency toward strict enforcement or a stable combination of strategies. Persistent oscillations introduce uncertainty for regulators and regulated companies, increase transaction costs, and reduce the credibility of policy commitments. Therefore, central governments must introduce evaluation mechanisms (AMFEP and EGSPM) as "damping factors" to break down conservative structures and guide the system toward a stable equilibrium. Our hybrid model achieves this by coupling the central government's effort resilience and social welfare loss terms, which together introduce negative feedback, making the central government a stable focus and thus restoring predictive power and policy relevance. The simulation results offer several practical guidelines for the central government and the local government in formulating policies to address industrial pollution. On the one hand, the central government should adopt corresponding appraisal mechanisms to the local government, such as the mechanism combining AMFEP and EGSPM in this work, if the local government tends to not carry out strategy. On the other hand, local governments should enhance their environmental awareness while pursuing economic development.

In this paper, we select four cases that satisfy the underlying assumptions. It is noted that the new terms introduced in Eqs (17), (19), and (20) contain product factors of state variables, and these new terms automatically become zero at any equilibrium point reached by the system. Therefore, the set of all equilibrium points of the new system coincides with that in Section 3. In the neighborhood of any equilibrium point, the contribution of the new terms to the first-order linearized matrix (Jacobi) is zero, so its local stability is determined by the Jacobian matrix analyzed in Section 3. Based on this invariance, we consider it unnecessary to repeat the Jacobian derivation of the same form. In addition, we randomly pick a probability of initial states of (x, y) with $p = 0.2, q = 0.8$. In the model with AMFEP, we set $p = 0.1$ and examine the influence of A_s on the convergence of the evolution path. However, the value of p also has an impact on the convergence. Similarly, we handle the value of A_s in the model with EGSPM in the same manner. In this work, we aim to set up the models with appraisal mechanisms and check their effects. We acknowledge that the values listed in Table 8 (e.g., cost and penalty values) are primarily used to demonstrate theoretical predictions under different parameter conditions, based on four scenarios that satisfy the Jacobian matrix stability analysis (Section 3.4). While these hypothetical scenarios do not directly correspond to specific real-world data, they are designed to cover all possible equilibrium outcomes derived from the theoretical model. To enhance the practical applicability of our findings, we plan to calibrate these parameters using real-world policy data (e.g., environmental spending and penalty records) in future work.

The model we present in this work can be applied to industrial pollution problems for many countries with the hierarchical organization of various levels of governments. It will facilitate the policy-making of both sides of the two agents. However, the conclusions are drawn from the simulations due to the lack of validation datasets. Moreover, we undertake a qualitative validation effort by comparing simulation results with well-documented empirical patterns in the environmental governance literature. Here, we aim to assess whether our models can produce behaviors consistent with observed real-world phenomena. Specifically, we compare the predictions of three models (the baseline model, the AMFEP model, the EGSPM model, and the hybrid model) with key facts identified in other empirical studies. First, our baseline model (Case 4) shows the pattern of "tightening and loosening" cycles when $\varphi > \max(\xi_1, \xi_2)$, capturing the intrinsic oscillatory tendency observed in practice, even though such oscillations are normatively undesirable. This is consistent with conclusions in other work [4,38], where the environmental enforcement exhibits periodic campaigns followed by relaxation. Second, our AMFEP model shows the positive effect of central appraisal mechanisms. This verifies the empirical findings in [10], that provinces with stricter central-government performance assessments on environmental indicators exhibit significantly higher local compliance rates. Third, our EGSPM model shows the deterrent effect of punishment mechanisms that higher penalties and stricter supervisions reduce non-compliance locally, consistent with the findings in [29]. These demonstrate that our model's predictions are qualitatively consistent with well-established empirical regularities, even in the absence of quantitative fitting. In the future, we will rigorously validate our models using real word datasets.

Furthermore, we use different time steps for various models (50 or 100 months) due to visualization. We aim to show the convergence procedure though this does not change the qualitative behavior (oscillations persist) or convergence trend using different time steps. In this work, the models are simplified, focusing only on bilateral interactions between central and local governments. However, the industrial pollution control also involves enterprises, the public, and environmental organizations. We plan to extend our framework by considering multi-stakeholders and conducting more systematic analysis in future work.

9. Conclusions

In this work, we present three mechanisms in a system dynamics model to handle industrial pollution problems. Numerical examples are given for the simulation, and the results show that the evolution path between the two agents cannot tend to converge to a stable focus in the basic model. Thus, we present two new models under AMFEP and EGSPM, and the new models are more conducive. However, this will not work for some cases. Therefore, we establish a new model that combines AMFEP and EGSPM, in which the evolution path between the local government and the central government can tend to converge to a stable focus. Finally, the local government is more likely to carry out the ER strategy, while the central government tends to show a weak willingness to supervise. This represents an improvement over the previous models, confirming that the combined AMFEP–EGSPM mechanism offers a more effective approach to guiding the central government in policy implementation in practice.

We provide the following guidance for the hybrid model adoption: First, simultaneously implementing AMFEP and EGSPM incurs significant administrative costs, including environmental monitoring systems, performance evaluation frameworks, and institutional reforms for self-accountability. These costs are not incorporated into our current model, and therefore, comprehensive cost-benefit analysis remains a key direction for future research. Policymakers should weigh these additional costs against expected environmental benefits when choosing between a single mechanism or a hybrid model. Second, the external validity of our findings depends on specific circumstances. Our model assumes a hierarchical governance structure with close central and local administrative links, best representing the situation in unitary states. In economies with limited institutional capacity and restricted technological monitoring, the expected effectiveness of AMFEP and EGSPM may be significantly reduced. Therefore, the hybrid model is best suited for centralized governance systems with sufficient fiscal and administrative resources. Adjustments and empirical calibrations to the model are needed for different political or developmental contexts. In future studies, researchers should prioritize cross-national comparative studies, empirical verification using real-world data, and incorporating implementation costs into the model framework to achieve more cost-effective policy optimization.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

Feng Gu is a guest editor for the special issue of the ERA and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

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