

Article

Research on Environmental Pollution Control Based on Tripartite Evolutionary Game in China's New-Type Urbanization

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Abstract: The inconsistency of interests among local governments, polluting companies, and the public reduces the efficiency of environmental pollution control, posing a significant challenge in harmonizing these interests to achieve environmental sustainability in China's new-type urbanization. To elucidate the strategic decision-making rules of each party in environmental pollution control, this study constructs a tripartite evolutionary game model and analyzes the evolutionary stable strategies (ESS), identifying the influencing factors of the parties' strategies. Subsequently, numerical simulations are used to examine the asymptotic stability of various ESS and the effects of parameter variation on these ESS. The results indicate the existence of optimal ESS wherein all three parties adopt environmentally friendly strategies. Specifically, local governments can mitigate expenses for polluting companies to implement low-pollution strategies, while concurrently facilitating public participation in pollution control. Public participation can enhance the supervisory capabilities of local governments and exert a positive influence on polluting companies. Furthermore, the simulation results suggest that the ESS of the parties can evolve into the expected ESS by adjusting the influencing factors reasonably, thereby supporting environmental sustainability in China's new-type urbanization.

Keywords: environmental pollution control; tripartite evolutionary game; numerical simulation; new-type urbanization



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1. Introduction

Over the past 40 years, China's rapid urbanization has facilitated economic development and enhanced living standards. However, this urbanization process has also been accompanied by population growth, industrial agglomeration, and increased energy consumption. Under the constraints of limited resource carrying capacity, these phenomena pose significant challenges to China's ecological environment, considering the limited carrying capacity of land resources [1,2]. Consequently, environmental pollution has become a critical factor hindering the sustainable development of urbanization. The Chinese government has implemented the National New-type Urbanization Plan, which advocates the complete integration of ecological civilization concepts into the urbanization process. The primary objectives of new-type urbanization encompass sustainable development. Despite the early implementation of numerous regulations by both central and local governments to mitigate environmental pollution, the results have remained largely unsatisfactory. Air and water pollution persistently degrade quality of life, frequently precipitating environmental emergencies [3]. These suboptimal results stem from the insufficient enforcement of the environmental regulations [4,5]. The enforcement of these regulations frequently clashes with the interests of multiple stakeholders [6], making environmental governance challenging during China's new-type urbanization process. Consequently, pollution incidents recurrently emerge across diverse regions [7,8].

The effectiveness of environmental pollution control in new-type urbanization is influenced by various parties, including local governments, polluting companies, and the public. Local governments assume a pivotal role in this regard, primarily through regulatory measures aimed at controlling pollutant emissions from industries and facilitating their transition to more sustainable practices [9,10]. Strict regulations have been shown to significantly enhance environmental sustainability [5]. Polluting companies, by virtue of their production activities, constitute the principal source of environmental pollution in new-type urbanization settings [11]. These companies, driven largely by economic considerations, make decisions regarding the adoption of pollution abatement technologies based on cost–benefit analyses while operating under the oversight of local governments [12]. It is noteworthy that some small and medium-sized township polluting companies may individually contribute little pollution, but collectively they can cause significant pollution, posing challenges for local governments in terms of supervision [13]. Consequently, these companies may engage in highly polluting production due to a fluke mentality. Furthermore, the public directly experiences the consequences of environmental pollution. They can exert pressure on local governments to strengthen environmental supervision. Additionally, the public may choose to boycott products from highly polluting companies, thereby employing a “vote with their feet” strategy to discourage high-pollution companies [14–16]. The conflicting interests among local governments, polluting companies, and the public diminish the effectiveness of environmental pollution control. This discord poses a substantial challenge to harmonizing the parties’ behaviors in favor of environmental sustainability.

Numerous scholars have investigated strategies to enhance environmental pollution control behaviors among stakeholders. By establishing an evolutionary game model, Fan et al. determined that, under conditions fostering stable cooperation, polluting firms progress more rapidly toward clean production when local governments increase subsidies for environmental costs [17]. Sun et al. concluded that greater incentives from the central government significantly enhance the likelihood that local governments and companies adopt environmentally friendly strategies. The primary influencing factors include the intensity of central government supervision, the cost–benefit analysis of local government oversight, and the financial implications of environmental investments by polluting firms [18]. Conversely, Mahmoudi and Rasti-Barzoki analyzed the impact of varied governmental oversight policies, including taxes, subsidies, and tariffs, on corporate environmental performance [19]. Awaga et al. developed an evolutionary game model for polluting companies to choose whether to implement green production mode when the government implements two different mechanisms of reward and punishment, and the results show that companies’ green production behavior needs the guidance and supervision of the government [20]. These studies provide valuable theoretical foundations for regulating environmental pollution control behaviors.

Nevertheless, the multifaceted initiative of new-type urbanization, which integrates urbanization rates, economic restructuring, environmental protection, and policy management, exerts a significant influence on stakeholders in environmental pollution control. China’s new-type urbanization may lead to failures in pollution control, but it also presents substantial opportunities to enhance these efforts. Specifically, local governments may opt to relax environmental supervision to boost urbanization rates and economic growth, or alternatively, they may strive to achieve a simultaneous balance of economic, social, and environmental development. New-type urbanization not only elevates the public’s income but also augments their environmental consciousness and transforms green consumption patterns [13,21]. The imperative to adapt industrial structures and upgrade within the framework of new-type urbanization significantly affects polluting companies, similarly to the trend toward green consumption encouraged by new-type urbanization [22,23]. Companies with lower pollution levels are poised to capitalize on greater market opportunities, whereas those unable to adapt might face market losses [24]. Consequently, it becomes

imperative to develop a tripartite evolutionary game model to investigate environmental pollution control issues within the ambit of China's new-type urbanization.

Based on the evolutionary game theory, this study establishes a $2 \times 2 \times 2$ asymmetric evolutionary game model composed of three parties: local governments, polluting companies, and the public. In this study, the replicator dynamic equation is used to explore the behavior evolution laws of each party and the conditions for the tripartite behavior strategies to reach a stable state in new-type urbanization. Then, numerical simulation experiments are used to simulate the influence process of the changes in the factors on the evolution results. The purpose of this study is to provide a theoretical basis and useful references for breaking through the current environmental pollution control dilemma, alleviating the conflicts among the parties and improving the efficiency of environmental pollution control in China's new-type urbanization.

2. Model Assumptions and Symbol Description

2.1. Description of the Model

Local governments, polluting companies, and the public belong to three groups with different interest preferences, meaning the environmental pollution control results will find it difficult to meet expectations [25]. While local governments consider overall interests, they should balance economic benefits, social benefits, and environmental pollution control when making decisions [26]. Occasionally, to encourage investment for economic growth, local governments may relax environmental standards and overlook excessive emissions from companies [27]. This can lead to a perception of collusion between local governments and highly polluting companies [17]. Factors such as supervision costs and efficiency also influence the behavior of local governments [28]. Due to the externality of environmental pollution, polluting companies are more inclined to maximize their own profits when considering the relationship among the influence of local governments' supervision, fines, environmental subsidies, and pollution treatment costs [18,29]. In addition, many empirical studies have shown that environmental supervision pressures from customers, stakeholders, and social organizations also have impacts on the environmental strategies of polluting companies [30,31]. Finally, the public is more inclined to individual interests (i.e., health, job opportunities) [32,33]. Economic development and environmental pollution both have an impact on the subjective well-being of the public [34,35]. Economic level, environmental awareness, and education degree also affect the degree of public participation [22]. Public participation can help lower the supervision costs, encourage strict supervision strategies through increased accountability to local governments, and incentivize polluting companies to implement low-pollution strategies by offering potential losses like reduced reputation and market sales. Correspondingly, China's new-type urbanization has promoted the improvement of the public's environmental awareness and consumption structure. The demand for green and environmentally friendly products has increased, and low-pollution companies can obtain additional market benefits [23].

In summary, local governments' environmental supervision behaviors, polluting companies' pollution behaviors, and the public's participation behaviors are constantly adjusted under different conditions of economy, environment, and other parties' strategies. Each party in the game is continuously adjusting the original choices to obtain the optimal strategy in the process of mutual exploratory learning and imitation. It can be seen that the environmental pollution control of new-type urbanization is essentially a multi-party evolutionary game participated in by local governments, polluting companies, and the public. The relationship among the three parties for environmental pollution control is shown in Figure 1.

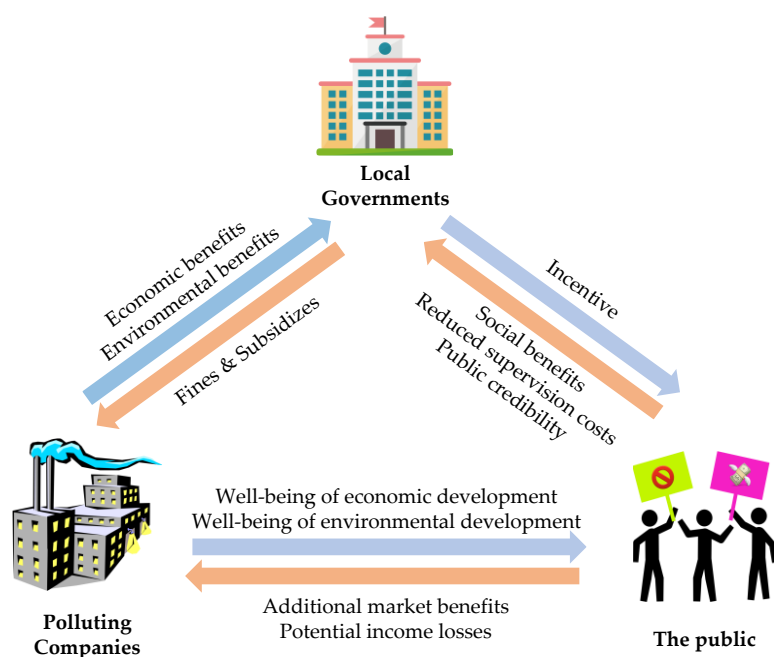


Figure 1. The relationship among the three parties for environmental pollution control in China's new-type urbanization.

2.2. Model Assumptions and Symbolic Assumptions

Hypothesis 1. The local governments, polluting companies, and the public are bounded rational. Due to the limited cognitive ability, all parties in the game constantly adjust their original choices through mutual learning and imitation to obtain the optimal strategies.

Hypothesis 2. The local governments' behavior strategies set $S_1 = \{\text{strict supervision, negative supervision}\}$, the polluting companies' behavior strategies set $S_2 = \{\text{low pollution, high pollution}\}$, and the public's behavior strategies set $S_3 = \{\text{participation, non-participation}\}$.

Hypothesis 3. The probability of local governments choosing strict supervision strategies is x and the probability of negative supervision strategies is $1 - x$. The probability of polluting companies choosing low-pollution strategies is y and the probability of choosing high pollution strategies is $1 - y$. The probability of the public choosing participation strategies is z and the probability of choosing non-participation strategies is $1 - z$.

It is assumed that the basic benefits of the local governments include basic economic benefits (E_0). When the local governments strictly supervise, the cost of supervision is C_0 , the additional environmental benefits are R , and the additional social benefits are S , whereas the negative supervision strategy leads to additional economic benefits (E) and public credibility loss (W_1). When polluting companies reduce their pollution levels, additional market benefits (U) arise from increased demand for green and environmentally friendly products. The compliance costs for low-pollution production are C_1 , and there is no cost during high-pollution production, but there may be fines (F), and the government will also incentivize the polluting companies to meet the emission standard by subsidizing (P). When polluting enterprises engage in high pollution, public participation will lead to a decline in reputation and sales, resulting in potential income loss (W_2) for polluting enterprises. The public will have a certain sense of subjective happiness when their material level is improved due to economic development. When the environment is damaged, the subjective well-being of the public will decrease, and the higher the level of economic development, the more the public pays attention to environmental pollution. It is assumed that the impact of economic development and environmental pollution on subjective well-

being is a positive correlation with the economic level, and the coefficients are a_1 and a_2 sequentially. When the public participates in environmental pollution control, they can oppose environmental pollution through letters, complaints, etc., or receive compensation sufficient to compensate for environmental losses, with corresponding costs (C_2). The participation of the public can reduce the supervision costs of the local government (C_3). The government can incentivize public participation by rewards (T) to reduce the public's participation costs. The descriptions of each parameter are listed in Table 1.

Table 1. Parameter descriptions of the evolutionary game model.

Parties	Parameters	Descriptions
Local governments	E_0	Basic economic benefits
	R	Additional environmental benefits due to positive supervision
	S	Additional social benefits due to positive supervision
	E	Additional economic benefits due to negative supervision
	C_0	Supervision costs of local governments
	C_3	Reduced supervision costs due to the public participation
Polluting companies	W_1	Public credibility losses due to negative supervision
	U	Additional market benefits for low pollution
	C_1	Compliance costs for low pollution
	F	Fines imposed by local governments for high pollution
	P	Subsidizes for low pollution from local governments
The public	W_2	Potential income losses due to public participation e.g., reputation & sales
	C_2	Participation costs
	T	Incentive for the public participation
	a_1	Well-being perception related to economic development
	a_2	Well-being perception related to environment development

Based on the above assumptions, a tripartite evolutionary game model of environmental pollution control formed by local governments, polluting companies, and the public is constructed. There are eight strategies sets of the tripartite evolutionary game, as shown in Figure 2.

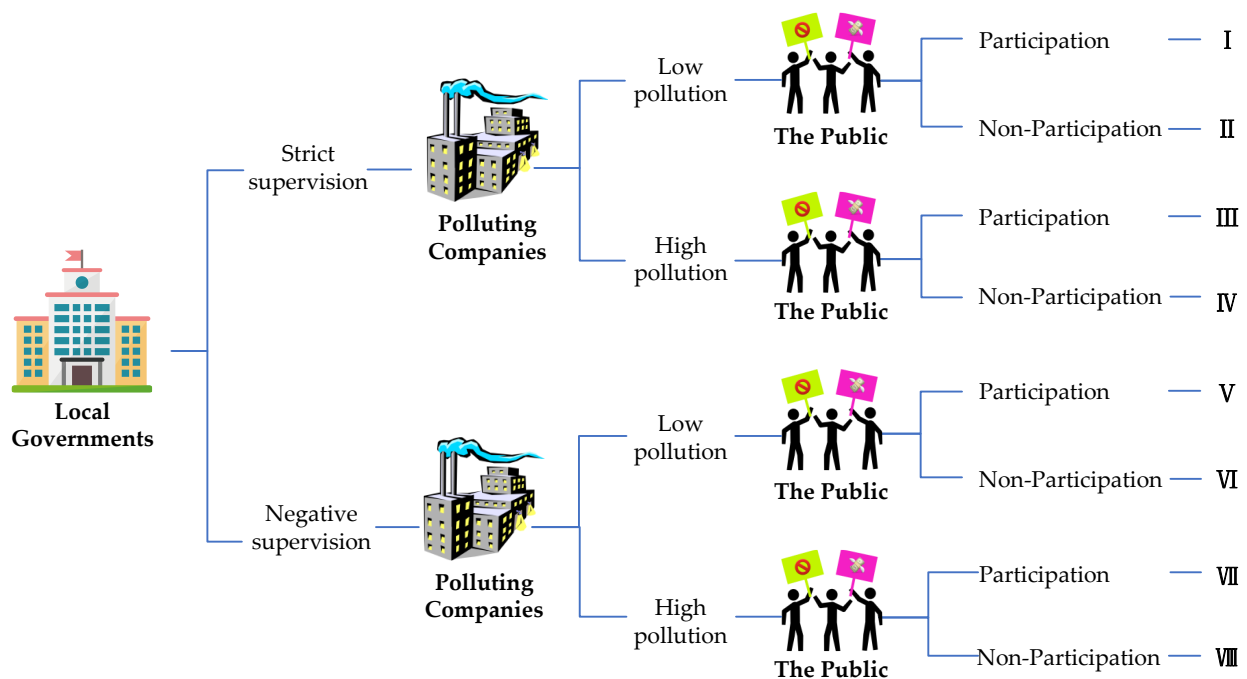


Figure 2. Schematic diagram of the tripartite evolutionary game and the strategies sets.

The payment and income matrix of the tripartite evolutionary game model are derived as shown in Table 2.

Table 2. Payment and income matrix of the tripartite evolutionary game model.

Options	Strategies Combination	Local Governments	Polluting Companies	The Public
I	(x, y, z)	$R + S - C_0 + C_3 - T - P$	$U - C_1 + P$	$a_1 E_0 - C_2 + T$
II	(x, y, 1 - z)	$R + S - C_0 - P$	$-C_1 + P$	$a_1 E_0$
III	(x, 1 - y, z)	$R + S - C_0 + C_3 + F - T$	$-W_2 - F$	$a_1 E_0 - C_2 + T$
IV	(x, 1 - y, 1 - z)	$R + S - C_0 + F$	$-F$	$a_1 E_0 - a_2 E_0$
V	(1 - x, y, z)	$E - W_1$	$U - C_1$	$a_1(E_0 + E) - C_2$
VI	(1 - x, y, 1 - z)	$E - W_1$	$-C_1$	$a_1(E_0 + E)$
VII	(1 - x, 1 - y, z)	$E - W_1$	$-W_2$	$a_1(E_0 + E) - C_2$
VIII	(1 - x, 1 - y, 1 - z)	$E - W_1$	0	$a_1(E_0 + E) - a_2(E_0 + E)$

3. Model Analysis

3.1. Expected Returns and Average Group Returns of Three Parties in Evolutionary Game Model

- (1) Assuming that the expected return and the average group return of local governments choosing strict supervision are M_{1y} and M_1 , respectively.

$$M_{1y} = yz(R + S - C_0 + C_3 - T - P) + (1 - y)z(R + S - C_0 + C_3 + F - T) + y(1 - z)(R + S - C_0 - P) + (1 - y)(1 - z)(R + S - C_0 + F) \quad (1)$$

$$M_1 = x\{M_{1y}\} + (1 - x)\left\{ \begin{array}{l} yz(E - W_1) + (1 - y)z(E - W_1) \\ + y(1 - z)(E - W_1) + (1 - y)(1 - z)(E - W_1) \end{array} \right\} \quad (2)$$

- (2) Assuming that the expected return and the average group return of the polluting companies choosing low pollution are M_{2y} and M_2 , respectively.

$$M_{2y} = xz(U - C_1 + P) + x(1 - z)(-C_1 + P) + (1 - x)z(U - C_1) + (1 - x)(1 - z)(-C_1) \quad (3)$$

$$M_2 = y\{M_{2y}\} + (1 - y)\{xz(-W_2 - F) + x(1 - z)(-F) + (1 - x)z(-W_2)\} \quad (4)$$

- (3) Assuming that the expected return and the average group return of the public choosing participation are M_{3y} and M_3 , respectively.

$$M_{3y} = xy(a_1 E_0 - C_2 + T) + x(1 - y)(a_1 E_0 - C_2 + T) + (1 - x)y(a_1(E_0 + E) - C_2) + (1 - x)(1 - y)(a_1(E_0 + E) - C_2) \quad (5)$$

$$M_1 = x\{M_{1y}\} + (1 - x)\left\{ \begin{array}{l} yz(E - W_1) + (1 - y)z(E - W_1) \\ + y(1 - z)(E - W_1) + (1 - y)(1 - z)(E - W_1) \end{array} \right\} \quad (6)$$

3.2. Evolutionary Stable Strategy Based on the Replicator Dynamics Equation

- (1) Replicator dynamics equation and stability analysis of local governments' strategies of strict supervision.

$$F(x) = \frac{dx}{dt} = x(M_{1y} - M_1) = x(1 - x)[R + S - C_0 - E + F + W_1 - y(F + P) + z(C_3 - T)] \quad (7)$$

$$\text{Let } z^* = \frac{C_0 + E - R - S - F - W_1 + y(F + P)}{C_3 - T} \quad (8)$$

- (i) When $z = z^*$, $F(x) \equiv 0$, indicating that x is stable for any value;

- (ii) When $z \neq z^*$, $x = 0$ and $x = 1$ may serve as two equilibrium points of x . The first derivative of $F(x)$ is as follows:

$$\frac{dF(x)}{dx} = (1 - 2x)[R + S - C_0 - E + F + W_1 - y(F + P) + z(C_3 - T)] \quad (9)$$

If $z > z^*$, then $x = 1$ is the stable point;

If $z < z^*$, then $x = 0$ is the stable point.

The dynamic evolutionary trends of local governments are shown in Figure 3. The upper and lower parts bounded by the surface Q_1 : $z^* = \frac{C_0 + E - R - S - F - W_1 + y(F + P)}{C_3 - T}$ of the square are denoted as K_{11} and K_{12} . When the relationships formed by y , z , and the parameters in the initial state of the game model conforms to the expression of z^* , the behavior strategies of the local governments remain unchanged regardless of the value of x , as depicted in Figure 3a. In the case where the initial state falls within the space K_{11} , as shown in Figure 3b, indicating $z > z^*$, the ultimate strategies of the local governments after the evolution of the system are strict supervision. Conversely, if the initial state is within the space K_{12} , the final strategies of the local governments is negative supervision, as demonstrated in Figure 3c.

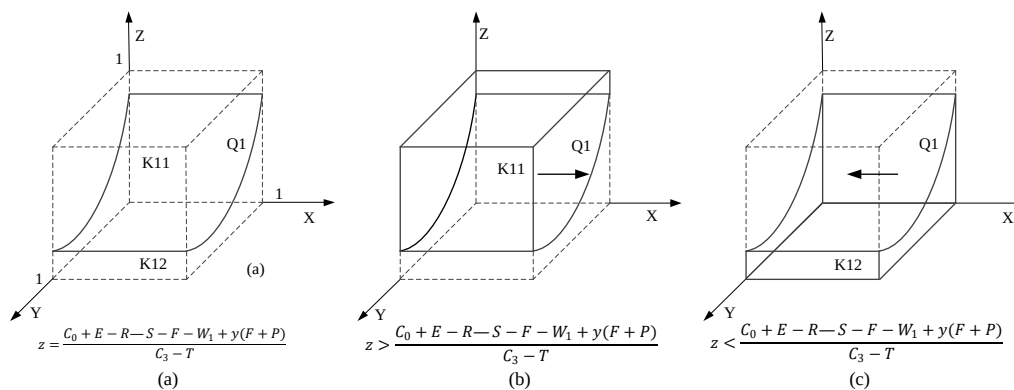


Figure 3. Replicator dynamics phase diagram of local governments. (a) Evolutionarily trend when $z = z^*$; (b) Evolutionarily trend when $z > z^*$; (c) Evolutionarily trend when $z < z^*$.

Based on the expression of the surface Q_1 , it can be seen that the decision of local governments to adopt strict supervision strategies is influenced by various factors such as supervision costs (C_0), the additional environmental benefits (R) and social benefits (S) caused by strict supervision, the additional economic benefits caused by negative supervision (E), fines (F), subsidies for low pollution (P), public participation cost (C_3), credibility loss (W_1), and incentives for public participation (T). Additionally, the probability of pollution from companies (y) and the probability of public participation (z) also play a role in determining the strategies of local governments. As the parameter z^* decreases, the likelihood of z exceeding z^* increases, leading to a higher chance of local governments transitioning toward adopting strict supervision strategies.

- (2) Replicator dynamics equation and stability analysis of polluting companies' strategies of low pollution.

$$F(y) = \frac{dy}{dt} = y(M_{2y} - M_2) = y(1 - y)[z(U + W_2) - C_1 + x(F + P)] \quad (10)$$

$$\frac{dF(y)}{dy} = (1 - 2y)[z(U + W_2) - C_1 + x(F + P)] \quad (11)$$

$$\text{Let } x^* = \frac{C_1 - z(U + W_2)}{F + P} \quad (12)$$

If $x = x^*$, then $F(y) \equiv 0$, indicating that y is stable for any value;

If $x > x^*$, then $y = 1$ is the stable point;

If $x < x^*$, then $y = 0$ is the stable point.

The dynamic evolution trends of the polluting companies are shown in Figure 4. The right and left parts bounded by the surface Q_2 : $x^* = \frac{C_1 - z(U + W_2)}{F + P}$ of the square are denoted as K_{21} and K_{22} . When the relationship formed by x , z , and other parameters in the initial state of the game conforms to the expression of x^* , the behavior strategies of the polluting companies remain unchanged regardless of the value of y , as shown in Figure 4a. In the case where the initial state falls within the space K_{21} , as shown in Figure 4b, indicating $x > x^*$, the ultimate strategies of the polluting companies after the evolution of the system are low pollution, otherwise. Conversely, if the initial state is within the space K_{22} , it means $x < x^*$, and the final strategies of polluting companies are high pollution, as demonstrated in Figure 4c.

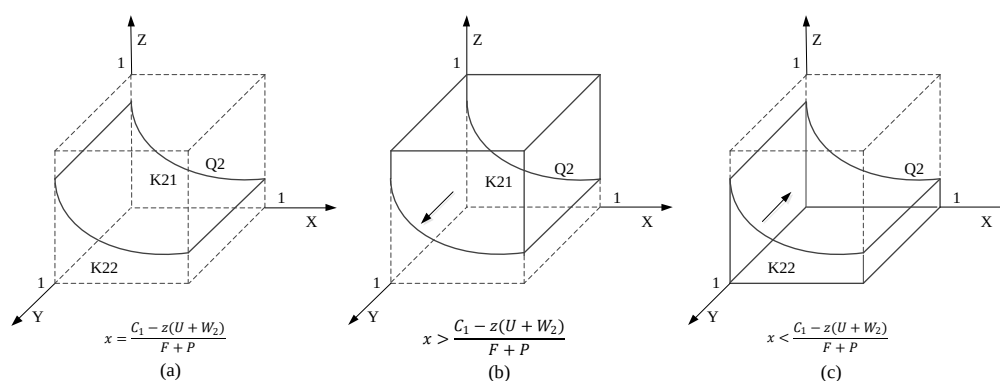


Figure 4. Replicator dynamics phase diagram of polluting companies. (a) Evolutionarily trend when $x = x^*$; (b) Evolutionarily trend when $x > x^*$; (c) Evolutionarily trend when $x < x^*$.

The analysis of the surface Q_2 suggests that the decision of polluting companies to adopt low-pollution strategies is influenced by various factors. These include additional market benefits (U), the costs of compliance for low pollution (C_1), potential income loss (W_2), fines (F), government subsidies for low pollution (P), as well as the likelihood of strict supervision by local governments (x) and public participation (z). The relationship between each parameter and x^* is consistently monotonic. Specifically, as C_1 decreases and W_2 , F , and P increase, the value of x^* decreases, creating more room for K_{22} and a higher chance that polluting companies will transition toward adopting low-pollution strategies in the context of China's new-type urbanization.

(3) Replicator dynamics equation and stability analysis of the public's strategies of participation.

$$F(z) = \frac{dz}{dt} = z(M_{3y} - M_3) = z(1 - z)[-C_2 + (1 - y)a_2E_0 + (1 - x)(1 - y)a_2E_0 + xT] \quad (13)$$

$$\frac{dF(z)}{dz} = (1 - 2z)[-C_2 + (1 - y)a_2E_0 + (1 - x)(1 - y)a_2E_0 + xT] \quad (14)$$

$$\text{Let } y^* = 1 - \frac{C_2 - xT}{a_2E_0 + (1 - x)a_2E} \quad (15)$$

If $y = y^*$, then $f(z) \equiv 0$, indicating that z is stable for any value;

If $y > y^*$, then $z = 0$ is the stable point;

If $y < y^*$, then $z = 1$ is the stable point.

The dynamic evolutionary trend of the public is shown in Figure 5. The front and back parts bounded by the surface Q_3 : $y^* = 1 - \frac{C_2 - xT}{a_2E_0 + (1 - x)a_2E}$ of the square are denoted as K_{31} and K_{32} . When the relationship formed by x , y , and the parameters in the initial state of the game conforms to the expression of x^* , the behavior strategies of the public remain unchanged regardless of the value of x , as depicted in Figure 5a. In the case where the

initial state falls within the space K_{31} , as shown in Figure 5b, indicating $y > y^*$, the ultimate strategies of the public after the evolution of the system are non-participation. Conversely, if the initial state is within the space K_{32} , it means $y < y^*$, and the final strategies of the public are participation, as demonstrated in Figure 5c.

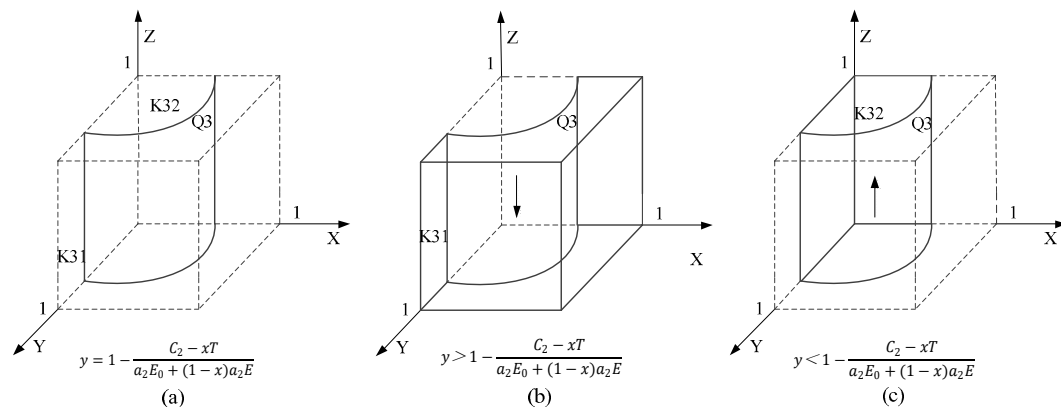


Figure 5. Replicator dynamics phase diagram of the public. (a) Evolutionarily trend when $y = y^*$; (b) Evolutionarily trend when $y > y^*$; (c) Evolutionarily trend when $y < y^*$.

The expression of the surface Q_3 suggests that the parameter a_1 does not significantly impact evolutionary outcomes. This implies that the public is not willing to sacrifice the environment to pursue the improvement of their own economical level. Conversely, the higher the level of economic development, the higher the possibility of public participation in environmental pollution control. As the economy ($E_0 + E$) grows, there is a gradual shift toward public participation in environmental protection. The decision of the public to adopt participation strategies are primarily influenced by factors such as participation costs (C_2), incentives for public participation (T), the perception coefficient of environmental pollution (a_2), the likelihood of strict supervision by local governments (x), and the probability of low pollution by companies (y). The relationship between each parameter and the optimal pollution level (y^*) is consistently monotonic. Decreasing C_2 , while increasing T and a_2 , leads to a decrease in y^* , creating more space for K_{32} . Consequently, there is a higher likelihood of the public eventually evolving toward participating in environmental pollution control in China's new-type urbanization.

Based on the analysis provided, adjustments to parameters can impact the other two parties' strategic decisions, potentially leading to indirect changes in other parties' strategies. The effects of each parameter modification on the evolution of all parties' strategies within the system is detailed in Table 3.

Table 3. The influence of various influencing factors in tripartite evolutionary strategies.

Parameter Change	Phase Diagram Volume Change	Change Direction of Evolution Results
R increase	K_{11} enlarge	$x \rightarrow 1$
S increase	K_{11} enlarge	$x \rightarrow 1$
W_1 increase	K_{11} enlarge	$x \rightarrow 1$
C_3 increase	K_{11} enlarge	$x \rightarrow 1$
P increase	K_{12} enlarge, K_{21} enlarge	$x \rightarrow 0, y \rightarrow 1$
F increase	K_{11} enlarge, K_{21} enlarge	$x \rightarrow 1, y \rightarrow 1$
U increase	K_{21} enlarge	$y \rightarrow 1$
W_2 increase	K_{21} enlarge	$y \rightarrow 1$
a_2 increase	K_{32} enlarge	$z \rightarrow 1$
C_2 increase	K_{32} enlarge	$z \rightarrow 1$
E_0 increase	K_{32} enlarge	$z \rightarrow 1$
T increase	K_{12} enlarge, K_{32} enlarge	$x \rightarrow 0, z \rightarrow 1$

Additionally, Table 3 illustrates that fines (F), subsidies (P), and incentives for public participation (T) will impact two different parties simultaneously. Fines (F) can promote $x \rightarrow 1$ and $y \rightarrow 1$, with positive effects for both, aiding in the effective implementation of environmental pollution control. However, the determination of fines (F) must also consider the influence of supervision costs and efficiency. It can be challenging to supervise small and medium-sized township-polluting companies, placing limitations on its effectiveness. The increase in environmental subsidies (P) can promote the adoption of low-pollution strategies by polluting companies ($y \rightarrow 1$), while the increase in incentives for public participation (T) can promote public participation in environmental pollution controls ($z \rightarrow 1$). However, the financial pressure on local governments from environmental investments may hinder strict government oversight. In reality, local governments often lack sufficient environmental subsidies (P) and incentives for public participation (T). Therefore, increasing environmental subsidies and incentives can effectively encourage polluting companies to adopt low-pollution strategies and promote public participation in environmental initiatives.

3.3. Analysis of Evolutionary Strategies Stability

According to the analysis of the replicator dynamics equations, the strategies of the parties are influenced by various factors, which in turn are determined by the behavior strategies adopted by each party. Therefore, it is necessary to examine the conditions for the system to form the ESS. In a multi-group evolutionary game with a replicator system, the ESS of the system must be a combination of the ESS of all parties. According to scholars' research, the stability of the equilibrium point of the evolutionary system can be determined by the Jacobian matrix local evolutionary stability analysis method [35–37]. It is further known that only eight pure strategies may exist in the tripartite evolutionary game, and no ESS exist for mixed strategies [22,38–40]. Therefore, the upcoming analysis will explore whether stable solutions exist for the eight pure strategies.

Take the strategies combination (1,1,1) as an example to discuss the condition of ESS. The Jacobian matrix of the system is as follows:

$$J = \begin{pmatrix} \frac{dF(x)}{dx} & 0 & 0 \\ 0 & \frac{dF(y)}{dy} & 0 \\ 0 & 0 & \frac{dF(z)}{dz} \end{pmatrix} \quad (16)$$

If this strategies combination (1,1,1) wants to state, all eigenvalues of the matrix should be less than 0, i.e., they need to satisfy the following:

$$\begin{cases} \lambda_1 = \frac{dF(x)}{dx} | (1, 1, 1) < 0 \\ \lambda_2 = \frac{dF(y)}{dy} | (1, 1, 1) < 0 \\ \lambda_3 = \frac{dF(z)}{dz} | (1, 1, 1) < 0 \end{cases} \quad (17)$$

The evolutionary stability conditions of the remaining seven pure strategies are determined in a similar manner. The criteria for judging the ESS of the eight pure strategies in the tripartite evolutionary game are then derived as presented in Table 4.

It can be seen from Table 4 that the equilibrium strategies (0,1,1) and (0,1,0) are unable to achieve a stable state. According to the evolutionary stability conditions of the equilibrium strategy (0,1,1), when polluting companies adopt low-pollution strategies, the public will not participate in environmental pollution control without suffering environmental losses, so the strategy (0,1,1) cannot form a stable state. Similarly, strategy (0,1,0) is unlikely to stabilize due to pollution treatment costs associated with low-pollution strategies compared to profit-maximizing high-pollution strategies in the absence of strict government oversight and public involvement. In the absence of local governments' strict supervision and the lack of public participation, polluting companies are bound to adopt high-pollution strategies to reach the goal of profit maximization. Thus, it is difficult for (0,1,0) to form a stable state in the end.

Table 4. Determination conditions of each stable strategy in tripartite evolutionary game.

Equilibrium Strategy	Evolutionary Stability Conditions	Stability
(1, 1, 1)	$R + S - C_0 - E + W_1 - P + C_3 - T > 0; -C_1 + U + F + W_2 + P > 0; C_2 - T < 0$	ESS
(1, 1, 0)	$R + S - C_0 - E + W_1 - P > 0; -C_1 + F + P > 0; -C_2 + T < 0$	ESS
(1, 0, 1)	$R + S - C_0 - E + W_1 + F + C_3 - T > 0; -C_1 + U + W_2 + F + P < 0; -C_2 + a_2E_0 + T > 0$	ESS
(1, 0, 0)	$R + S + W_1 - C_0 - E + F > 0; -C_1 + F + P < 0; -C_2 + a_2E_0 + T < 0$	ESS
(0, 1, 1)	$R + S + W_1 - C_0 - E - P + C_3 - T < 0; -C_1 + U + W_2 > 0; C_2 < 0$	Unstable
(0, 0, 1)	$R + S + W_1 - E + F + C_3 - T < 0; -C_1 + U + W_2 < 0; -C_2 + a_2E_0 + a_2E > 0$	ESS
(0, 1, 0)	$R + S + W_1 - C_0 - E - P < 0; C_1 < 0; -C_2 < 0$	Unstable
(0, 0, 0)	$R + S + W_1 - C_0 - E + F < 0; -C_1 < 0; -C_2 + a_2E_0 + a_2E < 0$	ESS

The game can achieve six ESS (1, 1, 1), (1, 1, 0), (1, 0, 1), (1, 0, 0), (0, 0, 1), (0, 0, 0) under specific conditions. For example, when the environmental benefits ($R + S + W_1 + C_3$) under local governments' strict supervision are greater than the costs ($E + C_0 + T + P$), and the benefits ($U + W_2 + P - C_1$) obtained from low pollution of polluting companies are greater than the costs (C_1), and the public can get incentives or costs compensation ($C_2 < T$) under their participation in environmental pollution control, the game will eventually evolve over time into a stable state ESS (1,1,1) with local governments' strict supervision, polluting companies' low pollution, and public participation.

Important conclusions regarding environmental pollution control in China's new-type urbanization can be drawn from the formation conditions of ESS and their implications, as analyzed through the tripartite evolutionary game model.

- Local governments play a crucial role in enforcing environmental pollution control. When local governments adopt negative supervision, two stable states emerge: ESS (0,0,0) and ESS (0,0,1). This implies that if local governments adopt negative supervision strategies, polluting companies may always choose high-pollution strategies regardless of whether the public engages in participation strategies.
- Under the strict supervision of the local governments, two evolutionary stable strategies are observed: ESS (1,0,1) and ESS (1,0,0). Despite strict supervision by local governments, polluting companies may still engage in high-pollution strategies due to factors such as fines (F), subsidies (P), potential income loss (W_2), and incentives (T) being insufficient for public participation, leading to environmental pollution control outcomes falling short of expectations.
- The conditions for ESS (1,1,1) and ESS (1,0,1) demonstrate that public participation can effectively enhance local government supervision and curb high-pollution strategies by polluting companies. Therefore, ESS (1,1,1) represents the most optimal state; especially through cooperation among the three parties, local governments can provide subsidies for polluting companies and incentives for public participation to enhance their motivation in environment pollution control. In return, the participation of the public can reduce the supervision costs of the local governments and provide a larger market for low-polluting enterprises. At the same time, polluting companies can provide economic development for local governments and the public, thereby maximizing the overall benefits.

However, the performance of environmental pollution control is determined by various factors mentioned above, so that the tripartite game results often reach a stable state in other unfavorable strategies. In order to guide the parties toward desired strategies, numerical

simulations are used to clarify evolution paths among different ESS, and offer a scientific basis for aligning the interests of all involved parties in China's new-type urbanization.

4. Numerical Simulation Analysis

The analysis of the game model reveals that the behavior strategies of each party are primarily influenced by the parameters. To further investigate the behavior strategies selection patterns and evolution paths of environmental pollution control parties in new-type urbanization, a simulation analysis was conducted using the MATLAB 7.6 simulation platform. The parties in the model are bounded rational due to their knowledge and information acquisition. The parties evaluate the costs and benefits of different behavior strategies based on their own understanding when making decisions. To enable quantification, all parameters in this study are normalized to a range of 0 to 1. A value of 0 indicates the smallest weight of payment/income representation for that parameter during decision-making, while a value of 1 indicates the largest. The weight increases continuously with the value.

The parameters forming the ESS (0,0,0) were chosen as the initial values of the simulation in order to thoroughly examine the influence of each parameter on the evolution results and the mutual transformation among the stable strategies. Taking into account the conditions for forming ESS (0,0,0) [$z < z^*$, $y < y^*$, $x > x^*$] and the actual background, the following assumptions were made:

The weight of environmental indicators in the performance appraisal is small, resulting in smaller additional environmental benefits (R) and social benefits (S) compared to additional economic benefits (E) when local governments implement strict supervision versus negative supervision ($R = 0.2$, $S = 0.1$, $E = 0.5$). In cases of negative supervision, local governments provide low incentives to both polluting companies and the public ($P = 0.2$, $T = 0.2$). Assuming environmental supervision control costs (C_0) are 0.3, polluting companies' costs incurred for equipment replacement and pollutant treatment (C_1) are 0.8, potential market benefits (U) for low pollution are 0.1, and fines for high pollution (F) are 0.2. High participation costs for the public due to barriers in participation channels ($C_2 = 0.6$) can be offset by reducing local government supervision costs ($C_3 = 0.3$) through public participation. The influence of local governments' credibility ($W_1 = 0.3$) and companies' pollution situation ($W_2 = 0.1$) is low. The public's well-being perception of environmental benefits is weak, represented by $a_2E_0 = 0.3$ ($a_2 = 0.3$, $E_0 = 1$). These probabilities of all parties adopting strict supervision, low-pollution strategies, and participation strategies are $x = 0.4$, $y = 0.5$, and $z = 0.6$, respectively.

The dynamic equation model is numerically simulated using MATLAB 7.6, and the evolution results are depicted in Figure 6. As shown in Figure 6, as the number of evolutionary iteration steps increases, the values of x , y , and z gradually decrease and approach 0, indicating that the stable strategies for the evolution of the interaction behavior of the parties are ESS (0,0,0). Taking into account the initial parameters, the local governments are expected to choose the negative supervision strategies, the pollution companies are likely to choose the high-pollution strategies, and the public is anticipated to choose the non-participation strategies.

Changes in the influencing factors can result in mutations of stable strategies. Therefore, based on the ESS (0,0,0), the impact of each parameter's changes based on the results of the evolutionary game is further examined by adjusting the magnitude of the parameters as follows:

As indicated in Table 4, this study found that local governments' supervision strategies are influenced by R, F, W_1 , and C_3 . To further validate this inference, the above parameters were increased individually. Specifically, if reset $R = 0.5$, $S = 0.4$, $F = 0.5$, $W_1 = 0.5$, and $C_3 = 0.5$ while keeping other variables constant, then $z > z^*$, $y < y^*$, and $x > x^*$. The evolution results are ESS (1,0,0), as shown in Figure 7. The results indicate that increasing additional environmental benefits (R), additional social benefits (S), fines (F), public credibility loss (W_1), and reduced supervision costs (C_3) led to a shift toward strict supervision strategies.

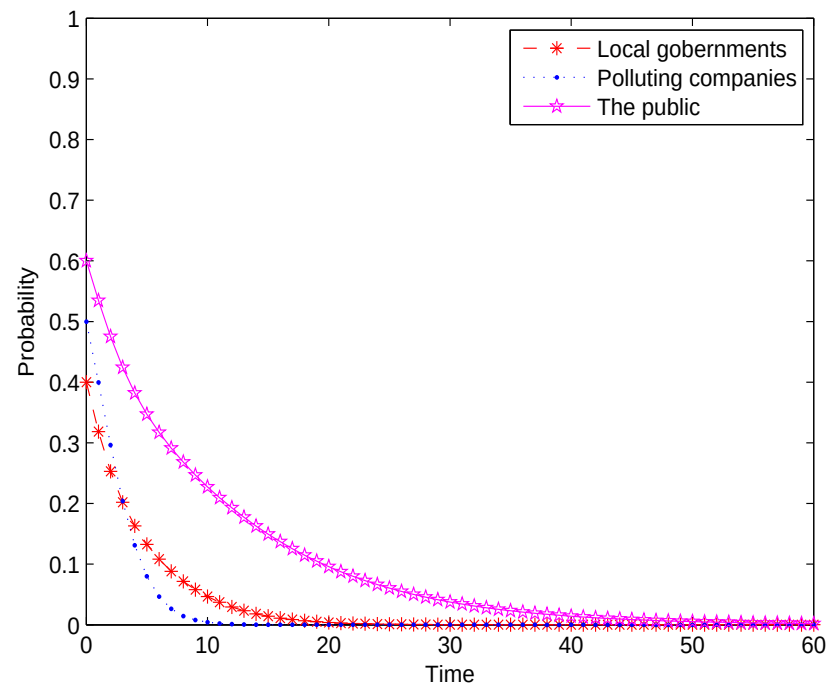


Figure 6. The evolution results based on the initial parameters.

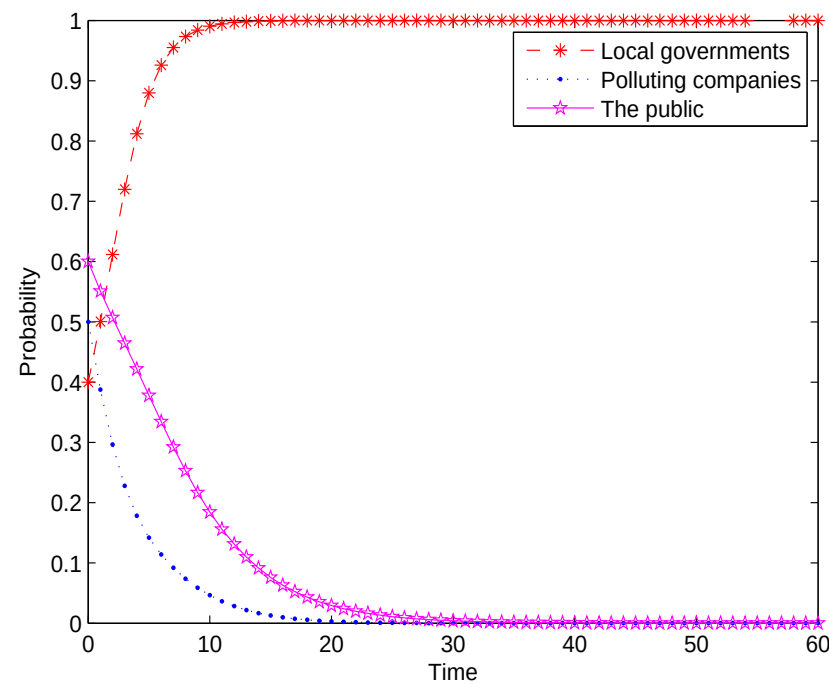


Figure 7. The evolution results after adjusting R , S , F , W_1 , and C_3 based on ESS (0,0,0).

The strategies of polluting companies are influenced by W_2 , F , and P . Therefore, based on the parameters of ESS (1,0,0), W_2 , F , and P are increased to $W_2 = 0.2$, $F = 0.6$, $U = 0.2$, and $P = 0.4$, which satisfies $z > z^*$, $x > x^*$, and $y > y^*$. The obtained simulation results are ESS (1,1,0), as shown in Figure 8. In other words, potential income loss due to public participation (W_2), coupled with higher fines (F) and increased subsidies (P), can drive polluting companies to shift toward actively engaging in environmental pollution control.

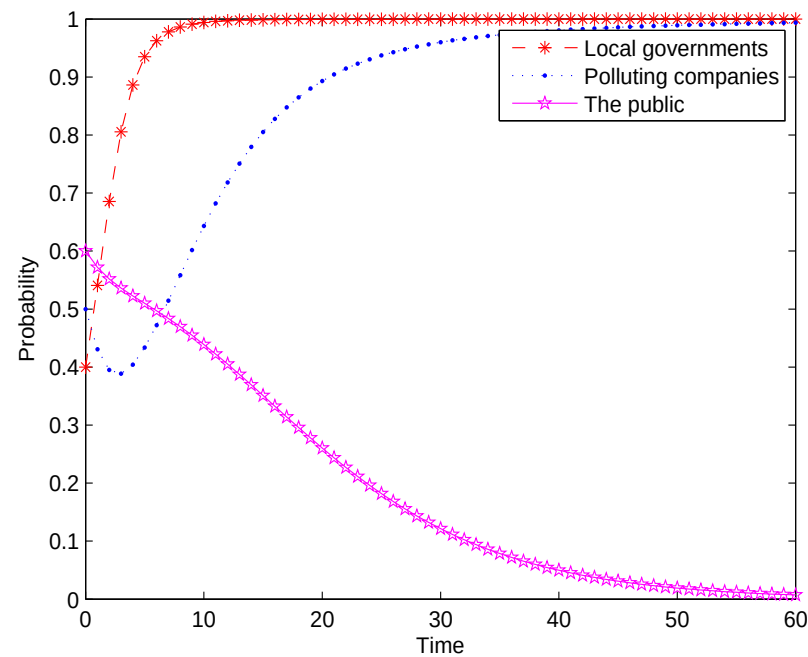


Figure 8. The evolution results after adjusting U , W_2 , F , and P based on ESS (1,0,0).

The strategies of the public are influenced by T , a_2 , and C_2 . Therefore, based on the initial parameters of ESS (0,0,0), reset $T = 0.3$, $a_2 E_0 = 0.6$, and $C_2 = 0.2$, which satisfies $z < z^*$, $y < y^*$, and $x < x^*$. The evolution results are ESS (0,0,1), as shown in Figure 9. That is to say, by increasing the incentives for public participation (T), increasing well-being perception of environmental benefits (a_2), and reducing the public participation cost (C_2), the public can be prompted to continue to actively participate in environmental pollution control.

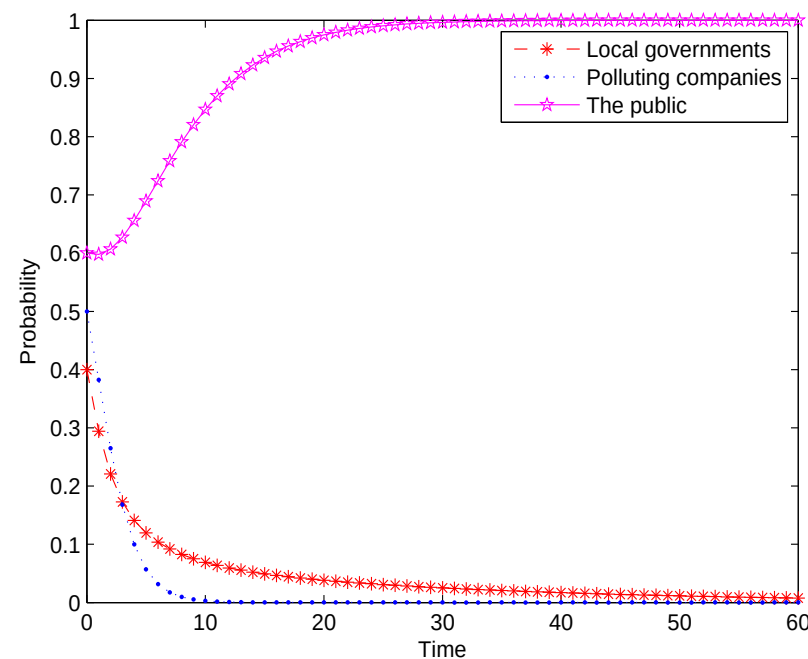


Figure 9. The evolution results after adjusting T , a_2 , and C_2 based on ESS (0,0,0).

Similarly, adjusting the values of R , F , W_1 , and C_3 based on the conditions of the ESS (0,0,1) can lead to a change in the evolutionary game outcome from ESS (0,0,1) to ESS (1,0,1), as illustrated in Figure 10.

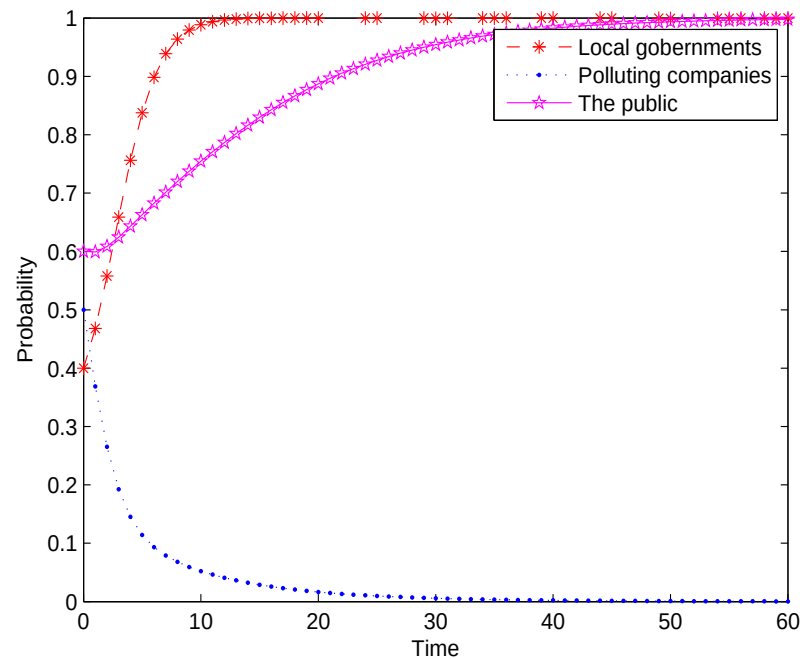


Figure 10. The evolution results after adjusting R , F , W_1 , and C_3 based on ESS (0,0,1).

Finally, based on the initial parameters of the ESS (0,0,0), adjusting parameters to change in the expected direction at the same time can guide the results of the system evolution game to change from ESS (0,0,0) to ESS (1,1,1), as illustrated in Figure 11.

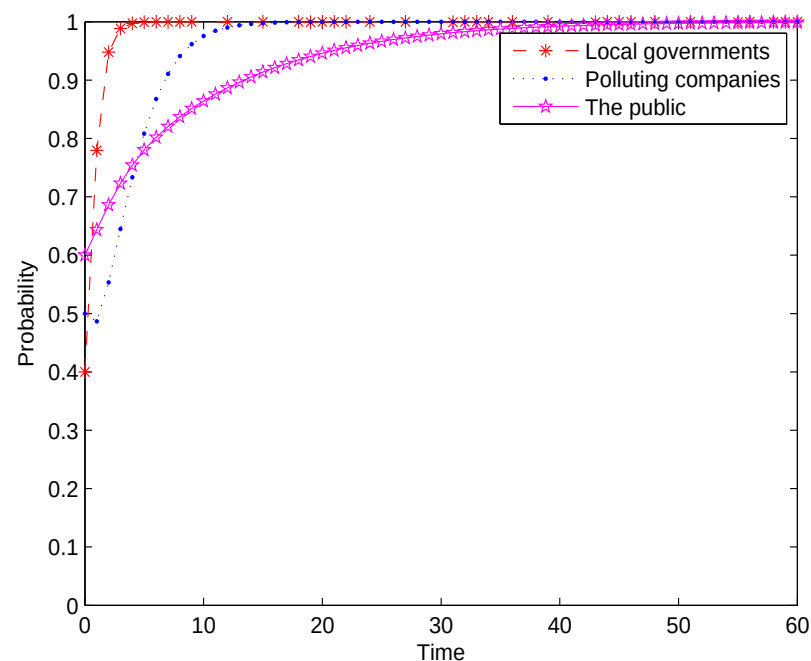


Figure 11. The evolution results after adjusting above parameters simultaneously from ESS (0,0,0).

Therefore, the mutual transformation laws among the stable strategies can be derived based on the influence of the aforementioned parameters on the evolution outcomes, as illustrated in Figure 12. There are six stable states that correspond to actual environmental pollution control scenarios. By adjusting different influencing factors through policies, the current stable state can be transitioned toward a target state that supports environmental pollution control in China's new-type urbanization.

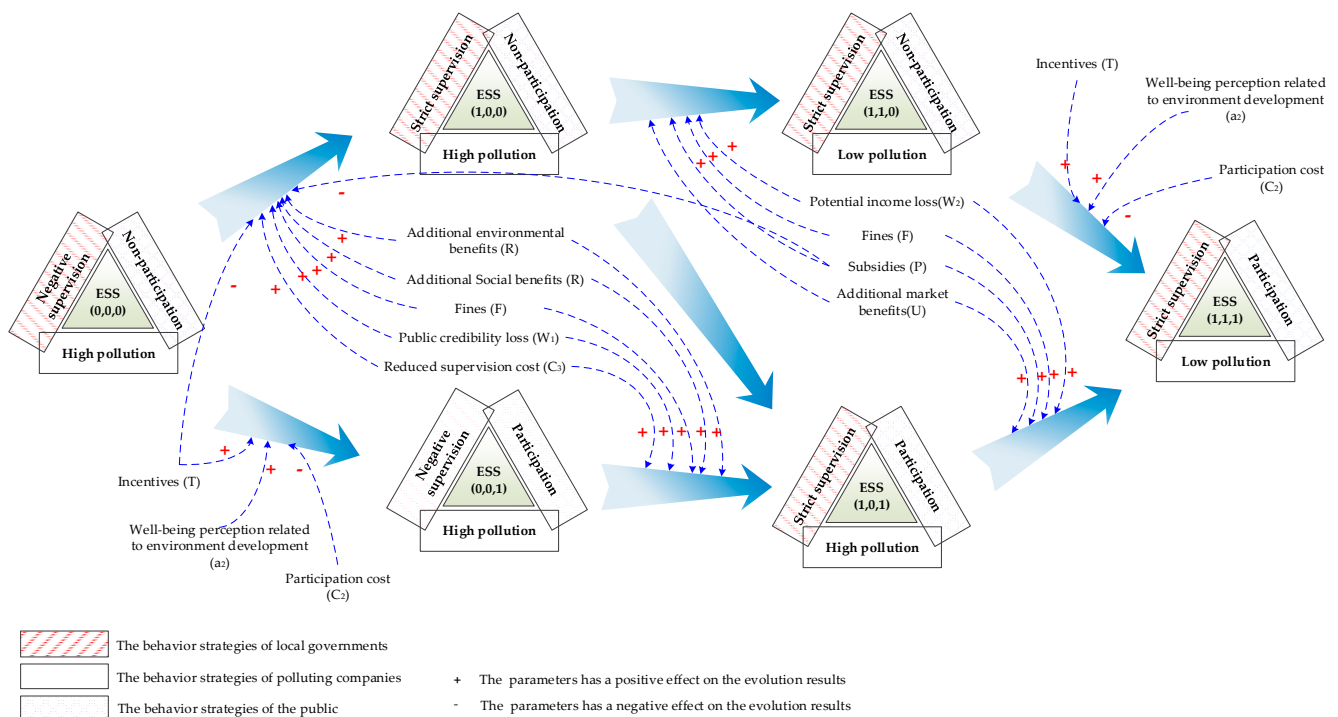


Figure 12. Evolutionary paths among stable strategies for environmental pollution control.

5. Conclusions

This study explores the concept of bounded rationality among various parties and introduces a tripartite evolutionary game model involving local governments, polluting companies, and the public. The model expands on the traditional two-dimensional game model by adding a third dimension. The research systematically examines the evolutionary process and decision-making behaviors of each party, leading to the following research conclusions:

- (1) The system's ESS may undergo sudden shifts as influencing factors continue to change during the process of environmental management. The supervision role of local governments can shift from negative to positive with improvements in factors such as additional environmental and social benefits, public credibility loss, and reduced supervision costs. Similarly, the behavioral strategies of polluting companies and the public can change based on related factors. By understanding the transformation paths among these stable states, a theoretical foundation can be established to guide the evolution of environmental pollution behaviors toward desired strategies.
- (2) Local governments play a crucial role in environmental pollution control in China's new-style urbanization. When local governments adopt negative supervision, two stable states emerge: ESS (0,0,0) and ESS (0,0,1). Without government regulatory policies and incentive measures for polluting enterprises and the public, it will be very difficult for polluting enterprises to establish stable low-pollution strategies. Thus, the central government should establish a performance evaluation system aimed at sustainable development, appropriately increasing the weight of environmental quality indicators within this system. Additionally, it should enhance the environmental monitoring system involving public participation and strengthen the oversight of local governments' actions in controlling environmental pollution.
- (3) The cooperation among various parties in environmental pollution control can effectively address conflicting interests in China's new-style urbanization. The strategies of local governments can help reduce the costs for polluting companies to adopt low-pollution measures, while also enabling public participation in environmental pollution control. The public's participation can enhance the supervisory efficiency

of local governments and impose a positive influence on the environmental strategies of polluting companies. By working together, these three parties can maximize their respective interests and encourage environmentally friendly practices, resolving challenges in balancing economic, environmental, and social development, balancing companies' transformation and pursuit of profitability, and ultimately promoting the sustainable development of China's new-type urbanization.

This study examines the behavior strategies of parties involved in environmental pollution control using evolutionary game theory and numerical simulations. It is important to note that the model relies on hypothetical parameters, which is useful for theoretical exploration but may not fully capture the complexities and variances found in real-world scenarios. Future research should focus on conducting empirical analyses to understand the behavioral tendencies and decision-making processes of parties, which can help identify the challenges and barriers they face in implementing pollution control measures. For example, case studies from various regions and sectors can help to understand how contextual factors influence the effectiveness of pollution control measures in China's new-type urbanization.

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