

Article

Governance of Toxic Metal Pollution in China's Farmland Soil: A Quadrilateral Evolutionary Game Analysis

Xinpei Qiao ^{1,2} , Mengyue Xu ¹, Xiao Fan ^{1,3,*}, Jingyuan Sun ¹ and Yuchao Li ⁴

¹ School of Business Administration, China University of Petroleum-Beijing at Karamay, Karamay 834000, China; 2032723@pcu.ac.kr (X.Q.)

² School of Accountancy, Shanghai University of Finance and Economics, Shanghai 200433, China

³ School of Economics, Central University of Finance and Economics, Beijing 102206, China

⁴ School of Economics and Management, Xinjiang University, Urumqi 830002, China

* Correspondence: 2024563309@cupk.edu.cn; Tel.: +86-188-5380-3231

Abstract

Toxic metal pollution in farmland soils has become a critical environmental issue threatening land security and agricultural sustainability. This study develops an evolutionary game model involving the government, enterprises, the public, and environmental public-interest organizations to analyze the dynamic interactions underlying multi-actor governance. By combining equilibrium analysis with numerical simulations, the study examines the conditions for collaborative governance and the effects of key parameters on the system's evolution. The results reveal a stage-based trajectory: weak regulation and limited participation in the early stage lead to persistent illegal discharge; strengthened government intervention and rising social participation in the transitional stage promote more coordinated supervision, although enterprises may still behave non-compliantly; in the mature stage, favorable cost–benefit conditions induce enterprises to adopt compliant treatment, reducing reliance on continuous external oversight. Further analysis shows that effective incentive and deterrence mechanisms are essential for activating multi-actor responses, while enterprises' strategies are mainly driven by pollution-control costs, expected returns, and potential losses, and social participation depends on monitoring costs, expected benefits, and government support. Initial strategy distributions have limited influence on long-term outcomes. These findings provide policy-relevant insights for improving institutional design and strengthening collaborative governance in the management of toxic metal pollution in China's farmland soils.

Keywords: toxic metal pollution; farmland soils; evolutionary game; collaborative governance; incentive and deterrence mechanisms



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1. Introduction

As the foundation of the agricultural production system, farmland soil serves as a vital resource base for ensuring food security and ecological stability in agriculture [1]. As the global population continues to grow amid increasing resource and environmental constraints, finite soil resources are expected to face intensifying pressure, with global food demand projected to be 35–56% higher by 2050 [2]. At the same time, soils worldwide are increasingly threatened by contamination from toxic substances, particularly toxic metals [3]. Toxic metals are non-degradable pollutants that accumulate in soils and can be transferred through the food chain, thereby amplifying long-term ecological and health risks [4]. The Food and Agriculture Organization of the United Nations (FAO) has pointed

out that, due to processes such as soil erosion, excessive pesticide use, and industrial pollution, about 90% of the world's soil resources may be under varying degrees of threat by 2050 [2].

Toxic metal pollution in soils is typically defined as the accumulation of these metals beyond ecological safety thresholds [5]. Toxic elements such as arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), and lead (Pb) can adversely affect plant growth and pose significant risks to human health through long-term dietary exposure [6]. Globally, toxic metal pollution affects 14% to 17% of cultivated land, amounting to approximately 242 million hectares, with Cd emerging as the most prominent contaminant, at an exceedance rate of roughly 9.0% [2]. Spatial distribution patterns indicate that hotspots are primarily concentrated along the eastern coast of Asia, while parts of Africa and Latin America also exhibit notable contamination levels. This pattern is driven by both natural geological conditions and intensive anthropogenic activities, including industrial emissions, mining operations, smelting, and agricultural production [7]. Notably, about 6.8% of global topsoil already exceeds the safety thresholds for human health and ecosystems [2]. Consequently, toxic metal pollution has evolved from a localized environmental issue into a transboundary risk, with the potential to spread through global agricultural trade [8].

In the Asia-Pacific region, toxic metal pollution in farmland soils is equally serious, presenting diverse challenges for countries in identifying polluters, risk control measures and developing governance plans [9]. Given its status as the world's largest developing nation, China faces particularly severe pressures in this regard. Driven by rapid industrialization and urbanization, the accumulation of toxic metals (e.g., Cd, Pb, and Hg) in farmland soils has emerged as a critical environmental and public health concern [10]. Toxic metal pollution in China directly leads to a reduction of about 10 billion kilograms each year and results in agricultural economic losses around 20 billion RMB [5]. Although the 2024 National Soil Environment Report shows some progress, such as a safe utilization rate of 92 per cent for polluted cultivated land and general decreases in toxic metal content at major monitoring points, the underlying risks associated with soil pollution remain far from fully resolved.

In 2025, China's State Council issued the Action Plan for Investigating and Remediating Hidden Environmental Safety Risks of Toxic Metals (2025–2030). This instruction targets key polluters directly and establishes an overall regulatory system that includes, but is not limited to, identification, assessment and establishment of long-term waste treatment sites. It signals a critical shift from isolated pollutant control to systematic governance. Despite these policy and technological advancements, the management of toxic metal pollution in farmland soils still faces severe practical constraints [11]. High remediation costs, long treatment cycles, and marked regional heterogeneity constrain the large-scale implementation of pollution control [12–14]. At the same time, pollution governance involves multiple stakeholders, including the government, enterprises, and the public, whose behavioral choices and strategic interactions are critical to governance effectiveness [15–18]. Although existing studies have made substantial progress in pollution assessment and remediation technologies, the dynamic evolutionary mechanisms underlying interactions among multiple actors remain underexplored. Grounded in multi-actor coordination and dynamic decision-making, this study simulates payoff and cost structures to examine how changes in regulatory intensity, incentives, and deterrence mechanisms influence the stability of strategic choices. Different from existing tripartite and quadripartite evolutionary game studies that mainly focus on equilibrium outcomes under fixed initial conditions, this study incorporates heterogeneous initial strategy settings by constructing high-probability and low-probability groups. This design enables a comparison of governance dynamics under different strategic starting points and allows evaluation of the robustness of evolutionary

outcomes. Furthermore, rather than treating equilibrium points as independent results, this study organizes stable outcomes into a stage-based governance evolution framework, revealing how governance gradually shifts from fragmented regulation to coordinated supervision and ultimately to self-sustaining enterprise compliance. By capturing both heterogeneous strategic conditions and dynamic governance transitions, this study extends evolutionary game analysis beyond static equilibrium interpretation and provides theoretical support and policy implications for improving governance efficiency in farmland soil toxic metal pollution control.

2. Literature Review

To explore the drivers of toxic metal pollution in farmland soils, Sun et al. [19] conducted a systematic assessment in the hilly basins of western Zhejiang. They found that toxic metal elements mainly originate from mixed sources, including natural inputs, agricultural activities, and transportation, reflecting the combined effects of anthropogenic and natural factors. In karst areas, Yang et al. [20] integrated source apportionment with health risk assessments, identifying mixed industrial-agricultural sources, natural sources, and mixed mining-atmospheric deposition as the primary contributors to pollution in farmland soils. They further noted that arsenic should be treated as a priority element for control. At the macro level, Hou et al. [2] constructed a global database of toxic metal pollution in soils using large-scale data, identifying that areas at high risks are clustered within the lower latitudinal zones of Eurasia. This spatial pattern is jointly driven by climate conditions, topographic features, and human activities. Their findings also indicate that mining, smelting, and industrial production further exacerbate toxic metal pollution in soils. Zhu et al. [6] emphasized that industrial operations, such as metal smelting and chemical production, introduce substantial quantities of toxic metals into soils, leading to the decline of soil quality and loss of ecosystem services, while existing remediation technologies still face practical limitations. Using data on toxic metal in soil from cities along the Yangtze River Economic Belt combined with a health risk assessment framework, Liang et al. [21] found significant spatial heterogeneity in soil toxic metal pollution, revealing that industrial activity, economic development, and population density are primary drivers of toxic metal accumulation. Regarding the risks to the food chain, Zwolak [22] argued that industrial production, transportation, and municipal wastewater are key pathways through which toxic metals enter soils, and that factors such as soil properties and plant types further influence the migration and transformation of toxic metals.

Zhou et al. [5] established a tripartite evolutionary game model of the government, polluting enterprises and external pollution control firms to study the governance patterns for toxic metals pollution in farmland soils through this mechanism. They found that penalty levels, regulatory costs, remediation costs, and government incentives are key determinants of the actors' strategic choices. Their further analysis suggests that governance dominated by a single party cannot effectively address soil pollution, highlighting a shift toward collaborative models involving various actors. Hou et al. [23] noted that current governance practices for soil pollution still struggle with inaccurate field surveys and a lack of proper risk assessment tools. Furthermore, the long-term effectiveness of existing remediation methods remains limited. To optimize the governance system, they called for a comprehensive management strategy encompassing the entire lifecycle, including investigation, assessment, risk control, and subsequent oversight. This approach further emphasizes the importance of advanced technology development and continuous monitoring under conditions of complex metal pollution. Xin et al. [24] found that toxic metal pollution in soils is mainly caused by industrial and agricultural activities. This finding indicates that beyond improving assessment, modeling, and regulatory standards, it is

also necessary to enhance remediation efficiency. Cai et al. [25] systematically compared methods for constructing pollution indices for toxic metals in soils. They argued that sensitivity and accuracy must be jointly considered in pollution assessments to provide methodological support for pollution identification and the governance decision-making process. Zhu et al. [6] reviewed the mechanisms of bioremediation technologies and their ideal conditions for use. The authors noted that relying on a single method often brings clear limitations in cost, stability, and overall applicability. By contrast, combining multiple approaches offers a highly effective strategy to boost overall remediation efficiency and lower energy consumption.

Existing research provides a solid foundation for understanding toxic metal contamination in agricultural soils. Previous studies successfully detail the various pollution sources, spatial patterns, and driving mechanisms. Scholars have also evaluated governance options through the lens of remediation technologies and regulatory policy. These evaluations rely heavily on tools like spatial analysis and health risk assessments to guide decisions. Nevertheless, existing studies on pollution governance still focus on centralized approaches or technical pathways. Despite the emergence of perspectives involving multiple actors, systematic analyses of more complex collaborative governance mechanisms remain scarce. Based on payoff and cost structures, this study constructs an evolutionary game model involving four players: the government, enterprises, the public, and environmental public-interest organizations. Through parameter simulations, it examines the strategic trajectories of these key players. Ultimately, this research contributes to the literature on multi-actor collaborative governance, providing robust theoretical foundations and policy insights for managing toxic metal pollution in farmland soils.

3. Model Assumptions and Framework

3.1. Evolutionary Game Strategy

Governing toxic metal pollution of farmland soils in China involves four main players: the government, polluting enterprises, environmental public-interest organizations and the public. Subject to institutional constraints and resource endowments, each player selects a strategy and updates it through repeated interactions based on payoff comparisons, thereby generating evolutionary dynamics [26].

The government has two available strategies: strict regulation and lax regulation. Under strict regulation, the government intensifies enforcement and increases inspection frequency, strictly enforces laws and regulations for the prevention and control of farmland soil pollution, conducts routine environmental monitoring and on-site inspections, and sanctions violators through fines, time-bound rectification orders, or license revocation [27]. In addition, by providing rewards for public reporting and subsidizing the costs of environmental public-interest litigation, the government encourages broader societal participation in oversight [28]. This regulatory posture increases the likelihood that corporate environmental violations are detected and penalized and improves governance outcomes, but it entails relatively high administrative and fiscal expenditures. Under lax regulation, by contrast, the government scales back enforcement and reduces penalty severity; deterrence weakens, and constraints on corporate environmental violations rely more on ex post remediation and publicly funded restoration than on high-intensity enforcement [29]. Although this approach can reduce short-term regulatory costs, it may erode institutional constraints and increase environmental risks.

Enterprises adopt one of two strategies: compliance or illegal discharge of toxic metals. Under the compliance strategy, enterprises comply with environmental laws and regulations, obtain the required regulatory permits, invest in pollution control and technological upgrading, adopt standardized treatment processes to control toxic metal

emissions, and submit to regulatory inspections [30]. Although compliance increases operating costs, it helps enterprises avoid administrative penalties and litigation exposure. Under the illegal strategy, enterprises evade compliance costs through illegal dumping, unauthorized burial, or excessive emissions, thereby contaminating farmland soils and securing short-term economic gains [31]. However, such conduct entails multiple oversight risks, notably government sanctions, public reporting, and environmental public-interest litigation. These risks may result in fines, compensation liabilities, and reputational losses.

Environmental public-interest organizations have two available strategies: initiating environmental public-interest litigation or refraining from litigation. Under the litigation strategy, the organizations incur costs for investigation and evidence collection, third-party testing, and legal procedures [32]. They pursue corporate accountability through judicial channels and promote remediation of farmland soil pollution. If litigation succeeds, the organizations may obtain reimbursement of litigation-related costs and reputational benefits, thereby strengthening external constraints on enterprises. Under the non-litigation strategy, the organizations avoid these direct expenditures but provide no judicial oversight. The relative attractiveness of non-litigation depends primarily on litigation costs and the level of governmental support.

The public has two available strategies: active reporting and non-reporting. Under active reporting, the public incurs information-collection and time costs, provides leads to regulators, thereby increasing the probability of detecting corporate environmental violations [33], and may receive reporting rewards. Under non-reporting, the public avoids participation costs, but corporate environmental violations may persist due to insufficient oversight. The level of public participation is jointly shaped by the design of reporting incentives and perceived environmental risk.

3.2. Strategy Probabilities and Parameter Definitions

In this study, all players are assumed to be boundedly rational and adjust their strategies through repeated interactions and evolutionary learning based on perceived utilities. Although real-world decisions are influenced by broader political, social, and institutional considerations, the evolutionary game framework represents these heterogeneous motivations through a unified utility structure to capture long-term strategic adaptation processes. Accordingly, the payoff terms in this model should be interpreted as generalized utilities rather than purely economic returns, encompassing both direct costs and benefits as well as implicit incentives such as political performance pressure, reputational concerns, environmental awareness, participation motivation, and institutional support. Under this interpretation, the bounded-rationality and utility-based assumptions provide a parsimonious yet analytically tractable approach for examining dynamic interactions in complex multi-actor environmental governance systems. The parameter settings are presented in Table 1.

In the governance system for toxic metal pollution in farmland soils, the government, environmental public-interest organizations, polluting enterprises, and the public constitute four boundedly rational players. Affected by information asymmetry and stochastic factors, the players make strategic choices to maximize their long-run expected payoffs and continuously adjust their behaviors through imitation and learning [34]. Based on evolutionary game theory, this study specifies the strategy proportions and model parameters for each player as follows:

The government adopts strict regulation with probability x and lax regulation with probability $1 - x$, where $x \in (0, 1)$. When an enterprise engages in illegal discharge and causes toxic metal pollution in farmland soils, the government incurs losses from deteriorating environmental quality, erosion of social trust, and reduced capacity for sustainable

agricultural development, denoted by L_g . If the government adopts strict regulation and detects the enterprise's illegal behavior, it can impose an administrative fine I on the enterprise. Under lax regulation, insufficient supervision allows pollution to accumulate, and the government must additionally bear soil remediation and governance costs for farmland soil pollution, denoted by C_n . The administrative enforcement cost required for strict regulation is denoted by C_g , whereas the expected benefit from environmental improvement and enhanced governmental credibility is denoted by R_g . Meanwhile, the government strengthens institutional constraints by incentivizing social oversight, providing a subsidy S_p to members of the public who actively report corporate environmental violations and a subsidy S_o to environmental public-interest organizations that initiate environmental public-interest litigation.

Table 1. Symbols and descriptions.

Parameter	Description
R_g	Expected payoff to the government
R_o	Expected payoff to environmental public-interest organizations
R_e	Expected payoff to polluting enterprises under normal production and operation
R_p	Expected payoff to the public
k	Discount factor for environmental losses caused by toxic metal pollution in farmland soils
S_p	Government subsidies to the public (reporting reward)
S_o	Government subsidies to environmental public-interest organizations
C_g	Regulatory cost incurred by the government
C_o	Cost incurred by environmental public-interest organizations
C_e	Pollution-control cost incurred by enterprises under compliance
C_p	Participation cost incurred by the public
C_n	Additional remediation cost borne by the government when illegal discharge contaminates farmland soils
L_g	Loss incurred by the government
L_o	Loss incurred by environmental public-interest organizations
L_e	Loss incurred by enterprises after illegal conduct is detected and sanctioned
L_p	Loss incurred by the public
I	Fine imposed by the government on enterprises for illegal discharge

Environmental public-interest organizations initiate environmental public-interest litigation with probability y and refrain from litigation with probability $1 - y$, where $y \in (0, 1)$. Initiating litigation entails costs for investigation and evidence collection, third-party testing, and legal procedures, denoted by C_o . If litigation succeeds, the organization obtains a positive expected payoff such as reputational gains and reimbursement of litigation-related costs, denoted by R_o . When illegal discharge by enterprises results in farmland soil pollution, environmental public-interest organizations incur an organizational credibility loss due to deteriorating environmental quality and a weakened oversight role, denoted by L_o .

Enterprises adopt compliant treatment of toxic metal pollutants with probability z and illegal discharge with probability $1 - z$, where $z \in (0, 1)$. Under compliance, enterprises incur pollution control and technological upgrading costs C_e and receive normal operating profits R_e . Under illegal discharge, enterprises obtain additional economic gains by avoiding compliance costs; if the illegal behavior is detected and sanctioned, they must pay the administrative fine I and incur reputational losses L_e .

The public adopts active reporting with probability m and non-reporting with probability $1 - m$, where $m \in (0, 1)$. Active reporting incurs information-collection and time costs C_p and yields a government reporting reward S_p as well as benefits from improved environmental quality, denoted by R_p . If enterprises engage in illegal discharge, the public incurs losses L_p due to farmland soil pollution and heightened food-safety risks.

Given the cumulative and long-term nature of environmental pollution, government regulatory effort can mitigate pollution-related damages. To capture this dynamic effect, we introduce an environmental-damage discount coefficient k , where $0 < k < 1$. Specifically, under a higher-intensity governance regime characterized by strict regulation and strengthened multi-actor oversight, the pollution-induced losses faced by all players are proportionally reduced. Accordingly, the environmental losses actually borne by the players are kL_g , kL_o , kL_e and kL_p , respectively. This specification captures the moderating role of regulatory stringency and multi-actor oversight in environmental-risk externalities.

4. Model Establishment and Solution

4.1. Model Establishment

In summary, the four-player evolutionary game yields 16 pure-strategy profiles, corresponding to all binary combinations of $(x, y, z, m) \in \{0, 1\}^4$: (x, y, z, m) , $(x, y, z, 1 - m)$, $(x, y, 1 - z, m)$, $(x, y, 1 - z, 1 - m)$, $(x, 1 - y, z, m)$, $(x, 1 - y, z, 1 - m)$, $(x, 1 - y, 1 - z, m)$, $(x, 1 - y, 1 - z, 1 - m)$, $(1 - x, y, z, m)$, $(1 - x, y, z, 1 - m)$, $(1 - x, y, 1 - z, m)$, $(1 - x, y, 1 - z, 1 - m)$, $(1 - x, 1 - y, z, m)$, $(1 - x, 1 - y, z, 1 - m)$, $(1 - x, 1 - y, 1 - z, m)$ and $(1 - x, 1 - y, 1 - z, 1 - m)$. Based on the evolutionary game model, Table 2 summarizes the strategy choices of the four players under the 16 pure-strategy scenarios.

Table 2. Strategy and return matrix.

Players		Enterprises Choose Compliance (z)		Enterprises Choose Illegal Discharge ($1 - z$)	
		Public Chooses Active Reporting (m)	Public Chooses Non-Reporting ($1 - m$)	Public Chooses Active Reporting (m)	Public Chooses Non-Reporting ($1 - m$)
Government adopts strict regulation (x)	Environmental public-interest organizations initiate environmental public-interest litigation (y)	$R_g - C_g - S_o - S_p,$ $R_o - C_o + S_o,$ $R_e - C_e,$ $R_p - C_p + S_p$	$R_g - C_g - S_o,$ $R_o - C_o + S_o,$ $R_e - C_e,$ R_p	$- C_n - C_g - k(L_g) + I - S_o - S_p,$ $- k(L_o) - C_o + S_o,$ $- k(L_e) - I,$ $- k(L_p) - C_p + S_p$	$- C_n - C_g - k(L_g) + I - S_o,$ $- k(L_o) - C_o + S_o,$ $- k(L_e) - I,$ $- k(L_p)$
	Environmental public-interest organizations refrain from litigation ($1 - y$)	$R_g - C_g - S_p,$ $R_o,$ $R_e - C_e,$ $R_p - C_p + S_p$	$R_g - C_g,$ $R_o,$ $R_e - C_e,$ R_p	$- C_n - C_g - k(L_g) + I - S_p,$ $- k(L_o),$ $- k(L_e) - I,$ $- k(L_p) - C_p + S_p$	$- C_n - C_g - k(L_g) + I,$ $- k(L_o),$ $- k(L_e) - I,$ $- k(L_p)$

Table 2. Cont.

Players		Enterprises Choose Compliance (z)		Enterprises Choose Illegal Discharge (1 – z)	
		Public Chooses Active Reporting (m)	Public Chooses Non-Reporting (1 – m)	Public Chooses Active Reporting (m)	Public Chooses Non-Reporting (1 – m)
Government adopts lax regulation (1 – x)	Environmental public-interest organizations initiate environmental public-interest litigation (y)	Rg, Ro – Co, Re – Ce, Rp – Cp	Rg, Ro – Co, Re – Ce, Rp	– Cn – k(Lg), – k(Lo) – Co, – k(Le), – k(Lp) – Cp	– Cn – k(Lg), – k(Lo) – Co, – k(Le), – k(Lp)
	Environmental public-interest organizations refrain from litigation (1 – y)	Rg, Ro, Re – Ce, Rp – Cp	Rg, Ro, Re – Ce, Rp	– Cn – k(Lg), – k(Lo), – k(Le), – k(Lp) – Cp	– Lg, – Lo, – Le, – Lp

4.2. Replication Dynamic Equation

Assume that M_{11} and M_{12} denote the government's expected payoffs under strict regulation and lax regulation, respectively, and let M_1 denote the government's average expected payoff. Based on the payoff matrix above, the government's replicator dynamic equation $F(x)$ is given by:

$$\begin{aligned}
 M_{11} &= yzm(Rg - Cg - So - Sp) + yz(1 - m)(Rg - Cg - So) + y(1 - z)m(-Cn - Cg - k(Lg) + I - So - Sp) + \\
 & y(1 - z)(1 - m)(-Cn - Cg - k(Lg) + I - So) + (1 - y)zm(Rg - Cg - Sp) + (1 - y)z(1 - m)(Rg - Cg) + (1 - y)(1 - \\
 & z)m(-Cn - Cg - k(Lg) + \\
 & I - Sp) + (1 - y)(1 - z)(1 - m)(-Cn - Cg - k(Lg) + I) \\
 M_{12} &= yzm(Rg) + yz(1 - m)(Rg) + y(1 - z)m(-Cn - k(Lg)) + y(1 - z)(1 - m)(-Cn - k(Lg)) + (1 - y)zm(Rg) + (1 \\
 & - y)z(1 - m)(Rg) + (1 - y)(1 - z)m(-Cn - k(Lg)) + (1 - y)(1 - z)(1 - m)(-Lg) \\
 M_1 &= -x(Cg + Cn - I + Lgk - Cnz + Spm + Iz - Rgz + Soy - Lgkz) - (x - 1)(Rgmyz + Lg(m - 1)(y - 1)(z - 1) \\
 & - m(Cn + Lgk)(y - 1)(z - 1) - y(Cn + Lgk)(m - 1)(z - 1) - Rgmz(y - 1) - Rgyz(m - 1) + Rgz(m - 1)(y - 1) + \\
 & my(Cn + Lgk)(z - 1)) \\
 F(x) &= dx/dt = x(x - 1)(Cg + Cn - I - Lg - Cnm + Lgk + Lgm - Cny - Cnz + Spm + Iz + Lgy + Lgz + Soy - \\
 & Lgkm + Cnmy + Cnmz - Lgky - Lgkz - Lgmy - Lgmz + Cnyz - Lgyz - Cnmyz + Lgkyz + Lgmyz + Lgkmyz \\
 & + Lgkmz - Lgkmyz)
 \end{aligned} \tag{1}$$

Assume that M_{21} and M_{22} denote the expected payoffs of environmental public-interest organizations when they initiate and refrain from environmental public-interest litigation, respectively, and that M_2 denotes their average expected payoff. Based on the payoff matrix above, the replicator dynamic equation for environmental public-interest organizations $F(y)$ is given by:

$$\begin{aligned}
M_{21} &= xzm(Ro - Co + So) + xz(1 - m)(Ro - Co + So) + x(1 - z)m(-k(Lo) - Co + So) + x(1 - z)(1 - m) \\
&\quad (-k(Lo) - Co + So) + (1 - x)zm(Ro - Co) + (1 - x)z(1 - m)(Ro - Co) + (1 - x)(1 - z)m(-k(Lo) - Co) + (1 - x)(1 - z)(1 - m)(-k(Lo) - Co) \\
M_{22} &= xzm(Ro) + xz(1 - m)(Ro) + x(1 - z)m(-k(Lo)) + x(1 - z)(1 - m)(-k(Lo)) + (1 - x)zm(Ro) + (1 - x)z(1 - m) \\
&\quad m(Ro) + (1 - x)(1 - z)m(-k(Lo)) + (1 - x)(1 - z)(1 - m)(-Lo) \\
M_2 &= -(y - 1)(Romxz + Lo(m - 1)(x - 1)(z - 1) - Romz(x - 1) - Roxz(m - 1) + Roz(m - 1)(x - 1) - Lokm(x - 1)(z - 1) - Lokx(m - 1)(z - 1) + Lokmx(z - 1)) - y(m(Co + Lok)(x - 1)(z - 1) - mxz(Ro - Co + So) - mz(Co - Ro)(x - 1) \\
&\quad - mx(z - 1)(Co - So + Lok) - (Co + Lok)(m - 1)(x - 1)(z - 1) + xz(m - 1)(Ro - Co + So) + z(Co - Ro)(m - 1)(x - 1) \\
&\quad + x(m - 1)(z - 1)(Co - So + Lok)) \\
F(y) &= dy/dt = y(y - 1)(Co - Lo + Lok + Lom + Lox + Loz - Sox - Lokm - Lokx - Lokz - Lomx - Lomz - Loxz \\
&\quad + Lokxz + Lomxz + Lokmx + Lokmz - Lokmxz)
\end{aligned} \tag{2}$$

Assume that M_{31} and M_{32} denote the expected payoffs of the public under active reporting and non-reporting, respectively, and that M_3 denotes their average expected payoff. Based on the payoff matrix above, the public's replicator dynamic equation $F(m)$ is given by:

$$\begin{aligned}
M_{31} &= xym(Re - Ce) + xy(1 - m)(Re - Ce) + x(1 - y)m(Re - Ce) + x(1 - y)(1 - m)(Re - Ce) + (1 - x)ym(Re - Ce) \\
&\quad + (1 - x)y(1 - m)(Re - Ce) + (1 - x)(1 - y)m(Re - Ce) + (1 - x)(1 - y)(1 - m)(Re - Ce) \\
M_{32} &= xym(-k(Le) - I) + xy(1 - m)(-k(Le) - I) + x(1 - y)m(-k(Le) - I) + x(1 - y)(1 - m)(-k(Le) - I) + (1 - x)ym(-k(Le)) \\
&\quad + (1 - x)y(1 - m)(-k(Le)) + (1 - x)(1 - y)m(-k(Le)) + (1 - x)(1 - y)(1 - m)(-Le) \\
M_3 &= -z(mxy(Ce - Re) - (Ce - Re)(m - 1)(x - 1)(y - 1) - mx(Ce - Re)(y - 1) - my(Ce - Re)(x - 1) - xy(Ce - Re)(m - 1) \\
&\quad + m(Ce - Re)(x - 1)(y - 1) + x(Ce - Re)(m - 1)(y - 1) + y(Ce - Re)(m - 1)(x - 1)) - (z - 1)(Le(m - 1)(x - 1)(y - 1) \\
&\quad - x(I + Lek)(m - 1)(y - 1) - mxy(I + Lek) + mx(I + Lek)(y - 1) + xy(I + Lek)(m - 1) - Lekm(x - 1)(y - 1) \\
&\quad - Leky(m - 1)(x - 1) + Lekmy(x - 1)) \\
F(z) &= dz/dt = -z(z - 1)(Le - Ce + Re - Lem + Ix - Lex - Ley + Lekm + Lekx + Leky + Lemx + Lemy + Lexy - Lekxy - Lemxy - Lekmx - Lekmy + Lekmxy)
\end{aligned} \tag{3}$$

Assume that M_{41} and M_{42} denote the expected payoffs of the public under active reporting and non-reporting, respectively, and that M_4 denotes their average expected payoff. Based on the payoff matrix above, the public's replicator dynamic equation $F(m)$ is given by:

$$\begin{aligned}
M_{41} &= xyz(Rp - Cp + Sp) + x(1 - y)z(Rp - Cp + Sp) + (1 - x)yz(Rp - Cp) + (1 - x)(1 - y)z(Rp - Cp) + xy(1 - z)(-k(Lp) - Cp + Sp) \\
&\quad + x(1 - y)(1 - z)(-k(Lp) - Cp + Sp) + (1 - x)y(1 - z)(-k(Lp) - Cp) + (1 - x)(1 - y)(1 - z)(-k(Lp) - Cp) \\
M_{42} &= xyz(Rp) + x(1 - y)z(Rp) + (1 - x)yz(Rp) + (1 - x)(1 - y)z(Rp) + xy(1 - z)(-k(Lp)) + x(1 - y)(1 - z)(-k(Lp)) \\
&\quad + (1 - x)y(1 - z)(-k(Lp)) + (1 - x)(1 - y)(1 - z)(-Lp) \\
M_4 &= -(m - 1)(Rpxyz + Lp(x - 1)(y - 1)(z - 1) - Rpxz(y - 1) - Rpyz(x - 1) + Rpz(x - 1)(y - 1) - Lpkx(y - 1)(z - 1) - Lpky(x - 1)(z - 1) + Lpkxy(z - 1)) \\
&\quad - m(y(Cp + Lpk)(x - 1)(z - 1) - xyz(Rp - Cp + Sp) - yz(Cp - Rp)(x - 1) - xy(z - 1)(Cp - Sp + Lpk) - (Cp + Lpk)(x - 1)(y - 1)(z - 1) + xz(y - 1)(Rp - Cp + Sp) + z(Cp - Rp)(x - 1)(y - 1) \\
&\quad + x(y - 1)(z - 1)(Cp - Sp + Lpk)) \\
F(m) &= dm/dt = m(m - 1)(Cp - Lp + Lpk + Lpx + Lpy + Lpz - Spx - Lpkx - Lpky - Lpkz - Lpxy - Lpxz - Lpyz + Lpkxy + Lpkxz + Lpkyz + Lpxyz - Lpkxyz)
\end{aligned} \tag{4}$$

4.3. Jacobian Matrix and Equilibrium Points

The quadrilateral evolutionary game converges to an equilibrium over time, at which $f(x) = 0$, $f(y) = 0$, $f(z) = 0$ and $f(m) = 0$. Because each player has two pure strategies (coded as 0 and 1), the system admits 16 candidate equilibrium points, namely $(0, 0, 0, 0)$,

(0, 0, 0, 1), (0, 0, 1, 1), (0, 1, 1, 1), (0, 1, 0, 1), (0, 1, 0, 0), (0, 1, 1, 0), (0, 0, 1, 0), (1, 0, 0, 0), (1, 0, 0, 1), (1, 0, 1, 1), (1, 1, 1, 1), (1, 1, 0, 1), (1, 1, 0, 0), (1, 1, 1, 0) and (1, 0, 1, 0). The Jacobian matrix of the quadrilateral evolutionary game is given by:

$$J = \begin{pmatrix} \frac{dF(x)}{dx} & \frac{dF(x)}{dy} & \frac{dF(x)}{dz} & \frac{dF(x)}{dm} \\ \frac{dF(y)}{dx} & \frac{dF(y)}{dy} & \frac{dF(y)}{dz} & \frac{dF(y)}{dm} \\ \frac{dF(z)}{dx} & \frac{dF(z)}{dy} & \frac{dF(z)}{dz} & \frac{dF(z)}{dm} \\ \frac{dF(m)}{dx} & \frac{dF(m)}{dy} & \frac{dF(m)}{dz} & \frac{dF(m)}{dm} \end{pmatrix} \quad (5)$$

Among them,

$$\begin{aligned} dF(x)/dx &= (x-1)(Cg + Cn - I - Lg - Cnm + Lgk + Lgm - Cny - Cnz + Spm + Iz + Lgy + Lgz + Soy - \\ &Lgkm + Cnmy + Cnmz - Lgky - Lgkz - Lgmy - Lgmz + Cnyz - Lgyz - Cnmyz + Lgkyz + Lgmyz + Lgkmy + \\ &Lgkmz - Lgkmyz) + x(Cg + Cn - I - Lg - Cnm + Lgk + Lgm - Cny - Cnz + Spm + Iz + Lgy + Lgz + Soy - \\ &Lgkm + Cnmy + Cnmz - Lgky - Lgkz - Lgmy - Lgmz + Cnyz - Lgyz - Cnmyz + Lgkyz + Lgmyz + Lgkmy + \\ &Lgkmz - Lgkmyz) \\ dF(x)/dy &= x(x-1)(Lg - Cn + So + Cnm - Lgk - Lgm + Cnz - Lgz + Lgkm - Cnmz + Lgkz + Lgmz - Lgkmz) \\ dF(x)/dz &= x(x-1)(I - Cn + Lg + Cnm - Lgk - Lgm + Cny - Lgy + Lgkm - Cnmy + Lgky + Lgmy - Lgkmy) \\ dF(x)/dm &= x(x-1)(Lg - Cn + Sp - Lgk + Cny + Cnz - Lgy - Lgz + Lgky + Lgkz - Cnyz + Lgyz - Lgkyz) \\ dF(y)/dx &= -y(y-1)(So - Lo + Lok + Lom + Loz - Lokm - Lokz - Lomz + Lokmz) \\ dF(y)/dy &= (y-1)(Co - Lo + Lok + Lom + Lox + Loz - Sox - Lokm - Lokx - Lokz - Lomx - Lomz - Loxz + \\ &Lokxz + Lomxz + Lokmx + Lokmz - Lokmxz) + y(Co - Lo + Lok + Lom + Lox + Loz - Sox - Lokm - Lokx - \\ &Lokz - Lomx - Lomz - Loxz + Lokxz + Lomxz + Lokmx + Lokmz - Lokmxz) \\ dF(y)/dz &= y(y-1)(Lo - Lok - Lom - Lox + Lokm + Lokx + Lomx - Lokmx) \\ dF(y)/dm &= y(y-1)(Lo - Lok - Lox - Loz + Lokx + Lokz + Loxz - Lokxz) \\ dF(z)/dx &= -z(z-1)(I - Le + Lek + Lem + Ley - Lekm - Leky - Lemy + Lekmy) \\ dF(z)/dy &= z(z-1)(Le - Lek - Lem - Lex + Lekm + Lekx + Lemx - Lekmx) \\ dF(z)/dz &= -(z-1)(Le - Ce + Re - Lem + Ix - Lex - Ley + Lekm + Lekx + Leky + Lemx + Lemy + Lexy - \\ &Lekxy - Lemxy - Lekmx - Lekmy + Lekmxy) - z(Le - Ce + Re - Lem + Ix - Lex - Ley + Lekm + Lekx + Leky \\ &+ Lemx + Lemy + Lexy - Lekxy - Lemxy - Lekmx - Lekmy + Lekmxy) \\ dF(z)/dm &= z(z-1)(Le - Lek - Lex - Ley + Lekx + Leky + Lexy - Lekxy) \\ dF(m)/dx &= -m(m-1)(Sp - Lp + Lpk + Lpy + Lpz - Lpky - Lpkz - Lpyz + Lpkyz) \\ dF(m)/dy &= m(m-1)(Lp - Lpk - Lpx - Lpz + Lpkx + Lpkz + Lpxz - Lpkxz) \\ dF(m)/dz &= m(m-1)(Lp - Lpk - Lpx - Lpy + Lpkx + Lpky + Lpxy - Lpkxy) \\ dF(m)/dm &= m(Cp - Lp + Lpk + Lpx + Lpy + Lpz - Spx - Lpkx - Lpky - Lpkz - Lpxy - Lpxz - Lpyz + Lpkxy + \\ &Lpkxz + Lpkyz + Lpxyz - Lpkxyz) + (m-1)(Cp - Lp + Lpk + Lpx + Lpy + Lpz - Spx - Lpkx - Lpky - Lpkz - \\ &Lpxy - Lpxz - Lpyz + Lpkxy + Lpkxz + Lpkyz + Lpxyz - Lpkxyz) \end{aligned} \quad (6)$$

The 16 equilibrium points are then substituted into the Jacobian matrix to obtain the corresponding eigenvalues. The eigenvalues, denoted by α_1 , α_2 , α_3 and α_4 , are reported in Tables 3 and 4 for the cases of strict regulation ($x = 1$) and lax regulation ($x = 0$), respectively. These equilibrium points represent all possible pure-strategy combinations generated by the quadrilateral evolutionary game framework; however, their stability properties differ according to the signs of the associated eigenvalues. Following Lyapunov stability criteria, equilibrium points with all eigenvalues having negative real parts are identified as locally asymptotically stable and interpreted as evolutionarily stable strategy (ESS) outcomes, whereas equilibrium points containing positive eigenvalues are regarded as unstable. As shown in Tables 3 and 4, eight equilibrium points satisfy the local stability condition, namely (0, 0, 0, 0), (0, 0, 0, 1), (0, 0, 1, 0), (0, 1, 0, 0), (1, 0, 0, 0), (1, 0, 0, 1), (1, 1, 0, 0), and (1, 1, 0, 1). Accordingly, the subsequent simulation and stage-based governance analysis are developed based on these stable equilibrium configurations.

Table 3. Equilibrium Points and Eigenvalues when the Government Adopts Strict Regulation ($x = 1$).

Equilibrium Points	$\alpha 1$	$\alpha 2$	$\alpha 3$	$\alpha 4$
(1, 0, 0, 0)	$Cg + Cn - I - Lg + Lgk$	$So - Co$	$I - Ce + Re + Lek$	$Sp - Cp$
(1, 0, 0, 1)	$Cg - I + Sp$	$So - Co$	$I - Ce + Re + Lek$	$Cp - Sp$
(1, 0, 1, 1)	$Cg + Sp$	$So - Co$	$Ce - I - Re - Lek$	$Cp - Sp$
(1, 0, 1, 0)	Cg	$So - Co$	$Ce - I - Re - Lek$	$Sp - Cp$
(1, 1, 1, 1)	$Cg + So + Sp$	$Co - So$	$Ce - I - Re - Lek$	$Cp - Sp$
(1, 1, 0, 1)	$Cg - I + So + Sp$	$Co - So$	$I - Ce + Re + Lek$	$Cp - Sp$
(1, 1, 0, 0)	$Co - So$	$Sp - Cp$	$Cg - I + So$	$I - Ce + Re + Lek$
(1, 1, 1, 0)	$Cg + So$	$Co - So$	$Ce - I - Re - Lek$	$Sp - Cp$

Table 4. Equilibrium Points and Eigenvalues when the Government Adopts Lax Regulation ($x = 0$).

Equilibrium Points	$\alpha 1$	$\alpha 2$	$\alpha 3$	$\alpha 4$
(0, 0, 0, 0)	$I - Cn - Cg + Lg - Lgk$	$Lo - Co - Lk$	$Le - Ce + Re$	$Lp - Cp - Lpk$
(0, 0, 0, 1)	$I - Cg - Sp$	$-Co$	$Re - Ce + Lek$	$Cp - Lp + Lpk$
(0, 0, 1, 1)	$-Cg - Sp$	$-Co$	$Ce - Re - Lek$	Cp
(0, 0, 1, 0)	$-Cg$	$-Co$	$Ce - Le - Re$	$-Cp$
(0, 1, 1, 1)	$-Cg - So - Sp$	Co	$Ce - Re - Lek$	Cp
(0, 1, 0, 1)	$I - Cg - So - Sp$	Co	$Re - Ce + Lek$	Cp
(0, 1, 0, 0)	$I - Cg - So$	$Co - Lo + Lok$	$Re - Ce + Lek$	$-Cp$
(0, 1, 1, 0)	$-Cg - So$	Co	$Ce - Re - Lek$	$-Cp$

5. Numerical Simulation Analysis

5.1. Parameter Simulation of Stability Point

For each equilibrium-point condition, we simulated the model under the parameter settings specified below. In the figure, each curve depicts the evolutionary trajectories of the government (x), environmental public-interest organizations (y), enterprises (z) and the public (m) under different initial states. To enhance the rigor of the simulations, we consider two enterprise initial-condition groups, namely a high-probability group and a low-probability group [26], and compare the strategy adjustments of the other three players across these two settings. Compared with conventional evolutionary game studies that rely on a single initial probability setting, this design enables us to evaluate whether governance outcomes remain stable under heterogeneous strategic tendencies and to identify the dynamic transition process across different governance stages.

As shown in Tables 3 and 4, some equilibrium points have at least one eigenvalue with a positive real part and are therefore unstable, implying that evolutionarily stable strategy (ESS) outcomes arise only in a subset of equilibrium points. Rather than interpreting these equilibrium points individually, this study further organizes the locally stable equilibria into three stages of governance evolution in China's farmland soil toxic metal pollution control according to enterprise behavioral patterns and the intensity of multi-actor participation. Accordingly, the proposed stage classification does not represent all candidate strategy combinations but instead summarizes different stable governance configurations and their corresponding evolutionary trajectories under varying incentive structures.

5.1.1. Early Governance Stage

In Stage I (Early Governance Stage), the system is characterized by weak regulatory intervention and limited participation from social actors, with enterprises predominantly engaging in illegal discharge [35]. The corresponding equilibrium points include (0, 0, 0, 0), (0, 0, 0, 1), and (0, 1, 0, 0), which collectively represent scenarios in which gover-

nance relies on low-intensity or fragmented supervision and fails to form an effective collaborative mechanism.

The simulation results for this stage are presented in Figures 1–6. As illustrated in these figures, the trajectories of the government, the public, and environmental public-interest organizations generally converge toward inactive strategies, indicating insufficient incentives to sustain active participation. Even in cases where individual actors exhibit partial engagement, such as public reporting or environmental litigation, their actions do not induce coordinated responses from other players. Meanwhile, enterprises maintain a stable tendency toward illegal discharge, reflecting the persistence of profit-driven behavior under weak regulatory constraints. The trajectories in this stage show relatively slow convergence and limited interaction among players, suggesting that the system remains in a low-level equilibrium characterized by passive governance and accumulating environmental risks.

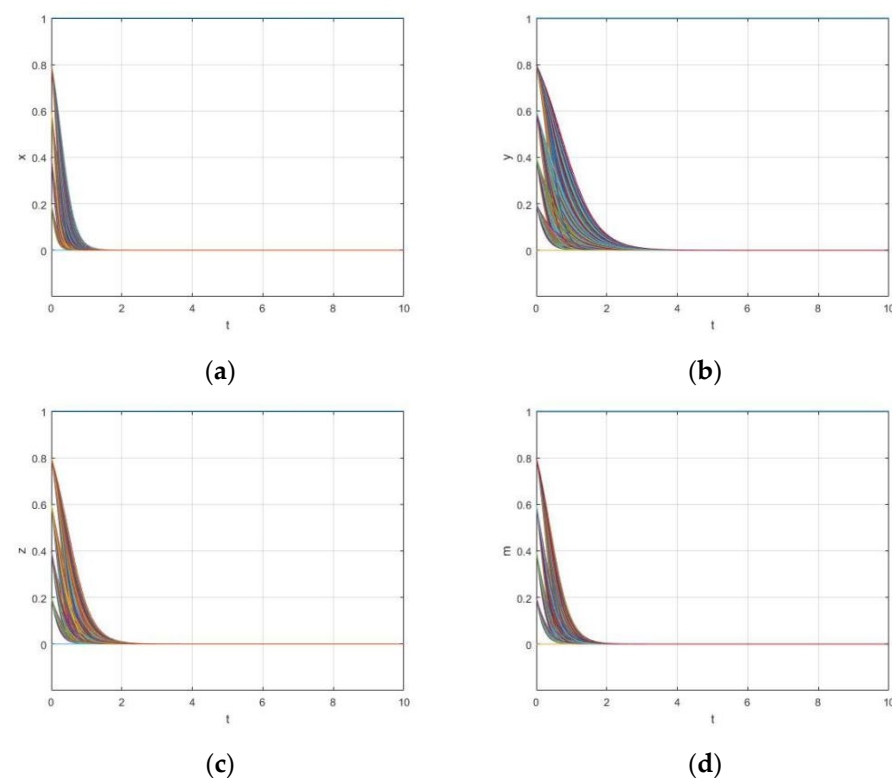


Figure 1. The Evolutionary Process of Different Players (0, 0, 0, 0): (a) Government; (b) Environmental public-interest organizations; (c) Enterprises; (d) Public. The horizontal axis represents time.

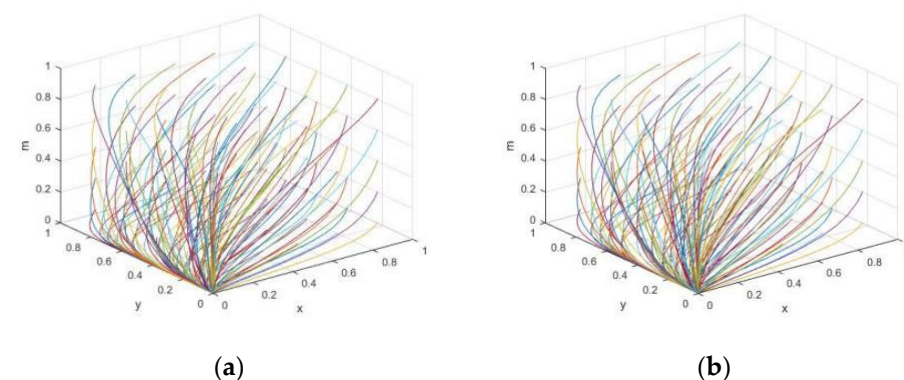


Figure 2. Parameter Simulation of Stable Point (0, 0, 0, 0): (a) $z = 0.1$; (b) $z = 0.7$.

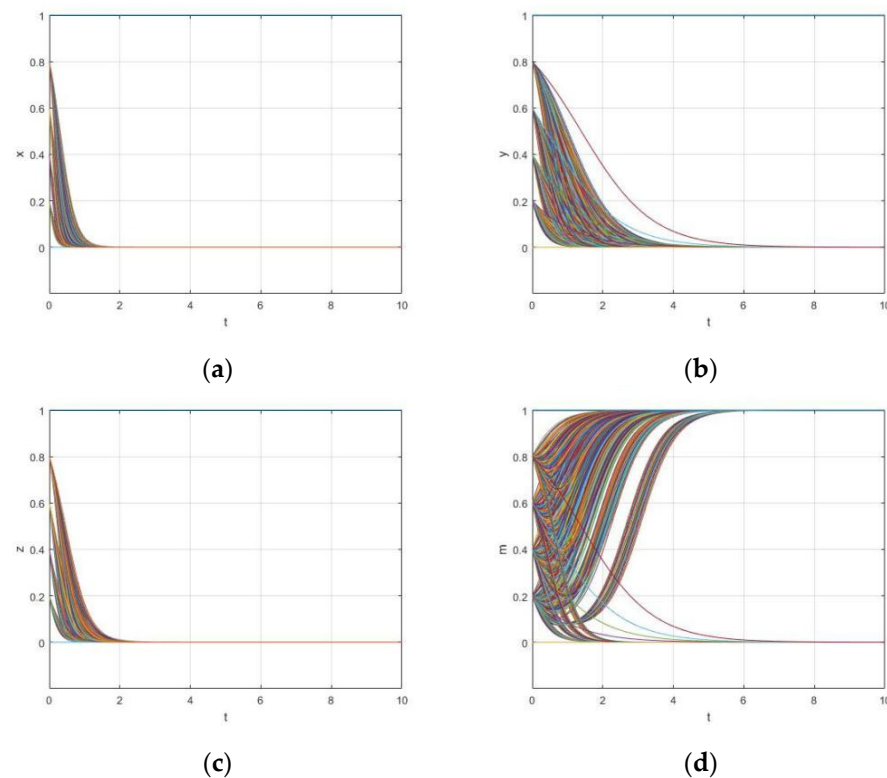


Figure 3. The Evolutionary Process of Different Players (0, 0, 0, 1): (a) Government; (b) Environmental public-interest organizations; (c) Enterprises; (d) Public. The horizontal axis represents time.

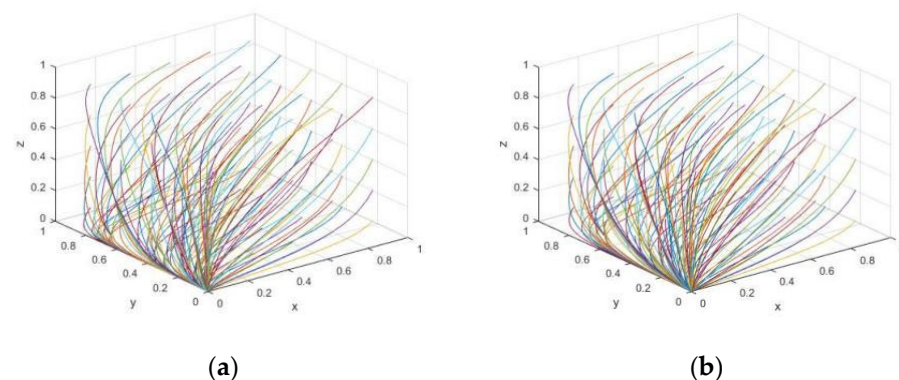


Figure 4. Parameter Simulation of Stable Point (0, 0, 0, 1): (a) $z = 0.3$; (b) $z = 0.9$.

At the equilibrium point (0, 0, 0, 0), if $I - C_n - C_g + L_g - kL_g < 0$, $L_o - C_o - kL_o < 0$, $L_e - C_e + R_e < 0$ and $L_p - C_p - kL_p < 0$, then this point is locally asymptotically stable. To satisfy these stability conditions, we set the parameters to plausible values based on practical considerations. Specifically, we set $R_g = 10$, $R_o = 5$, $R_e = 6$, $R_p = 15$, $k = 0.5$, $S_p = 2$, $S_o = 3$, $C_g = 5$, $C_o = 5$, $C_e = 15$, $C_p = 6$, $C_n = 5$, $L_g = 6$, $L_o = 6$, $L_e = 6$, $L_p = 5$, and $I = 2$. The simulation results are reported in Figures 1 and 2. Over time, the government, the public, and environmental public-interest organizations all converge toward inactive strategies, indicating that the system stabilizes at a low-participation equilibrium. This pattern suggests that, in the absence of effective incentive mechanisms and under relatively low perceived environmental risks, none of the social actors has sufficient motivation to engage in active governance. As a result, external supervision remains weak and fails to exert meaningful constraints on enterprise behavior. The trajectories exhibit limited interaction and smooth convergence, suggesting weak strategic interdependence and insufficient conditions for collaborative governance. Comparing $z = 0.1$ and $z = 0.7$

further shows that variations in enterprises' initial strategy distribution mainly affect the pace of adjustment rather than the overall governance outcome.

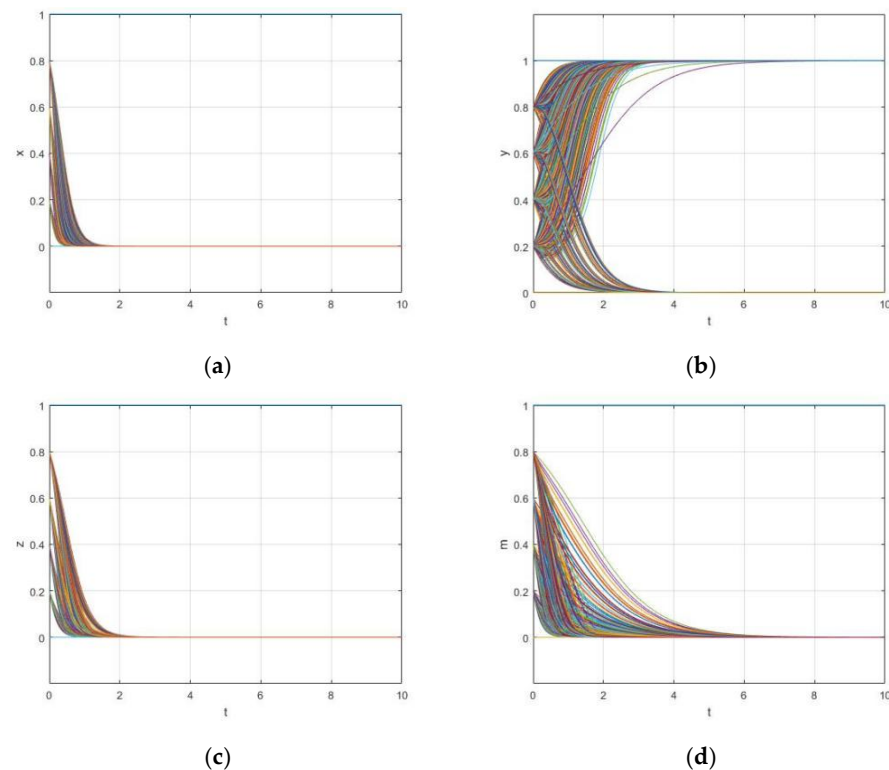


Figure 5. The Evolutionary Process of Different Players (0, 1, 0, 0): (a) Government; (b) Environmental public-interest organizations; (c) Enterprises; (d) Public. The horizontal axis represents time.

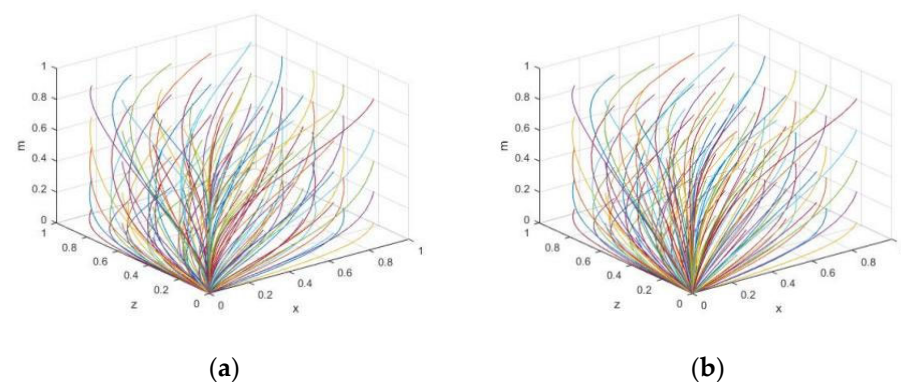


Figure 6. Parameter simulation of stable point (0, 1, 0, 0): (a) $z = 0.2$; (b) $z = 0.9$.

At the equilibrium point (0, 0, 0, 1), if $I - C_g - S_p < 0$, $-C_o < 0$, $R_e - C_e + kL_e < 0$, and $C_p - L_p + kL_p < 0$, then this point is locally asymptotically stable. To satisfy these stability conditions, we set the parameters to plausible values based on practical considerations. Specifically, we set $R_g = 10$, $R_o = 5$, $R_e = 6$, $R_p = 15$, $k = 0.5$, $S_p = 4$, $S_o = 3$, $C_g = 5$, $C_o = 4$, $C_e = 15$, $C_p = 3$, $C_n = 5$, $L_g = 7$, $L_o = 5$, $L_e = 6$, $L_p = 10$ and $I = 2$. The simulation results are reported in Figures 3 and 4. Over time, the government and environmental public-interest organizations converge toward inactive strategies, while the public converges toward active reporting, indicating a partially activated governance equilibrium driven primarily by individual participation. This pattern suggests that, despite weak overall incentive and deterrence mechanisms, the public retains a relatively strong motivation to engage in reporting due to the direct exposure to environmental risks, whereas other actors lack sufficient incentives to participate in active governance. As a result, supervision

remains fragmented and fails to form an effective multi-actor collaborative framework. The trajectories exhibit limited interaction among players, suggesting that individual participation alone remains insufficient to generate coordinated strategic responses. Comparing $z = 0.3$ and $z = 0.9$ further shows that variations in enterprises' initial strategy distribution do not substantially alter the convergence pattern of the governance system.

At the equilibrium point $(0, 1, 0, 0)$, if $I - C_g - S_o < 0$, $C_o - L_o + kL_o < 0$, $R_e - C_e + kL_e < 0$, and $-C_p < 0$, then this point is locally asymptotically stable. To satisfy these stability conditions, we set the parameters to plausible values based on practical considerations. Specifically, we set $R_g = 10$, $R_o = 5$, $R_e = 6$, $R_p = 15$, $k = 0.5$, $S_p = 2$, $S_o = 3$, $C_g = 5$, $C_o = 2$, $C_e = 15$, $C_p = 6$, $C_n = 5$, $L_g = 7$, $L_o = 10$, $L_e = 6$, $L_p = 10$, and $I = 2$. The simulation results are reported in Figures 5 and 6. Over time, the government and the public converge toward inactive strategies, while environmental public-interest organizations converge toward initiating litigation, indicating a selectively activated governance equilibrium driven by organizational action. This pattern suggests that, even in the absence of government subsidies, environmental public-interest organizations retain sufficient incentives to participate due to potential reputational gains, whereas the government and the public lack comparable motivations for active engagement. As a result, supervision remains uneven and does not evolve into a coordinated multi-actor governance structure. The trajectories exhibit limited interaction among players, indicating that organizational participation alone remains insufficient to activate broader collaborative governance. Comparing $z = 0.2$ and $z = 0.9$ further shows that variations in enterprises' initial strategy distribution have only a marginal impact on the evolutionary paths of the other players, suggesting that enterprise behavior does not effectively trigger broader governance responses in this setting.

5.1.2. Transitional Governance Stage

In Stage II (Transitional Governance Stage), against the backdrop of persistent illegal discharge by enterprises, the simulation results reflect a governance pattern involving government-led strengthening of regulatory intervention and a gradual increase in participation from other social actors [36,37]. The transition toward this stage occurs as the incentive structures of multiple stakeholders begin to change. For the government, higher expected governance benefits and increasing environmental losses make stricter regulation more attractive despite additional regulatory costs. For the public and environmental public-interest organizations, stronger participation incentives and lower relative monitoring costs increase the willingness to engage in reporting and litigation. These strategic adjustments collectively shift the governance system from fragmented supervision toward coordinated intervention. The corresponding equilibrium points include $(1, 0, 0, 0)$, $(1, 0, 0, 1)$, $(1, 1, 0, 0)$, and $(1, 1, 0, 1)$, which collectively represent scenarios in which government regulation becomes more stringent and social supervision gradually intensifies, eventually evolving toward a fully coordinated governance mechanism. In particular, the equilibrium point $(1, 1, 0, 1)$ captures a state in which all stakeholders actively participate, reflecting a highly coordinated governance structure.

The simulation results for this stage are presented in Figures 7–14. As illustrated in these figures, the trajectories show more dynamic adjustments and stronger interdependence among players compared with Stage I. The government generally converges toward strict regulation, while the public and environmental public-interest organizations exhibit varying degrees of active participation depending on incentive structures.

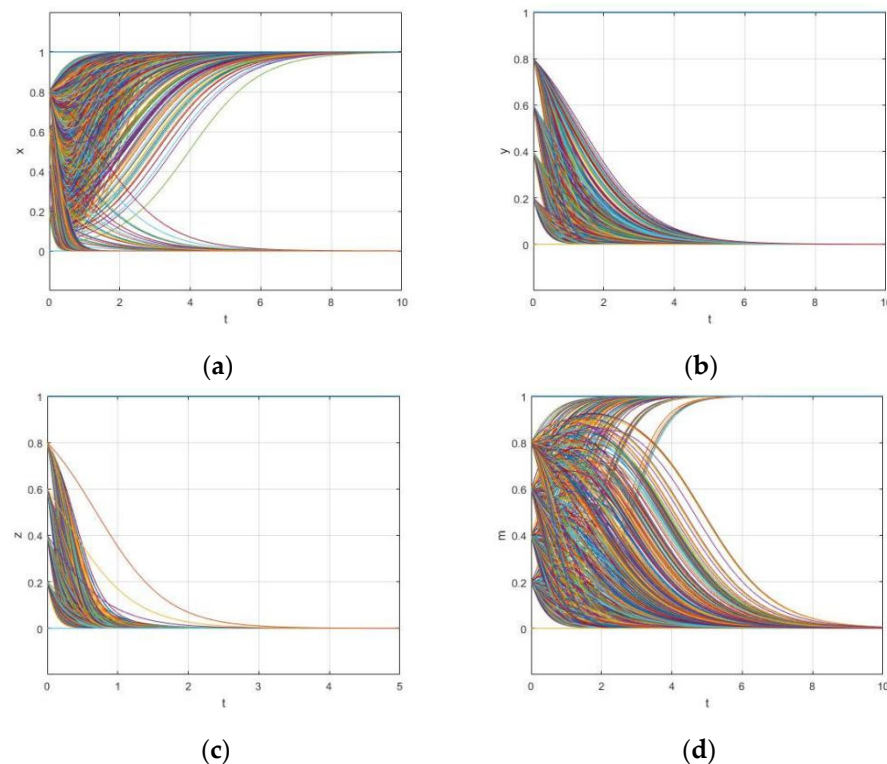


Figure 7. The Evolutionary Process of Different Players (1, 0, 0, 0): (a) Government; (b) Environmental public-interest organizations; (c) Enterprises; (d) Public. The horizontal axis represents time.

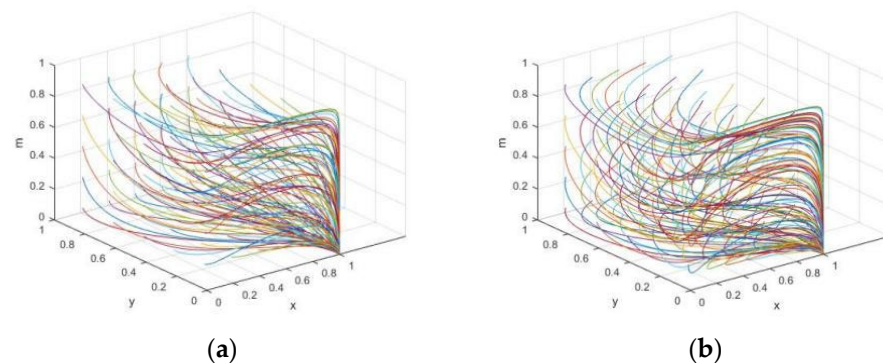


Figure 8. Parameter simulation of stable point (1, 0, 0, 0): (a) $z = 0.2$; (b) $z = 0.8$.

At the equilibrium point (1, 0, 0, 0), if $C_g + C_n - I - L_g + kL_e < 0$, $S_o - C_o < 0$, $I - C_e + R_e + kL_e < 0$ and $S_p - C_p < 0$, then this point is locally asymptotically stable. To satisfy these conditions, we calibrate the parameters to plausible values based on practical considerations. Specifically, we set $R_g = 10$, $R_o = 5$, $R_e = 6$, $R_p = 15$, $k = 0.5$, $S_p = 2$, $S_o = 3$, $C_g = 5$, $C_o = 4$, $C_e = 20$, $C_p = 3$, $C_n = 5$, $L_g = 7$, $L_o = 5$, $L_e = 6$, $L_p = 10$ and $I = 9$. The simulation results are reported in Figures 7 and 8. Over time, the government converges toward strict regulation, while environmental public-interest organizations and the public converge toward inactive strategies, indicating a government-led but weakly supported governance equilibrium. This pattern suggests that, although regulatory intervention is strengthened, the absence of sufficient incentives and deterrence mechanisms limits the participation of other social actors, resulting in a governance structure dominated by unilateral government action rather than coordinated oversight. The trajectories exhibit limited interaction among players, suggesting that strengthened regulation alone cannot yet establish sustained collaborative participation. Comparing $z = 0.2$ and $z = 0.8$ further shows

that variations in enterprises' initial strategy distribution mainly influence adjustment dynamics rather than final strategic outcomes.

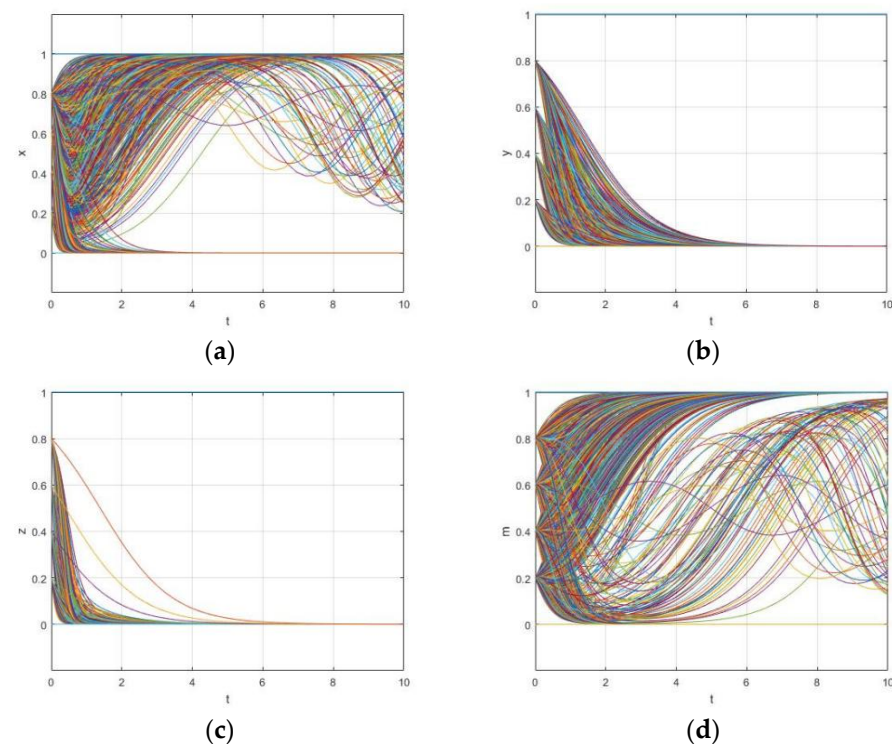


Figure 9. The Evolutionary Process of Different Players (1, 0, 0, 1): (a) Government; (b) Environmental public-interest organizations; (c) Enterprises; (d) Public. The horizontal axis represents time.

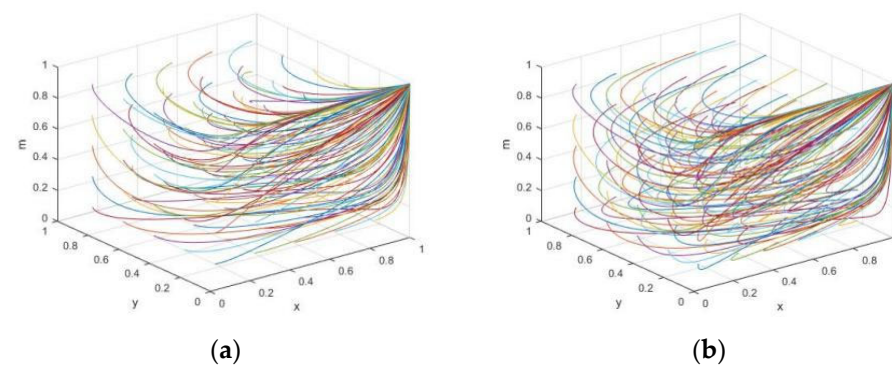


Figure 10. Parameter Simulation of Stable Point (1, 0, 0, 1): (a) $z = 0.2$; (b) $z = 0.7$.

At the equilibrium point (1, 0, 0, 1), if $C_g - I + S_p < 0$, $S_o - C_o < 0$, $I - C_e + R_e + kL_e < 0$, and $C_p - S_p < 0$, then this point is locally asymptotically stable. To satisfy these stability conditions, we set the parameters to plausible values based on practical considerations. Specifically, we set $R_g = 10$, $R_o = 5$, $R_e = 6$, $R_p = 15$, $k = 0.5$, $S_p = 4$, $S_o = 3$, $C_g = 5$, $C_o = 4$, $C_e = 20$, $C_p = 3$, $C_n = 5$, $L_g = 7$, $L_o = 5$, $L_e = 6$, $L_p = 10$, and $I = 10$. The simulation results are reported in Figures 9 and 10. Over time, the government converges toward strict regulation and the public converges toward active reporting, while environmental public-interest organizations converge toward non-litigation, indicating a government-driven and partially responsive governance equilibrium. This pattern suggests that, as regulatory efforts are continuously strengthened by the government, certain social actors such as the public are gradually mobilized to participate, whereas environmental public-interest organizations remain inactive due to insufficient incentive and deterrence mechanisms, resulting in an incomplete and uneven governance structure. The trajectories

exhibit moderate interaction among players, indicating that government-led regulation begins to induce participation from some actors but does not yet generate fully coordinated responses across all stakeholders. Comparing $z = 0.2$ and $z = 0.7$ further shows that variations in enterprises' initial strategy distribution mainly affect the speed and transitional process of strategic adjustment among the other players, while the long-term governance outcomes remain largely associated with the prevailing incentive structure. This indicates that enterprise behavior may influence short-term governance responses, but sustained changes in governance patterns require coordinated adjustments in regulatory and participation mechanisms.

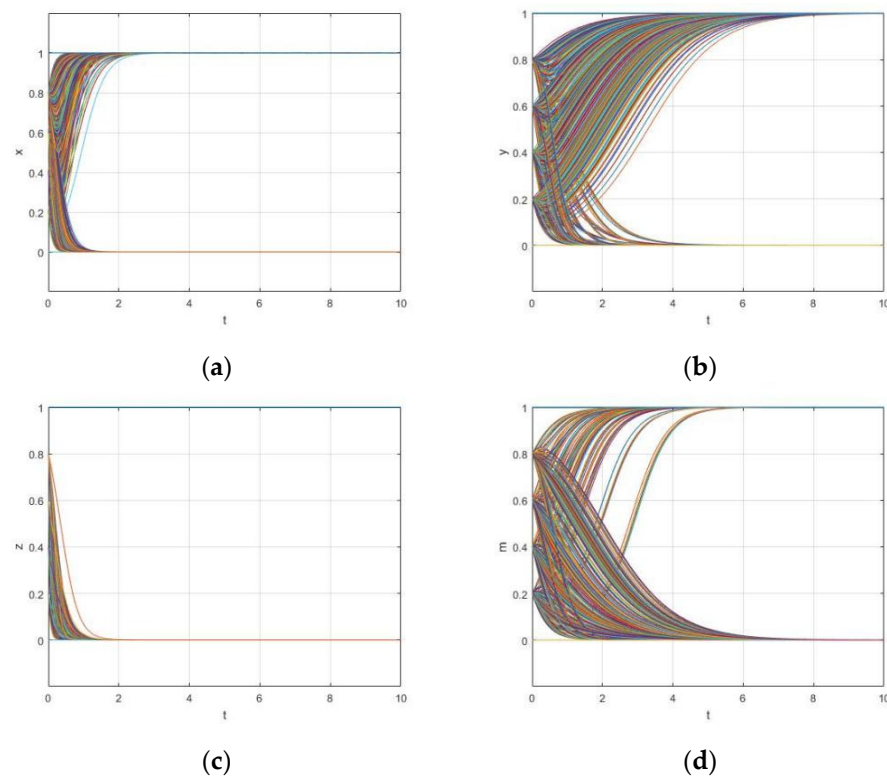


Figure 11. The Evolutionary Process of Different Players (1, 1, 0, 0): (a) Government; (b) Environmental public-interest organizations; (c) Enterprises; (d) Public. The horizontal axis represents time.

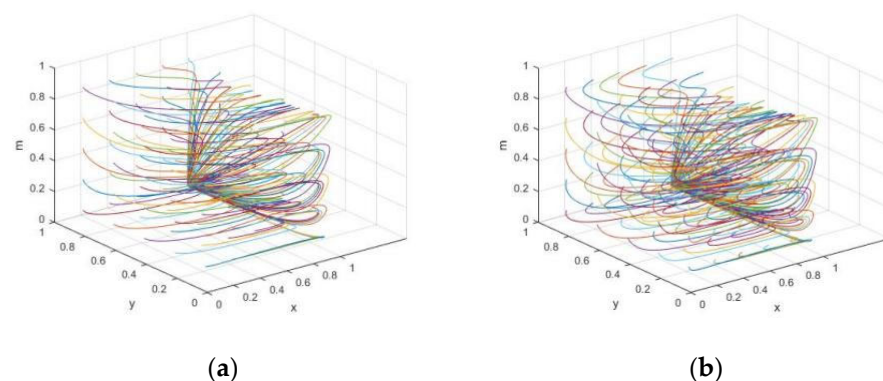


Figure 12. Parameter Simulation of Stable Point (1, 1, 0, 0): (a) $z = 0.3$; (b) $z = 0.8$.

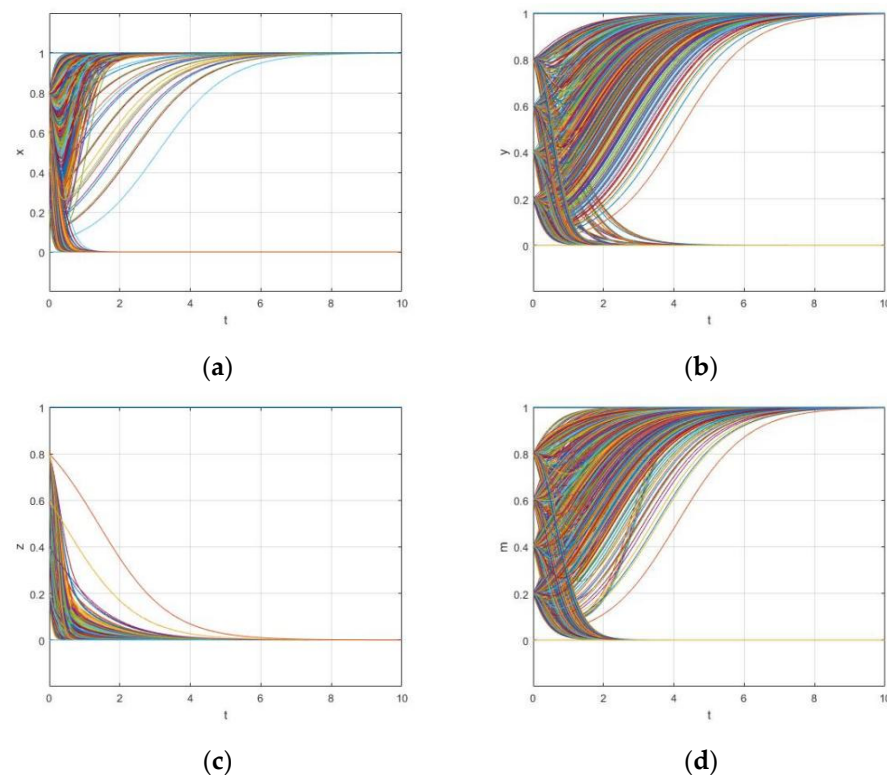


Figure 13. The Evolutionary Process of Different Players (1, 1, 0, 1): (a) Government; (b) Environmental public-interest organizations; (c) Enterprises; (d) Public. The horizontal axis represents time.

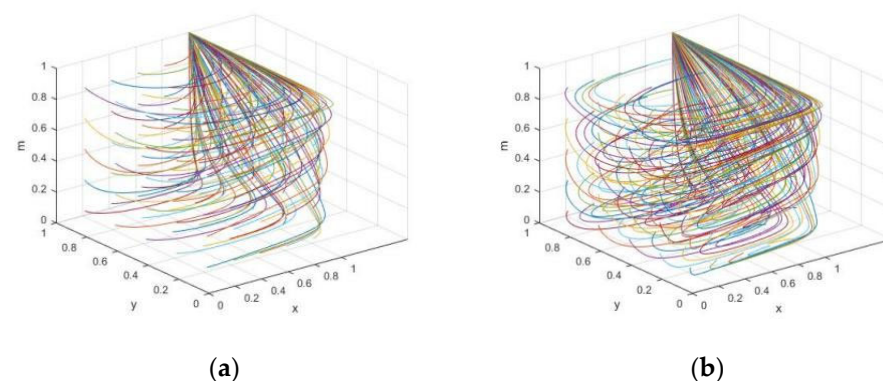


Figure 14. Parameter Simulation of Stable Point (1, 1, 0, 1): (a) $z = 0.1$; (b) $z = 0.9$.

At the equilibrium point (1, 1, 0, 0), if $C_o - S_o < 0$, $S_p - C_p < 0$, $C_g - I + S_o < 0$, and $I - C_e + R_e + kL_e < 0$, then this point is locally asymptotically stable. To satisfy these stability conditions, we set the parameters to plausible values based on practical considerations. Specifically, we set $R_g = 10$, $R_o = 5$, $R_e = 3$, $R_p = 15$, $k = 0.5$, $S_p = 2$, $S_o = 5$, $C_g = 5$, $C_o = 4$, $C_e = 25$, $C_p = 3$, $C_n = 5$, $L_g = 7$, $L_o = 5$, $L_e = 6$, $L_p = 10$, and $I = 15$. The simulation results are reported in Figures 11 and 12. Over time, the government converges toward strict regulation and environmental public-interest organizations converge toward initiating litigation, while the public converges toward non-reporting, indicating a government-driven and organization-responsive governance equilibrium. This pattern suggests that, as regulatory efforts are strengthened and targeted support is provided, environmental public-interest organizations are effectively mobilized to participate in governance, whereas the public remains inactive due to insufficient incentive and deterrence mechanisms, resulting in an imbalanced and partially coordinated governance structure. The trajectories exhibit moderate interaction among players, indicating that

government-led regulation can induce active responses from environmental public-interest organizations but does not yet generate broad-based participation across all stakeholders. Comparing $z = 0.3$ and $z = 0.8$ further shows that variations in enterprises' initial strategy distribution mainly affect the speed and transitional process of strategic adjustment among the other players, while the long-term governance outcomes remain largely associated with the prevailing incentive structure.

At the equilibrium point $(1, 1, 0, 1)$, if $C_g - I + S_o + S_p < 0$, $C_o - S_o < 0$, $I - C_e + R_e + L_e k < 0$, and $C_p - S_p < 0$, then this point is locally asymptotically stable. To satisfy these stability conditions, we set the parameters to plausible values based on practical considerations. Specifically, we set $R_g = 10$, $R_o = 5$, $R_e = 6$, $R_p = 15$, $k = 0.5$, $S_p = 4$, $S_o = 5$, $C_g = 5$, $C_o = 4$, $C_e = 25$, $C_p = 3$, $C_n = 5$, $L_g = 7$, $L_o = 5$, $L_e = 6$, $L_p = 10$, and $I = 15$. The simulation results are reported in Figures 13 and 14. Over time, the government, the public, and environmental public-interest organizations all converge toward active strategies, reflecting the emergence of a stable collaborative governance structure. This pattern suggests that, under sufficiently strong incentive and deterrence mechanisms, government support effectively offsets the participation costs of other social actors, while heightened environmental risks further strengthen the motivation for joint supervision, thereby enabling the formation of a stable and collaborative governance structure. The trajectories exhibit strong interaction among players, indicating that the strategies of different actors reinforce each other and jointly promote the emergence of coordinated governance. Comparing $z = 0.1$ and $z = 0.9$ further shows that variations in enterprises' initial strategy distribution mainly influence the adjustment process and convergence speed of the other players, while the coordinated governance outcome remains broadly consistent under the prevailing incentive structure.

5.1.3. Mature Governance Stage

In Stage III (Mature Governance Stage), this stage represents a governance configuration in which enterprise compliance becoming the dominant strategy, with governance relying primarily on internalized incentives rather than continuous external enforcement [38]. The transition toward this stage occurs as the strategic incentives of stakeholders gradually align with long-term environmental governance objectives. For enterprises, higher expected returns from compliant treatment, lower relative compliance costs, and increasing losses associated with detected violations progressively strengthen the attractiveness of compliant behavior, allowing environmental responsibility to become internalized into routine decision-making. As enterprise compliance becomes self-sustaining, the need for intensive regulatory intervention gradually decreases, enabling the government to shift from direct supervision toward maintaining institutional support and governance stability. Meanwhile, the public and environmental public-interest organizations reduce active intervention as environmental risks are effectively controlled and continuous external supervision becomes less necessary. These strategic adjustments collectively promote the evolution of the governance system from externally coordinated regulation toward a stable and self-reinforcing compliance mechanism. The corresponding equilibrium point is $(0, 0, 1, 0)$, which represents a scenario in which enterprises adopt compliant treatment of toxic metal pollutants, while the government, the public, and environmental public-interest organizations gradually withdraw from active intervention as regulatory pressure becomes less necessary.

The simulation results for this stage are presented in Figures 15 and 16. As illustrated in these figures, the trajectories converge rapidly and smoothly toward a stable configuration in which enterprise compliance is sustained, while the other actors remain largely inactive. This pattern suggests that, when the cost of compliance is sufficiently low relative to

the expected benefits and environmental risks are effectively internalized, enterprises are able to maintain compliant behavior without persistent external supervision. The trajectories in this stage exhibit fast convergence and minimal interaction among players, indicating that the system has reached a self-sustaining governance equilibrium driven by endogenous incentives.

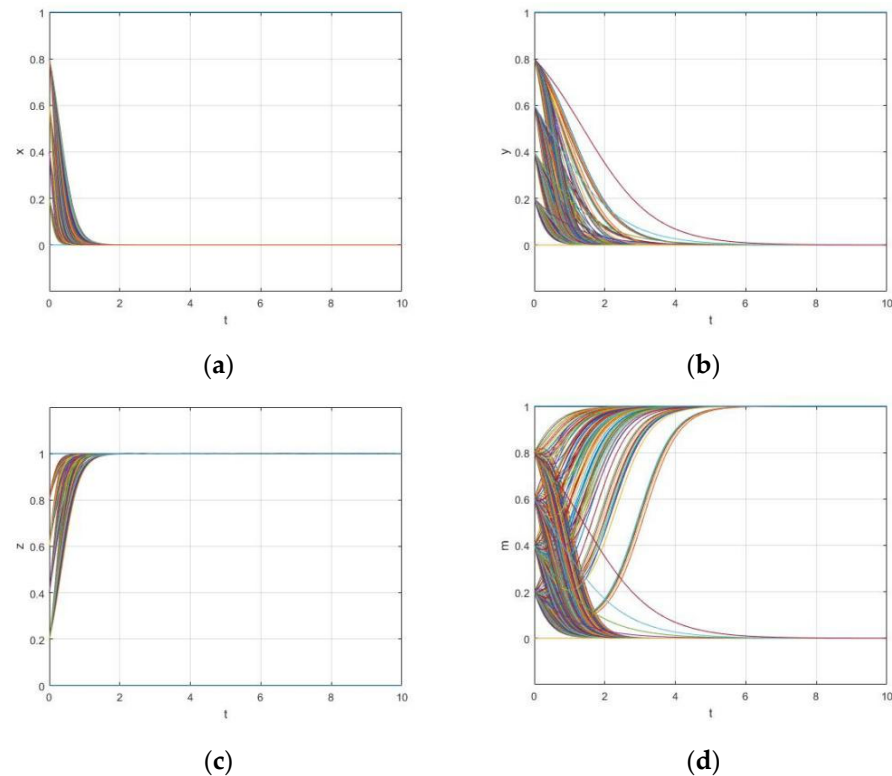


Figure 15. The Evolutionary Process of Different Players (0, 0, 1, 0): (a) Government; (b) Environmental public-interest organizations; (c) Enterprises; (d) Public. The horizontal axis represents time.

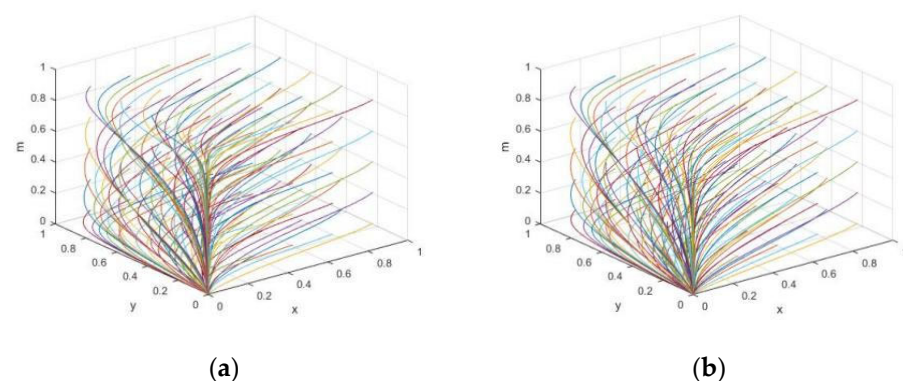


Figure 16. Parameter Simulation of Stable Point (0, 0, 1, 0): (a) $z = 0.1$; (b) $z = 0.8$.

At the equilibrium point (0, 0, 1, 0), if $-C_g < 0$, $-C_o < 0$, $C_e - L_e - R_e < 0$, and $-C_p < 0$, then this point is locally asymptotically stable. To satisfy these stability conditions, we set the parameters to plausible values based on practical considerations. Specifically, we set $R_g = 10$, $R_o = 5$, $R_e = 6$, $R_p = 15$, $k = 0.5$, $S_p = 2$, $S_o = 3$, $C_g = 5$, $C_o = 4$, $C_e = 5$, $C_p = 3$, $C_n = 5$, $L_g = 7$, $L_o = 5$, $L_e = 6$, $L_p = 10$, and $I = 2$. The simulation results are reported in Figures 15 and 16. Over time, enterprises converge toward compliant treatment of toxic metal pollutants, while the government, the public, and environmental public-interest organizations converge toward inactive strategies, indicating a self-sustaining

and compliance-driven governance equilibrium. This pattern suggests that, when treatment costs are relatively low and the returns to compliant behavior are sufficiently high, enterprises can maintain long-term profitability while internalizing environmental responsibilities, thereby reducing the need for continuous external supervision. The trajectories exhibit rapid convergence and minimal interaction among players, indicating that the system has reached a stable state in which enterprise behavior is primarily driven by endogenous incentives rather than external regulatory pressure. Comparing $z = 0.1$ and $z = 0.8$ further shows that variations in enterprises' initial strategy distribution mainly influence the adjustment process and convergence speed of the other players, while the governance outcome remains broadly consistent under the prevailing incentive structure.

5.2. Effect of Parameters

In the context of toxic metal pollution governance in farmland soils, government regulation, public participation, and supervision by environmental public-interest organizations have gradually evolved into a pluralistic and collaborative governance framework, while enterprises may still engage in illegal discharges under conditions of high compliance and remediation costs. Given this context, selecting the equilibrium point (1, 1, 0, 1) as the baseline for sensitivity analysis makes strong practical sense. This strategy profile reflects a highly realistic scenario. In this setup, enterprises have a positive probability of engaging in illegal discharge. Meanwhile, the government adopts strict regulation, environmental public-interest organizations initiate environmental public-interest litigation, and the public participates in reporting and monitoring. This dynamic captures a transitional phase in the current governance of toxic metal pollution in farmland soils. It highlights a period where multi-actor oversight is strengthening, yet companies have not fully committed to compliance. Conducting parameter-based simulations under this setting allows us to examine how changes in key variables (such as penalty intensity, government subsidies, and the cost structures faced by each player) shape the system's evolutionary trajectory, thereby clarifying how different institutional instruments affect the stability of multi-actor collaborative governance.

In Figures 17 and 18, the initial probability vectors (x, y, z, m) for the low-probability and high-probability groups are set at (0.4, 0.3, 0.2, 0.3) and (0.7, 0.8, 0.9, 0.7), respectively. The enterprise pollution-control cost C_e is assigned values of 10, 15, 20, and 25. As C_e increases, enterprises become less inclined to choose compliant treatment of toxic metal pollutants, indicating a negative relationship between compliance and pollution-control costs. As enterprises shift toward illegal discharge, the other three players correspondingly show a stronger tendency to adopt active oversight strategies. Changes in C_e exert a substantial influence on the strategic choices of all players in the model. By contrast, holding other conditions constant, differences in the initial probability levels primarily influence the pace and transitional dynamics of strategic adjustment.

In Figure 19, the initial probability vectors (x, y, z, m) for the low-probability and high-probability groups are set to (0.2, 0.4, 0.1, 0.3) and (0.9, 0.7, 0.8, 0.7), respectively. The environmental-damage discount coefficient k , which captures losses induced by toxic metal pollution in farmland soils, is set to 0.2, 0.5, and 0.9. A larger k implies smaller pollution-induced losses. As k increases, enterprises' propensity for illegal discharge fluctuates, and the regulatory willingness of the other three players adjusts in response to enterprises' strategy, with the government exhibiting the largest fluctuations. This suggests that as toxic metal pollution is mitigated, the regulatory pressure faced by enterprises correspondingly weakens. The coefficient k exerts a substantial influence on the strategy choices of the government and enterprises. By contrast, holding other conditions constant, differences

in the initial probability levels primarily influence the pace and transitional dynamics of strategic adjustment.

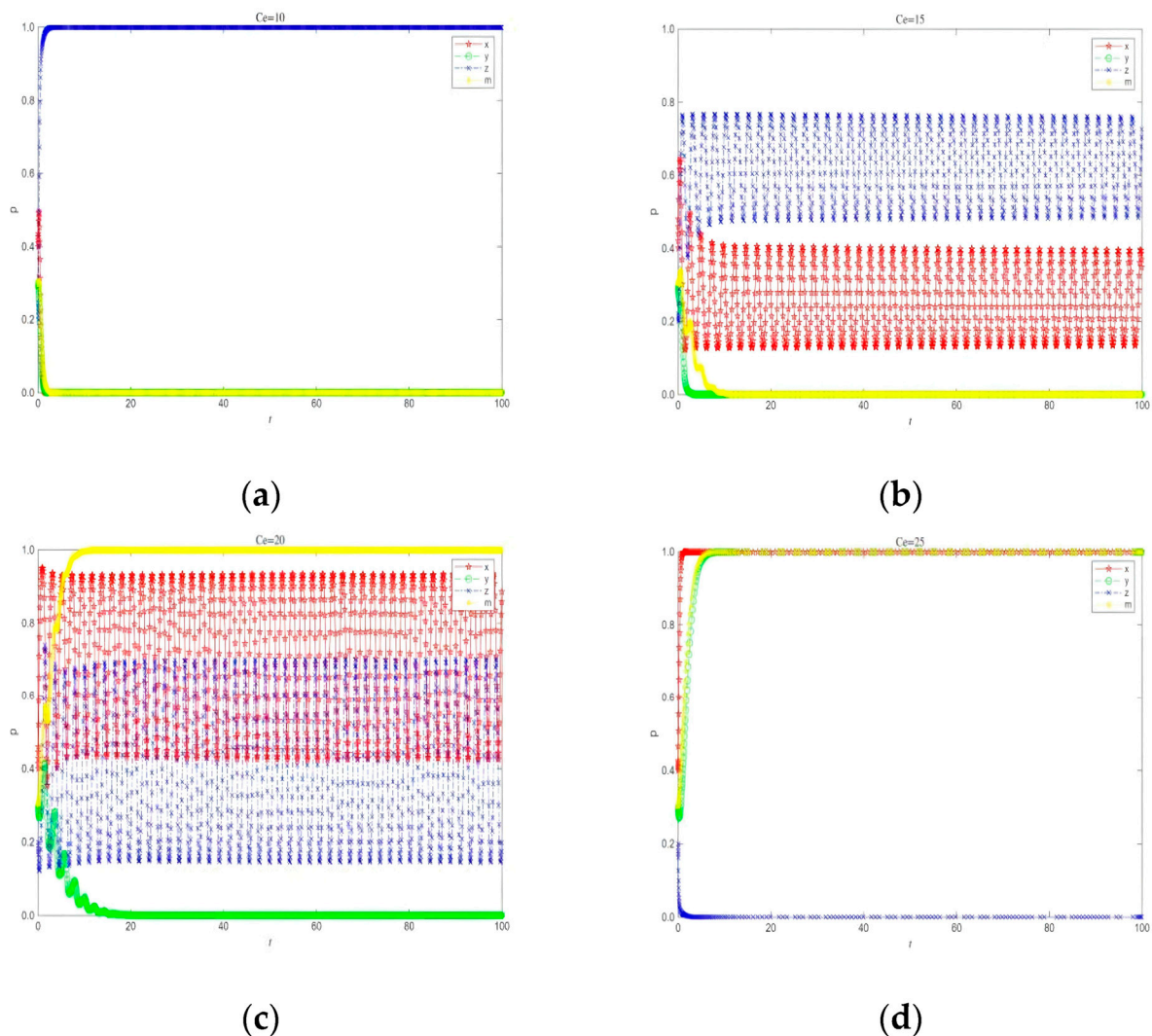


Figure 17. The Effect of C_e in Low Probability Group: (a) $C_e = 10$; (b) $C_e = 15$; (c) $C_e = 20$; (d) $C_e = 25$.

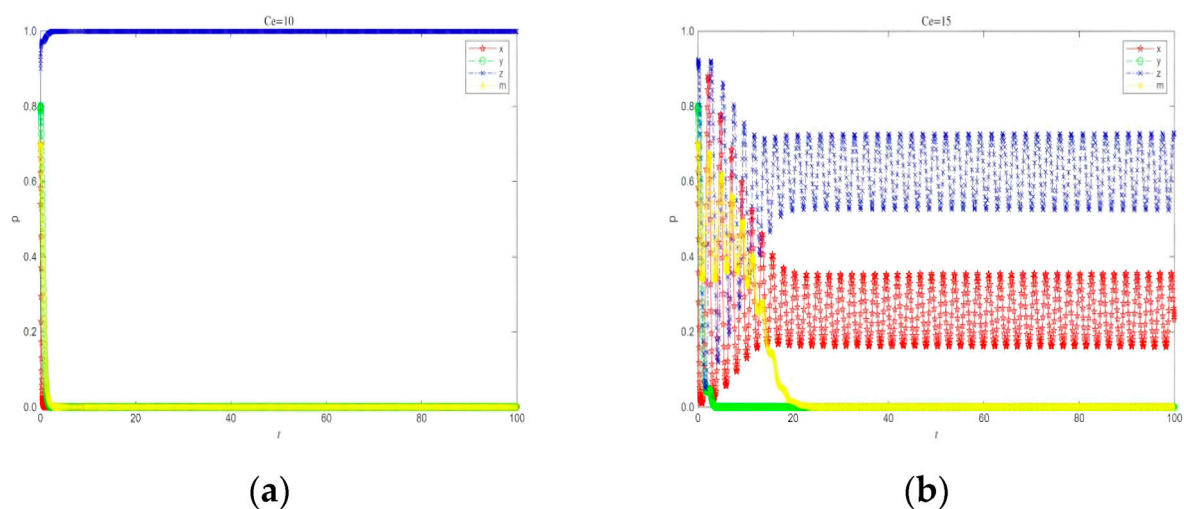
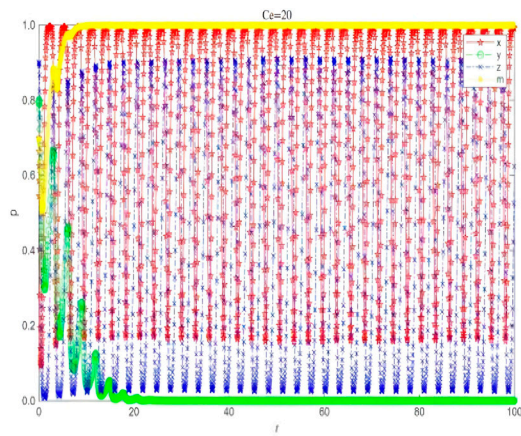
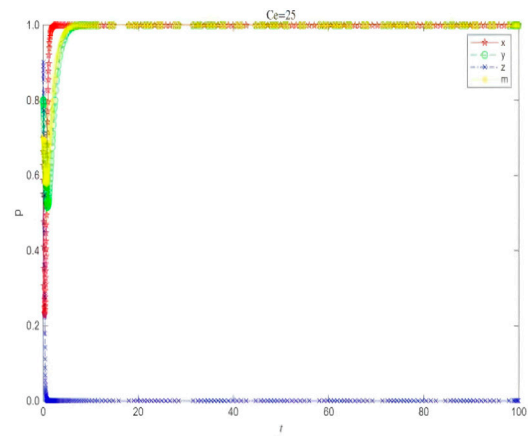


Figure 18. Cont.

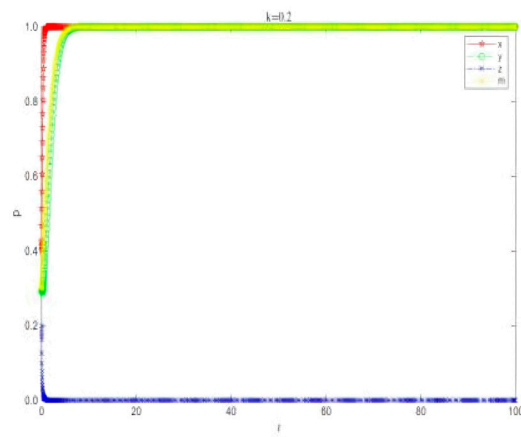


(c)

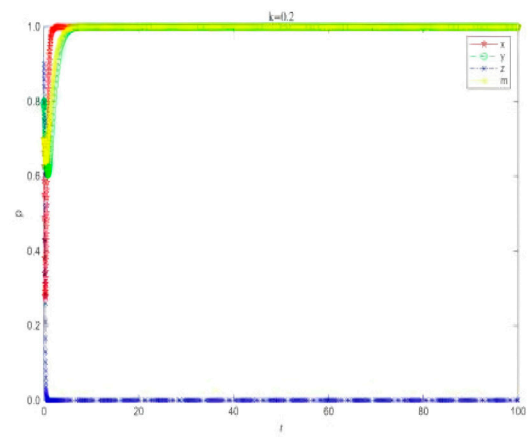


(d)

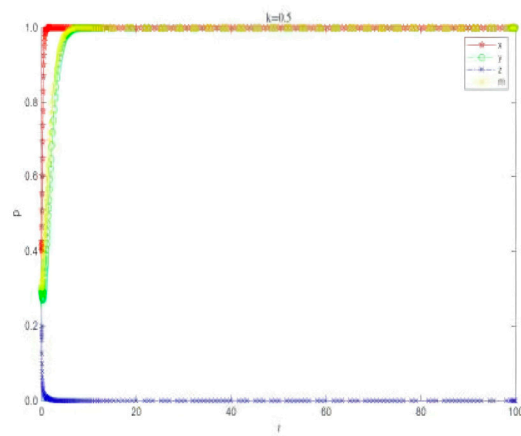
Figure 18. The Effect of C_e in High Probability Group: (a) $C_e = 10$; (b) $C_e = 15$; (c) $C_e = 20$; (d) $C_e = 25$.



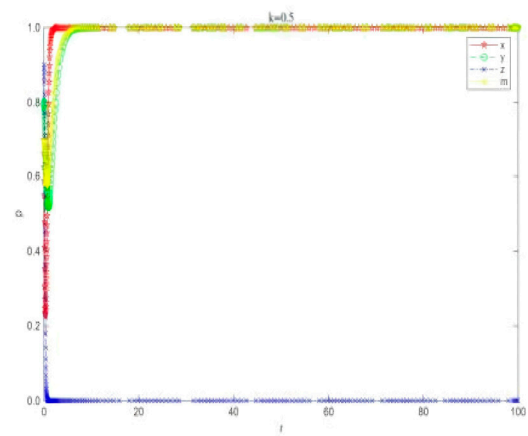
(a)



(a1)



(b)



(b1)

Figure 19. Cont.

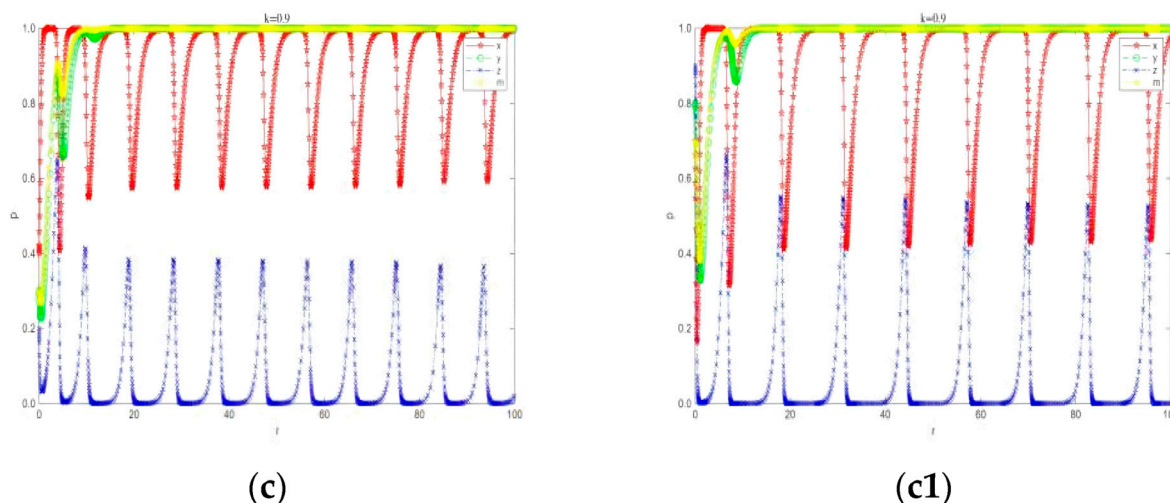


Figure 19. The Effect of k in Low Probability Group: (a) $k = 0.2$; (b) $k = 0.5$; (c) $k = 0.9$; The Effect of k in High Probability Group: (a1) $k = 0.2$; (b1) $k = 0.5$; (c1) $k = 0.9$.

In Figure 20, the initial probability vectors (x, y, z, m) for the low-probability and high-probability groups are set to $(0.3, 0.2, 0.1, 0.2)$ and $(0.8, 0.9, 0.8, 0.7)$, respectively. For environmental public-interest organizations, the litigation subsidy S_o is set to 2, 3, and 5. As the government increases S_o , environmental public-interest organizations become more inclined to initiate environmental public-interest litigation, indicating a positive relationship between the subsidy level and the propensity to litigate. Subsidy expenditures have only a limited effect on the government's strategy choice, because such subsidies function as institutionalized policy instruments through which the government fulfills its environmental and social responsibilities. As a result, the government's decision is driven less by short-term cost-benefit considerations than by public-interest objectives. By contrast, holding other conditions constant, differences in the initial probability levels primarily influence the pace and transitional dynamics of strategic adjustment.

In Figure 21, the initial probability vectors (x, y, z, m) for the low-probability and high-probability groups are set to $(0.1, 0.2, 0.3, 0.2)$ and $(0.7, 0.8, 0.9, 0.9)$, respectively. The litigation cost C_o for environmental public-interest organizations is set to 2, 4, and 6; the public's reporting cost C_p is set to 1, 3, and 5; and the government's incentive S_p to the public is set to 2, 4, and 6. As the monitoring costs borne by the public and environmental public-interest organizations increase, both actors become less likely to adopt active monitoring strategies, indicating a negative relationship between monitoring costs and participation. As the government increases reporting rewards to the public, individuals become more likely to adopt active monitoring strategies, indicating a positive relationship between S_p and public participation. Variations in C_o , C_p , and S_p exert substantial influences on the strategy choices of the players in the model. By contrast, holding other conditions constant, differences in the initial probability levels primarily influence the pace and transitional dynamics of strategic adjustment.

In Figures 22 and 23, to better illustrate the strategic interactions, the initial probability vector for all players is set to $(0.5, 0.5, 0.5, 0.5)$. The enterprise expected return from normal production and operation, R_e , is set to 6, 13, and 20. A higher expected return is associated with a stronger propensity to choose compliant treatment of toxic metal pollutants, indicating a positive relationship between R_e and compliance. Under this condition, the other three players tend to adopt relatively inactive oversight strategies.

In Figures 24 and 25, to better illustrate the strategic interactions, the initial probability vector for all players is set to $(0.5, 0.5, 0.5, 0.5)$. The loss incurred by enterprises once illegal behavior is detected, L_e , is set to 6, 16, and 26. As L_e increases, enterprises become

more inclined to choose compliant treatment of toxic metal pollutants, indicating a positive relationship between L_e and compliance. Under this condition, the other three players tend to adopt relatively inactive oversight strategies.

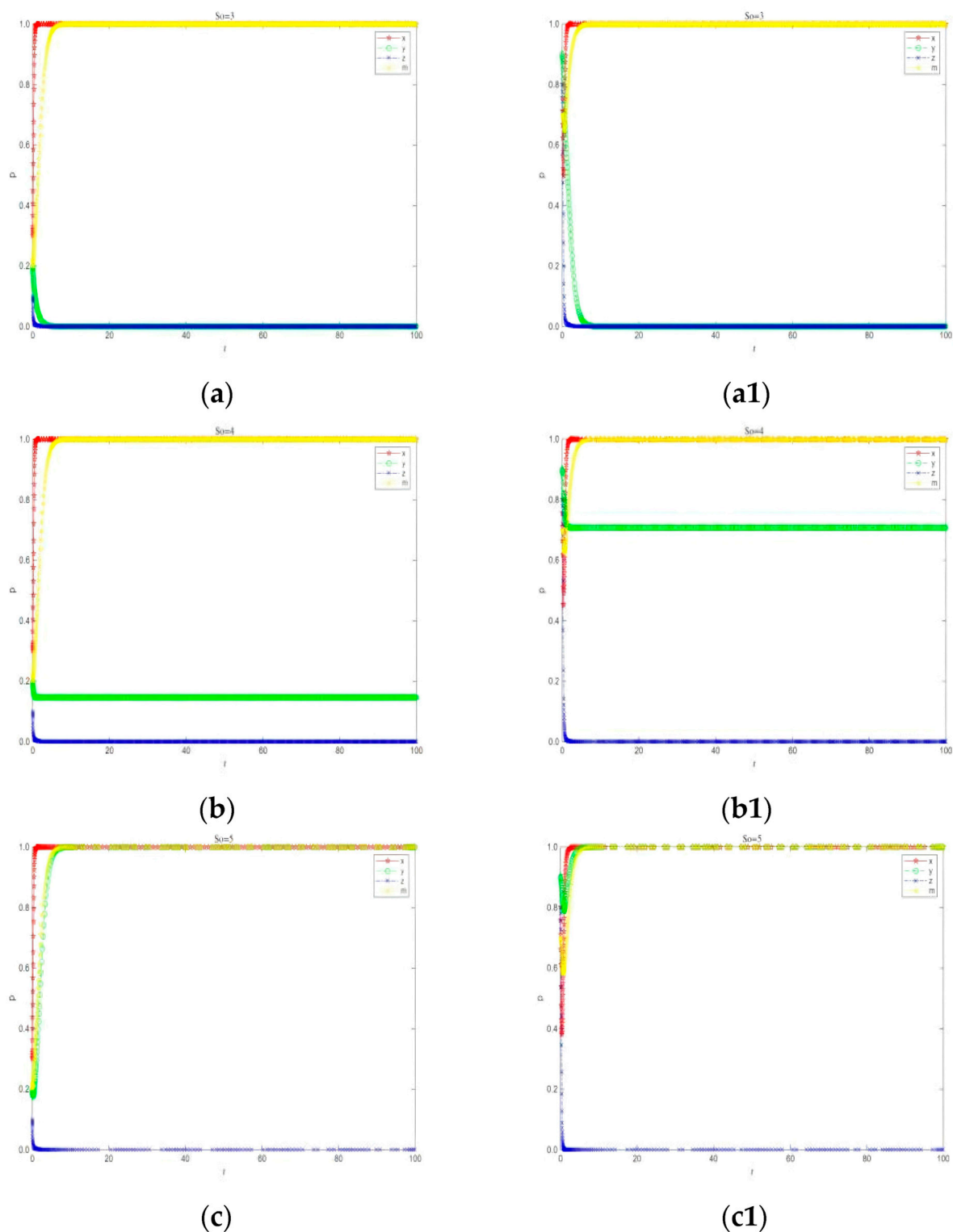


Figure 20. The Effect of S_o in Low Probability Group: (a) $S_o = 3$; (b) $S_o = 4$; (c) $S_o = 5$; The Effect of S_o in High Probability Group: (a1) $S_o = 3$; (b1) $S_o = 4$; (c1) $S_o = 5$.

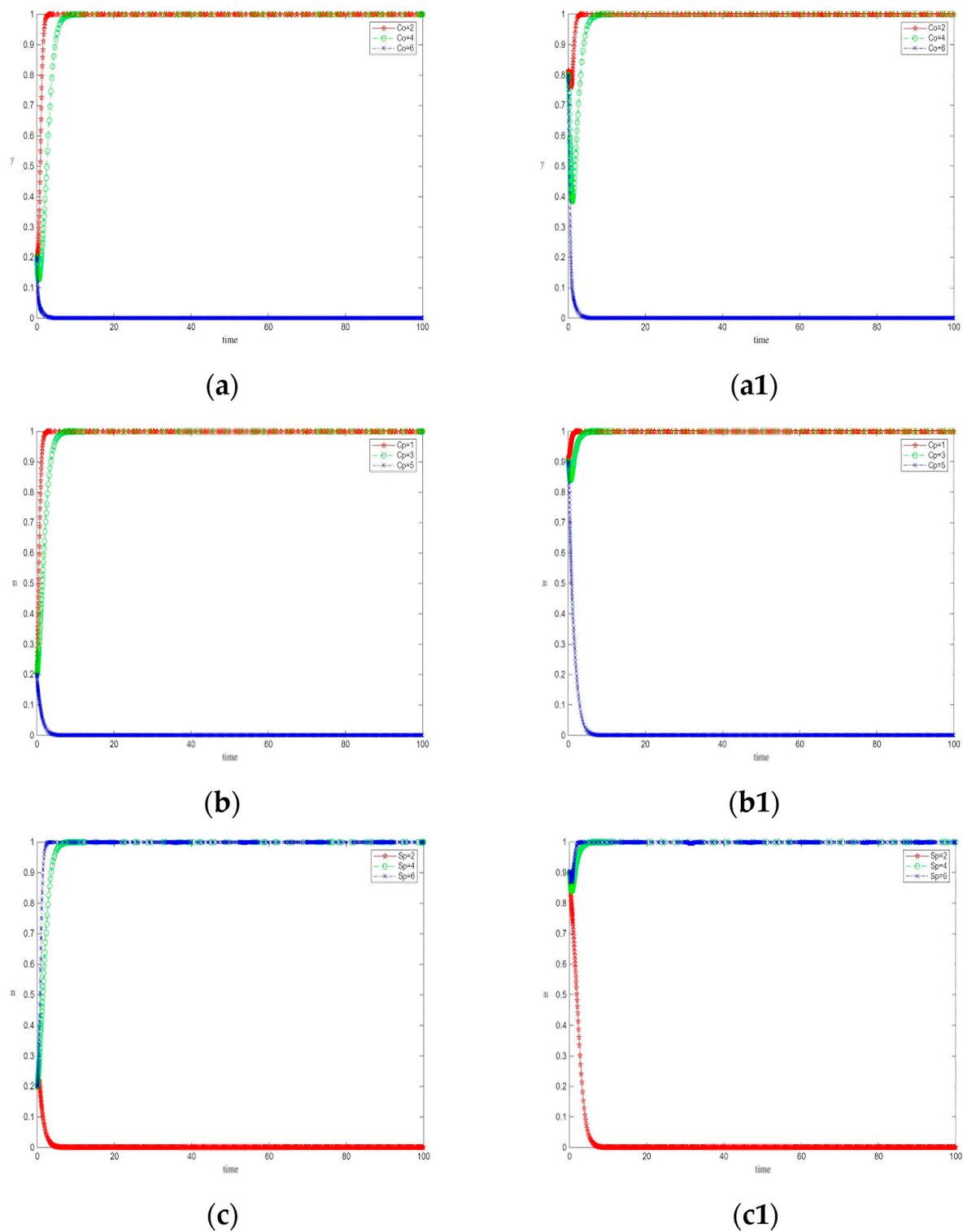


Figure 21. The Effect of Co , Cp and Sp in Low Probability Group: (a) Co ; (b) Cp ; (c) Sp ; The Effect of Co , Cp and Sp in High Probability Group: (a1) Co ; (b1) Cp ; (c1) Sp .

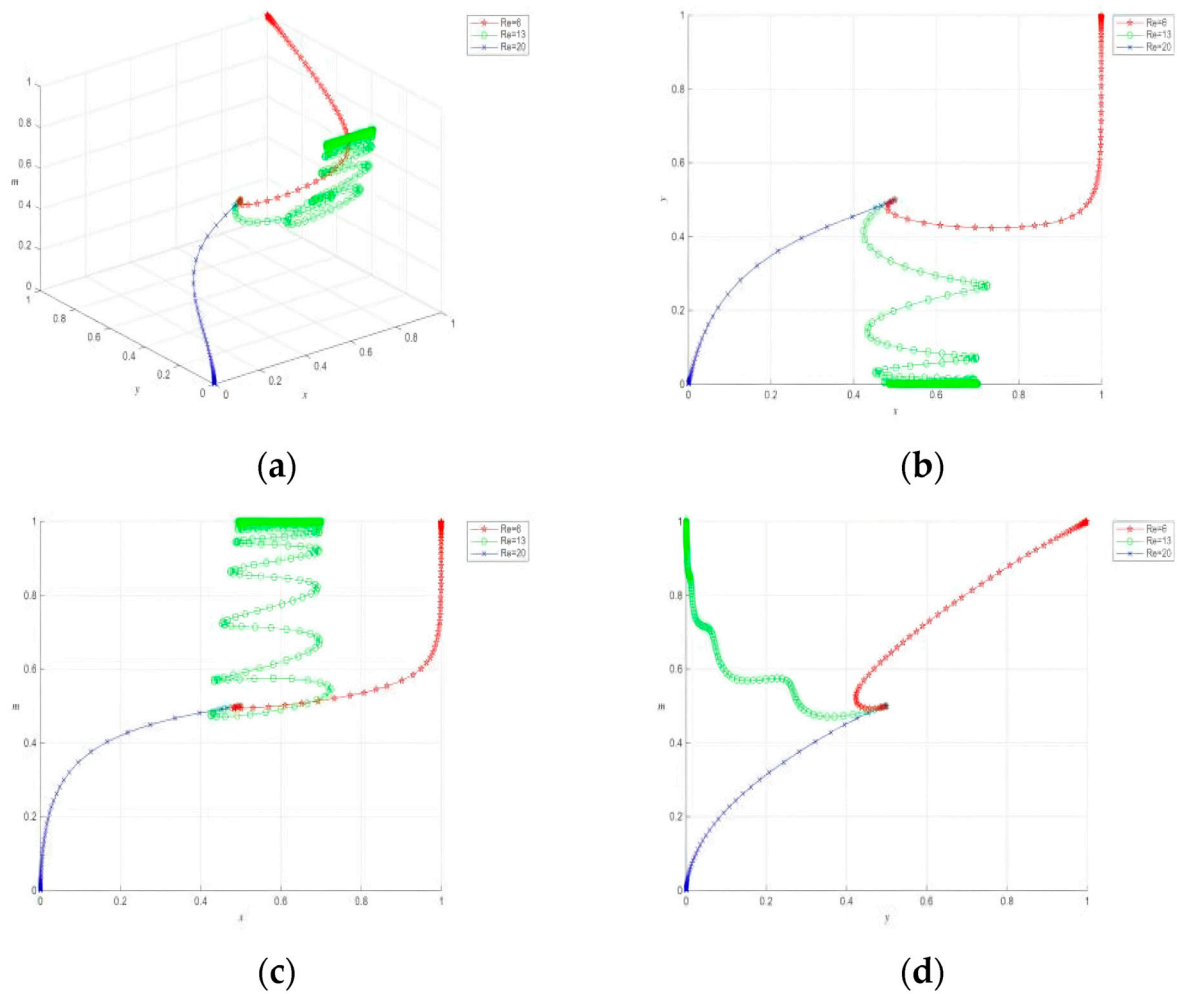


Figure 22. The Effect of Re: (a) (x, y, m) ; (b) (x, y) ; (c) (x, m) (d) (y, m) .

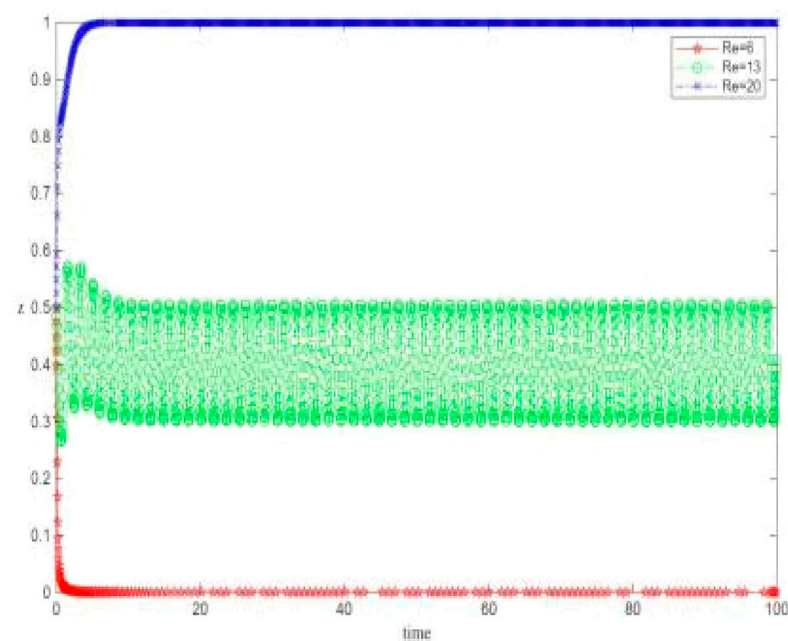


Figure 23. The Effect of Re: (t, z) .

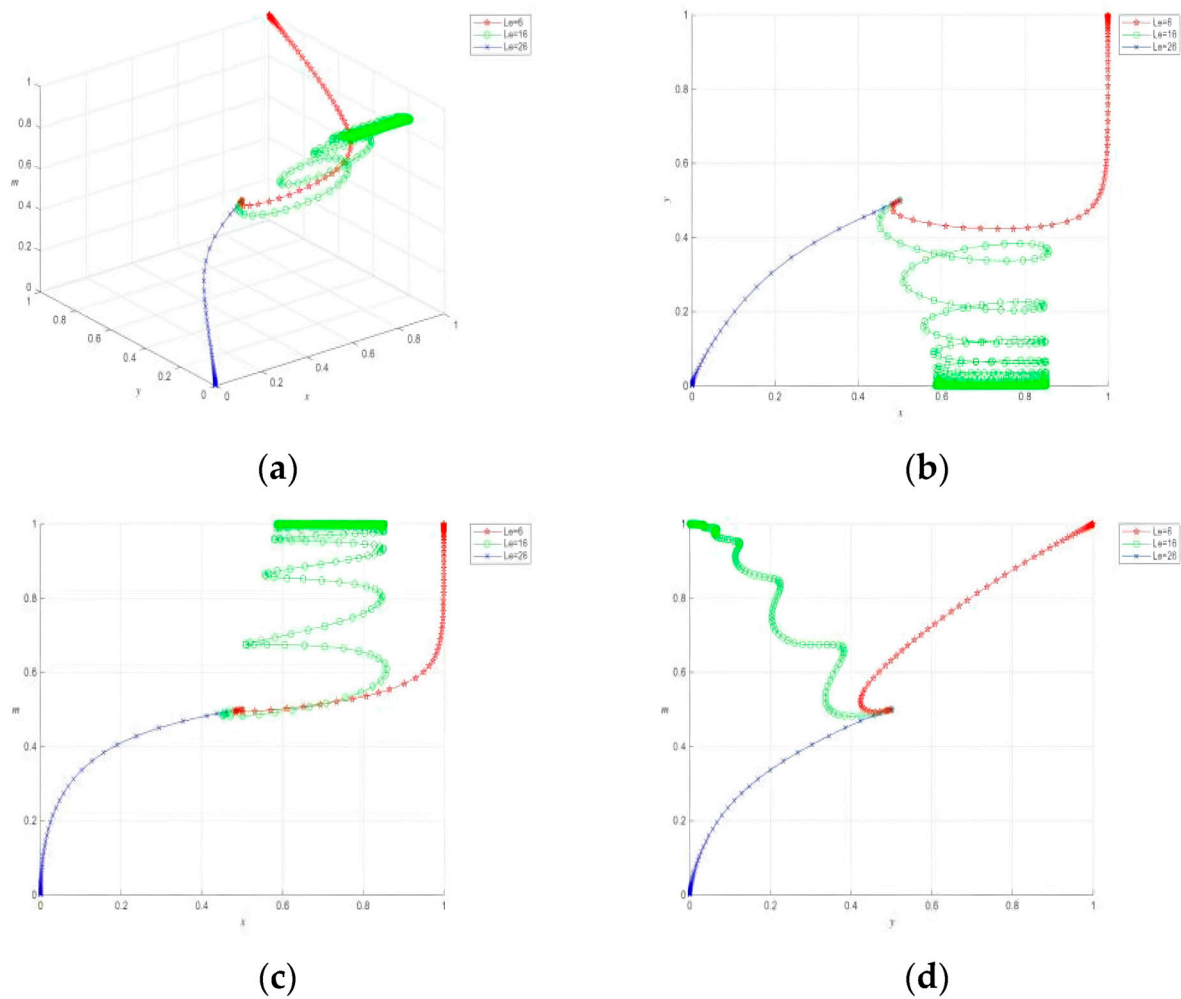


Figure 24. The Effect of Le : (a) (x, y, m) ; (b) (x, y) ; (c) (x, m) (d) (y, m) .

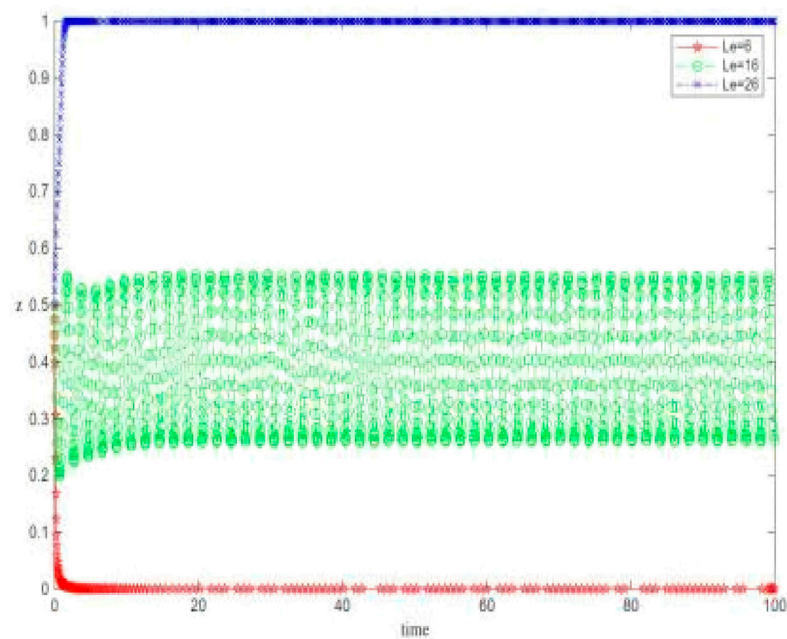


Figure 25. The effect of Le : (t, z) .

6. Discussion and Conclusions

This study constructs an evolutionary game model involving the government, enterprises, the public, and environmental public-interest organizations to examine the governance mechanisms of toxic metal pollution in farmland soils. By combining equilibrium analysis with numerical simulations, the results reveal a clear evolutionary pathway of governance, moving from fragmented and passive responses to coordinated regulation and ultimately to stable compliance.

First, the system exhibits distinct stage characteristics. In the early stage, governance is dominated by weak regulation and low participation, resulting in persistent illegal discharge. In the transitional stage, government-led regulation and increasing social participation strengthen external oversight, gradually promoting coordinated governance. In the mature stage, enterprises shift toward compliant behavior as a result of favorable cost–benefit conditions, thereby reducing the reliance on continuous external supervision.

Second, the formation of collaborative governance critically depends on the effectiveness of incentive and deterrence mechanisms. The results indicate that, under strengthened regulatory enforcement and improved policy instruments, such as subsidies, penalties, and cost compensation, multiple actors are more likely to participate in supervision following enterprise misconduct.

Third, the strategic choices of all players are primarily shaped by key economic and institutional factors. For enterprises, compliance is strongly influenced by pollution-control costs, expected returns from compliant production, and potential losses from detected violations. For the government, regulatory intensity depends on the trade-off between regulatory costs, environmental damage, and governance performance, leading it to adjust its strategy in response to changes in pollution risks and social participation. For the public and environmental public-interest organizations, participation is determined by monitoring costs, expected benefits, and government support. The simulation results further indicate that changes in these parameters can substantially alter governance trajectories across stakeholders, whereas differences in initial strategy distributions mainly affect the pace and transitional process of governance adjustment. In practical governance contexts, early behavioral conditions may influence how quickly coordination emerges, but sustained governance outcomes depend more on whether incentive structures and institutional arrangements support long-term strategic adaptation.

These findings also provide broader theoretical insights into collaborative environmental governance by highlighting that effective pollution control is driven not by the actions of any single stakeholder, but by the dynamic alignment of incentives among multiple actors. This conclusion is consistent with previous studies emphasizing the importance of collaborative governance in soil pollution control [5,23], while extending existing research by explicitly incorporating the strategic interactions among government, enterprises, the public, and environmental public-interest organizations. Furthermore, unlike previous studies that primarily focused on remediation technologies or equilibrium outcomes [5,6,24], the proposed framework offers an analytical perspective for interpreting how different stable governance configurations emerge through changes in stakeholder incentives and strategic adaptation, thereby extending the application of evolutionary game theory to the analysis of governance evolution processes.

7. Policy Recommendations

Building on the above findings, several policy implications are proposed to improve the governance of toxic metal pollution in China's farmland soils.

First, it is essential to strengthen incentive and deterrence mechanisms to enhance the effectiveness of multi-actor supervision [18,39]. Governments should increase penalties for

illegal discharge and improve enforcement credibility, while providing targeted subsidies and cost compensation for environmental public-interest organizations and the public. By improving the cost–benefit structure of participation, such measures can effectively activate social supervision in response to enterprise misconduct.

Second, reducing enterprises' compliance costs and improving the economic returns to compliant behavior are critical for promoting long-term environmental responsibility. Policymakers should support technological innovation, provide financial incentives, and facilitate access to cleaner production methods, thereby improving the relative attractiveness of compliant treatment [40]. Strengthening the internal economic viability of compliance can help shift enterprise behavior from externally driven adjustment to stable compliance.

Third, governance strategies should be dynamically adjusted according to different stages of development, with a focus on enhancing coordination among stakeholders. In the early stage, priority should be given to strengthening regulatory enforcement and raising awareness. In the transitional stage, policies should emphasize incentive alignment and broaden participation. In the mature stage, efforts should focus on maintaining stable institutional arrangements and reinforcing self-sustaining governance. At the same time, institutional platforms for information sharing and coordination should be improved to facilitate effective interaction between the government and various stakeholders [41]. It should also be recognized that the effectiveness of policy interventions may vary across governance contexts and may not follow a strictly proportional relationship with policy intensity. In practice, stakeholder responses can involve adaptive adjustments and interaction effects, suggesting that policy design should emphasize coordinated incentive structures rather than relying solely on stronger subsidies or stricter penalties.

8. Research Deficiencies and Prospects

Although this study combines evolutionary game theory with numerical simulations to investigate the governance of toxic metal pollution in farmland soils, several limitations remain. The proposed framework focuses on four key actors and may not fully reflect the complexity of real-world governance systems. In addition, although the parameter settings are designed based on cost and benefit relationships, the model inevitably simplifies factors such as behavioral preferences, institutional heterogeneity, and regional differences. The assumption of bounded rationality and utility-based decision-making improves analytical tractability but does not explicitly capture broader influences on stakeholder behavior, such as political performance evaluations, environmental awareness, social trust, and mission-oriented motivations. Furthermore, the study does not comprehensively examine how alternative strategy combinations affect long-term governance outcomes. Future research may incorporate additional stakeholders, introduce empirically calibrated parameters, and integrate behavioral and institutional dimensions to provide a more comprehensive understanding of collaborative environmental governance. Future research may incorporate additional stakeholders, introduce empirically calibrated parameters, and integrate behavioral, institutional, and nonlinear policy interaction mechanisms to better capture heterogeneous stakeholder responses and provide a more comprehensive understanding of collaborative environmental governance.

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Conflicts of Interest: The authors declare no conflicts of interest.

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