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From Shirking to Sharing: Evolutionary Game Analysis of Responsibility Mechanisms in Digital Environmental Governance

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Abstract

Government–enterprise collaboration does not automatically produce responsibility sharing in digital environmental governance. Integrating Social Role Theory with evolutionary game theory, this study constructs a role-based evolutionary game model to examine how governments and enterprises adjust responsibility strategies under bounded rationality. The model incorporates legitimacy benefits, role-deviation losses, digital governance capacity, compliance costs, penalties, and governance costs. Results show two possible stable outcomes—mutual responsibility fulfillment and mutual shirking—with threshold-sensitive dynamics. Stronger digital capacity, detection probability, penalties, and legitimacy incentives, combined with lower costs, expand the attraction basin of mutual responsibility fulfillment; weak monitoring, high costs, insufficient penalties, and ambiguous boundaries increase shirking risk. A focused VRBG mechanism—value cultivation, responsibility identification, benefit sharing, and guarantee mechanisms—is proposed to adjust the incentive conditions that make responsibility fulfillment self-reinforcing.

Keywords: digital era; government enterprise collaboration; digital ecological governance; responsibility mechanism; evolutionary game model

1. Introduction

Digital transformation is reshaping both the instruments and incentive structure of environmental governance (Lyu et al., 2023). Online monitoring systems, environmental data platforms, artificial intelligence, remote sensing, and digital information disclosure mechanisms have expanded the capacity of governments and enterprises to monitor ecological risks, reduce information asymmetry, and coordinate regulatory action (Y. Zhang et al., 2026). More importantly, these technologies may alter the payoff structure of responsibility fulfillment. For governments, digital governance can reduce regulatory and coordination costs by improving data collection, real-time monitoring, and interdepartmental information sharing. For enterprises, it can increase the probability that environmental shirking is detected and penalized, while strengthening reputational and legitimacy incentives for responsible behavior (Jin & Yang, 2025). Therefore, digital governance should not be treated merely as a contextual background; it should be incorporated into the analytical model as a mechanism that affects regulatory cost, detection probability, expected penalty, and responsibility incentives (Y. Li & Zhu, 2026).

However, digital tools do not automatically lead to effective responsibility fulfillment (Horn & Felt, 2025). In practice, digital environmental governance may still coexist with



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fragmented responsibility allocation, weak accountability, strategic non-compliance, and symbolic collaboration. This problem is particularly evident in government–enterprise collaboration, where governments are expected to regulate, coordinate, and enforce environmental accountability, while enterprises are expected to control pollution, disclose environmental information, pursue green innovation, and fulfill environmental responsibilities (Jiang & Luo, 2025; Qian et al., 2022). Yet these role expectations do not necessarily translate into actual behavior. Governments may reduce regulatory effort when supervision is costly or accountability pressure is weak (Tian, 2026), and enterprises may shirk environmental responsibilities when compliance costs are high, short-term benefits are attractive, or the probability of detection is low (Y. Chen et al., 2026). Therefore, the central issue is not simply whether digital technologies are adopted, but whether they can reshape responsibility boundaries and behavioral incentives so that government–enterprise interaction evolves toward mutual responsibility fulfillment rather than mutual shirking.

To explain this mechanism, this study integrates Social Role Theory with evolutionary game theory. Social Role Theory is used to clarify the role expectations and responsibility positions of governments and enterprises in digital environmental governance (Biddle, 1986), while evolutionary game theory is employed to examine how these actors adjust their strategies under bounded rationality and repeated interaction (Zhou et al., 2025). In this framework, role-based legitimacy gains and role-deviation losses are introduced into the payoff structure, and digital governance capacity is modeled as a factor that changes governmental regulatory costs and the expected consequences of corporate shirking (Q. Pan et al., 2025; Zhan & Lv, 2025).

This study addresses three research questions. First, how can the role expectations of governments and enterprises in digital environmental governance be operationalized within an evolutionary game framework? Second, under what parameter conditions does government–enterprise interaction evolve toward mutual responsibility fulfillment rather than mutual shirking? Third, how do digital governance capacity, legitimacy incentives, regulatory costs, detection probability, and penalty intensity shape the evolutionary trajectory of responsibility sharing?

This study contributes by (1) operationalizing role expectations and legitimacy gains or losses as payoffs in an evolutionary game; (2) redefining digital governance capacity as an institutional condition that alters regulatory costs, detection probability, penalties, and responsibility incentives, rather than a mere technological background; and (3) showing that institutional accountability, digital monitoring, and legitimacy-based incentives jointly determine whether government–enterprise interaction evolves toward responsibility sharing or shirking, challenging the assumption that collaboration automatically ensures responsible behavior.

2. Literature Review and Research Gap

2.1. Digital Environmental Governance and Responsibility Fulfillment

Digital environmental governance has attracted increasing scholarly attention as public authorities and enterprises rely more heavily on data-driven tools to support environmental monitoring, regulatory enforcement, and information disclosure (Chai et al., 2026; OECD, 2021). Existing studies generally emphasize the functional value of digitalization: it improves the visibility of pollution behavior, facilitates cross-departmental information sharing, strengthens environmental disclosure, and supports more precise and timely regulatory intervention (Q. Li et al., 2025; Zhao et al., 2025). Related research on the digital economy also shows that digitalization can promote green and low-carbon transformation by improving production efficiency, data processing capacity, and environmental management practices (W. Zhang et al., 2022).

However, this functional perspective remains insufficient for explaining responsibility fulfillment. Treating digital governance primarily as a technical instrument may obscure the fact that environmental responsibility is ultimately shaped by incentives, accountability, and strategic interaction (Kovacic & Argüelles, 2025). Digital tools may improve visibility and traceability, but they do not automatically prevent fragmented responsibility allocation, symbolic compliance, or strategic non-compliance (Xu et al., 2026). Therefore, the key question is not only what digital technologies enable, but how digital governance capacity changes the conditions under which governments and enterprises choose to fulfill or shirk environmental responsibilities. This requires shifting the analysis from the technical functions of digital governance to its effects on regulatory cost, detection probability, expected penalties, reputational pressure, and role-based responsibility incentives (X. Chen et al., 2025; Du, 2014).

2.2. Government–Enterprise Collaboration and Responsibility Sharing

Government–enterprise collaboration has been widely examined in the literature on collaborative governance, public–private partnerships, environmental regulation, and corporate environmental responsibility. Prior research has emphasized that environmental governance increasingly depends on the joint participation of public and private actors rather than unilateral government control (Jiaqi, 2023; Qiang & Ruan, 2025; B. Wang et al., 2024; S. Wang et al., 2024). Public–private partnerships have been discussed as institutional arrangements for mobilizing private resources, managerial capacity, and collaborative mechanisms in the delivery of public goods and sustainability-related projects (De Matteis et al., 2024). At the same time, PPP-based governance is exposed to risks related to contractual uncertainty, responsibility ambiguity, and implementation failure, especially when public and private actors face different objectives and accountability pressures (Ampratwum et al., 2022). Broader studies on adaptive governance and grand challenges also show that complex public problems often require multi-level coordination, institutional flexibility, and bottom-up participation (Bours et al., 2021).

In environmental governance, governments are usually conceptualized as policy designers, regulators, coordinators, and public-interest guardians, while enterprises are treated as key private actors whose environmental behavior is shaped by regulatory pressure, compliance costs, market incentives, reputational concerns, and expected returns from green transformation (L. Gao & Wan, 2023; X. Li et al., 2024). Recent studies on water environmental governance further emphasize the importance of multi-agent coordination under regulatory inspection mechanisms (Q. Li et al., 2024). This literature moves beyond a purely normative view of responsibility by highlighting the institutional and incentive constraints under which governments and enterprises decide whether to cooperate, comply, or behave strategically. Government–enterprise interaction may also produce strategic distortions: environmental signals, collusion, and pollution transfer indicate that enterprises may respond strategically to regulation rather than simply comply with public environmental objectives (Hong et al., 2020), and recent research has directly framed government–enterprise collaboration in environmental management as a gaming dilemma shaped by regulatory incentives, enterprise costs, and expected benefits (Cao et al., 2024). However, existing studies still do not fully explain how responsibility expectations are transformed into strategic choices under conditions of bounded rationality, asymmetric information, and digital monitoring. In particular, the link between responsibility boundaries and behavioral incentives remains underdeveloped, making it necessary to develop a framework that connects responsibility allocation with the evolutionary logic of government–enterprise strategy selection.

2.3. Social Role Theory and Role-Based Responsibility

Social Role Theory provides a useful theoretical foundation for explaining why governments and enterprises are expected to assume different responsibilities in environmental governance. According to Social Role Theory, actors' behavior is shaped by institutionalized expectations, social norms, role identities, legitimacy requirements, and sanctions for role deviation (Biddle, 1986). Roles are not merely descriptive categories; they define what actors are expected to do, how their behavior is evaluated, and what consequences follow when they conform to or deviate from expected conduct (Burke, 1991).

In digital environmental governance, the role of government is not limited to economic regulation. Governments are expected to act as institutional leaders, coordinators, regulators, enforcers, and guardians of public environmental interests (Jordan et al., 2005). Enterprises are not merely profit-seeking organizations; they are also expected to act as collaborative partners, technological enablers, sustainability contributors, and information disclosers (Buccella et al., 2026; George et al., 2021). Digital transformation further reshapes these role expectations by increasing transparency, expanding data-based supervision, and strengthening public and regulatory scrutiny (Jho & Song, 2015).

However, existing applications of Social Role Theory in governance research are often conceptual or normative. They clarify what actors ought to do, but they rarely explain how role expectations become incentives that affect strategic behavior. This creates a theoretical gap between role-based responsibility and formal behavioral analysis. To address this gap, role expectations need to be translated into modelable payoff components. In this study, role fulfillment is associated with legitimacy gains, reputational benefits, and institutional recognition, while role deviation is associated with legitimacy losses, accountability pressure, and potential sanctions. This operationalization allows Social Role Theory to inform the payoff logic of an evolutionary game model rather than functioning only as a descriptive theoretical background.

2.4. Evolutionary Game Approaches to Environmental Governance

Evolutionary game theory has been widely used to analyze environmental governance because it is well suited to contexts characterized by bounded rationality, repeated interaction, incomplete information, and adaptive learning (Tang et al., 2026; J. Wang et al., 2023; Yan et al., 2026; Zhou et al., 2025). Existing evolutionary game studies have analyzed strategic interactions among local governments in environmental regulation (L. Zhang et al., 2023), regional collaborative governance in haze pollution control (Hussain et al., 2025), and ecological governance strategies in the Yangtze River Delta region (F. Li et al., 2017). Evolutionary game analysis has also been applied to digital innovation ecosystems and government–enterprise environmental management, showing its usefulness for explaining cooperation, conflict, and strategic adjustment in complex governance systems (J. Gao et al., 2026; N. Li et al., 2025).

Despite these contributions, many existing evolutionary game models remain conventional cost–benefit models. They usually focus on economic payoffs, compliance costs, regulatory costs, penalties, and losses, while paying insufficient attention to role-based legitimacy and responsibility expectations. In addition, digital governance is often mentioned as a contextual feature but is not formally incorporated into the payoff structure. As a result, existing models do not sufficiently explain how digital monitoring, data transparency, information disclosure, and platform-based supervision change the strategic conditions under which governments and enterprises choose whether to fulfill environmental responsibilities.

This limitation is particularly important in the digital era. Digital governance capacity may reduce government regulatory and coordination costs, increase the probability of detecting corporate shirking, improve the enforceability of penalties, and amplify the

reputational consequences of environmental misconduct (Yang et al., 2026). These effects directly influence the expected payoffs of both governments and enterprises. Therefore, evolutionary game analysis of digital environmental governance should not treat digitalization as a general background condition. It should explicitly incorporate digital governance capacity and role-based incentives into the payoff structure.

2.5. Research Gap

In summary, prior studies have examined PPP-based collaboration and sustainability governance, multi-agent environmental governance, corporate environmental responsibility, and evolutionary game models of environmental regulation and ecological governance. However, three gaps remain. First, digital environmental governance is often discussed in terms of technical functions, while its effects on regulatory costs, detection probability, expected penalties, and responsibility incentives are rarely incorporated into formal models of government–enterprise interaction. Second, research on government–enterprise collaboration has examined institutional design and governance performance, but has not sufficiently explained how responsibility boundaries and role expectations shape strategic behavior. Third, existing evolutionary game models in environmental governance mainly rely on economic costs, benefits, penalties, and losses, with limited operationalization of role-based legitimacy gains and role-deviation losses.

To address these gaps, this study develops a role-based evolutionary game model of government–enterprise responsibility sharing in digital environmental governance. By incorporating digital governance capacity and role-based incentives into the payoff structure, the model explains responsibility sharing as a dynamic process of role–incentive alignment rather than as a static division of duties.

3. Methodology and Model Construction

3.1. Analytical Framework

To connect the preceding theoretical discussion with the formal model, this study develops an analytical framework for government–enterprise responsibility sharing in digital environmental governance. The framework links three elements: role-based responsibility allocation, digital governance conditions, and evolutionary strategy adjustment. Rather than treating governments and enterprises as purely economic actors, it conceptualizes them as role-bearing agents whose strategic choices are shaped by institutional expectations, accountability pressure, legitimacy evaluation, and adaptive learning under bounded rationality (Biddle, 1986; Eagly & Wood, 2012).

As shown in Figure 1, governments and enterprises occupy differentiated but interdependent responsibility positions. Governments act as institutional leaders, coordinators, regulators, enforcers, and guardians of public environmental interests, while enterprises act as collaborative partners, technological enablers, sustainability contributors, and environmental information disclosers (Buccella et al., 2026; George et al., 2021; Jordan et al., 2005). These role positions define not only what each actor is expected to do, but also how responsibility fulfillment or shirking is evaluated in collaborative ecological governance.

The framework serves as the bridge between Social Role Theory and the evolutionary game model. Role fulfillment is translated into legitimacy and reputational gains, whereas role deviation is translated into legitimacy loss, accountability pressure, and reputational damage. Meanwhile, digital governance capacity is treated as a governance condition that changes the incentive environment rather than as a general technological background: it affects the probability that corporate shirking is detected and the effective cost of governmental supervision and coordination. Accordingly, the framework provides the logical

basis for introducing role legitimacy benefits, role-deviation losses, digital detection probability, and effective governance costs into the payoff matrix developed below.

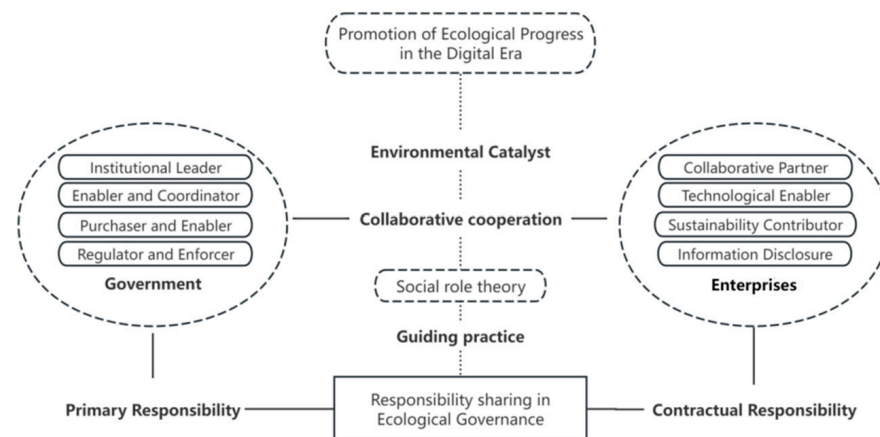


Figure 1. Responsibility sharing in government–enterprise ecological governance cooperation in the digital age.

3.2. Role-Based Responsibility Operationalization

Building on the role positions identified in Figure 1, this section specifies how role-based responsibility is translated into modelable payoff items. Responsibility fulfillment is not treated merely as cost-bearing behavior, and responsibility shirking is not treated merely as cost-saving behavior. Instead, this study incorporates two role-theoretic mechanisms into the payoff structure: legitimacy gains generated by role-conforming responsibility fulfillment and role-deviation losses generated by responsibility shirking (Akerlof & Kranton, 2000; Suchman, 1995).

For enterprises, fulfilling ecological responsibility conforms to their expected roles as sustainability contributors, green innovators, and environmental information disclosers. Therefore, enterprise fulfillment generates not only long-term operational benefits but also legitimacy, reputation, and stakeholder trust gains. Conversely, enterprise shirking may create short-term economic gains, but it also produces role-deviation losses, including reputational damage, weakened stakeholder trust, reduced legitimacy, and increased market or financing pressure (Bansal & Clelland, 2004; Freeman, 1984).

For governments, fulfilling regulatory and coordination responsibilities conforms to their expected roles as regulators, coordinators, and guardians of environmental public interests. Therefore, government fulfillment generates governance performance, role legitimacy, and public recognition. Government shirking, by contrast, violates its public responsibility role and produces role-deviation and accountability losses, including declining public trust, administrative accountability pressure, legitimacy erosion, and damage to governance credibility (Bovens, 2007; Skarlatidou et al., 2024).

Accordingly, the model operationalizes role-based responsibility through actor-specific legitimacy gains and role-deviation losses for both enterprises and governments. These role-based items are incorporated into the payoff matrix together with economic benefits, responsibility costs, regulatory penalties, governance losses, and digital-governance-related parameters.

3.3. Model Assumptions

To examine the evolutionary mechanism of responsibility fulfillment in digital environmental governance, this study constructs a two-population evolutionary game model between governments and enterprises. Different from a conventional cost benefit model, the proposed model explicitly incorporates role legitimacy benefits, role-deviation losses,

and digital governance capacity into the payoff structure. The main assumptions are as follows.

Assumption 1. *Bounded rationality and adaptive strategy adjustment.*

Both governments and enterprises are boundedly rational actors. In repeated interactions, they cannot obtain complete information at once, nor can they immediately make fully optimal decisions. Instead, they gradually adjust their strategies according to expected payoffs, past experience, and feedback from previous interactions.

Enterprises have two strategic choices: assuming ecological responsibility, denoted by A , and shirking ecological responsibility, denoted by S . Let x denote the proportion of enterprises choosing A , and $1 - x$ denote the proportion choosing S . Governments also have two strategic choices: fulfilling regulatory and coordination responsibilities, denoted by I , and shirking governmental responsibility, denoted by N . Let y denote the proportion of governments choosing I , and $1 - y$ denote the proportion choosing N , and $(x, y \in [0, 1])$.

Assumption 2. *Enterprise responsibility fulfillment is shaped by both economic incentives and role expectations.*

When enterprises assume ecological responsibility, they obtain a long-term basic benefit R_1 . This benefit may arise from green production, compliant operation, pollution control, technological upgrading, and improved environmental management. However, enterprises also bear a responsibility fulfillment cost C_E , including the costs of green technology investment, pollution treatment, environmental information disclosure, technical upgrading, and compliance management. In addition, enterprises obtain a role legitimacy or reputational benefit L_E , because their behavior conforms to the expected role of enterprises as sustainability contributors, green innovators, and environmental information disclosers.

When enterprises shirk ecological responsibility, they may obtain a short-term benefit R_2 by reducing environmental protection investment, avoiding pollution-control costs, weakening information disclosure, or lowering compliance expenditure. However, shirking also generates a role-deviation loss H_E , including reputational damage, declining stakeholder trust, weakened social legitimacy, and increased market or financing pressure. If the government fulfills its regulatory responsibility, an enterprise that shirks ecological responsibility will be detected with probability $p(\theta)$, where $p(\theta)$ denotes the detection probability under the level of digital governance capacity θ , with $p'(\theta) > 0$. Once detected, the enterprise is subject to a penalty with intensity F . Therefore, the expected penalty loss of enterprise shirking is $Fp(\theta)$. The collected penalties accrue to the government as a source of regulatory revenue.

Assumption 3. *Government responsibility fulfillment is shaped by governance performance, role legitimacy, and accountability pressure.*

This study does not treat governments as private profit-maximizing actors. Government payoff refers to public governance utility rather than commercial profit. When governments fulfill regulatory and coordination responsibilities, they bear an effective governance cost $C_G(\theta)$, including environmental monitoring, administrative coordination, enforcement, data processing, platform operation, and routine regulatory implementation. At the same time, governments obtain a role legitimacy and governance-performance benefit L_G , because responsibility fulfillment conforms to their institutional role as regulators, coordinators, and guardians of public environmental interests.

If enterprises assume ecological responsibility A and governments fulfill their responsibilities I , governments additionally obtain a governance performance benefit D , such as environmental improvement, enhanced governance performance, and increased public satisfaction. The government payoff in this case is $L_G - C_G(\theta) + D$.

If enterprises shirk ecological responsibility S and governments fulfill their responsibilities I , governments still obtain the role legitimacy benefit L_G and, crucially, receive the penalty revenue $Fp(\theta)$ collected from non-compliant enterprises. However, they also suffer a governance loss E caused by enterprises' shirking behavior and bear the governance cost $C_G(\theta)$. The government payoff is therefore $L_G - C_G(\theta) + Fp(\theta) - E$.

If governments shirk responsibility N , they avoid the direct governance cost $C_G(\theta)$ but incur a role-deviation and accountability loss H_G , including declining public trust, administrative accountability pressure, legitimacy loss, and damage to governance credibility. Enterprise shirking always leads to a governance loss E , irrespective of the government's own action.

When enterprises assume responsibility A and governments shirk N , governments obtain only a partial spillover benefit αD (where $0 < \alpha < 1$) and suffer the loss H_G . Payoff: $\alpha D - H_G$.

When enterprises shirk S and governments shirk N , governments suffer both the role-deviation loss H_G and the governance loss E . Payoff: $-H_G - E$.

Assumption 4. *Digital governance capacity affects both violation detection probability and effective governmental governance cost.*

The parameter θ denotes the level of digital governance capacity in digital environmental governance, where $\theta \in [0,1]$. A higher value of θ indicates a higher degree of integration of digital monitoring infrastructure, environmental data platforms, cross-departmental data sharing, online regulatory systems, remote sensing technologies, sensor networks, and algorithmic identification tools into the governance process.

Digital governance affects the government enterprise game through two mechanisms. First, digital governance increases the probability that enterprise shirking behavior is detected, denoted by $p(\theta)$, where $0 < p(\theta) < 1$ and $p'(\theta) > 0$. Second, digital governance reduces the effective cost of governmental supervision, coordination, and information processing, denoted by $C_G(\theta)$, where $C_G(\theta) > 0$ and $C_G'(\theta) < 0$. This means that stronger digital governance capacity lowers the effective cost of information search, routine monitoring, cross-departmental coordination, platform operation, and regular enforcement.

This assumption does not imply that digital governance eliminates all governmental governance costs. Rather, it means that once digital infrastructure is embedded in the governance process, digital technologies can reduce the effective costs of information search, daily monitoring, interdepartmental coordination, platform operation, and routine enforcement.

Assumption 5. *Partial governance-benefit spillover and strategic dilemma.*

Government enterprise responsibility fulfillment involves both cooperative gains and free-riding incentives. When enterprises assume ecological responsibility while governments shirk responsibility, governments may still benefit partially from enterprises' responsible behavior. This partial benefit is expressed as αD , where $0 < \alpha < 1$. The parameter α captures the spillover effect of enterprise responsibility fulfillment or the governmental free-riding effect: even if governments do not actively fulfill their responsibilities, enterprise responsibility fulfillment may still improve environmental outcomes and governance performance to some extent, but this benefit is incomplete.

To ensure that the model captures a real strategic dilemma rather than presupposing inevitable cooperation, the parameter setting should allow both responsibility fulfillment and responsibility shirking to emerge under different conditions. The basic feasibility conditions are:

$$R_1, R_2, C_E, D, E, F, L_E, L_G, H_E, H_G > 0, C_G(\theta) > 0, 0 < \alpha < 1, 0 < p(\theta) < 1$$

To allow the system to potentially exhibit both “mutual shirking” and “mutual responsibility sharing” as evolutionary outcomes, the following directional conditions can be considered and further verified through replicator dynamics, Jacobian matrix analysis, and numerical simulation:

$$\begin{aligned} R_2 - H_E &> R_1 - C_E + L_E, \\ R_1 - C_E + L_E &> R_2 - H_E - p(\theta)F \\ C_G(\theta) &> L_G + H_G + p(\theta)F \\ L_G + H_G + (1 - \alpha)D &> C_G(\theta) \end{aligned}$$

These conditions indicate that, when governmental supervision is absent, enterprises may be more inclined to shirk responsibility. However, when governments fulfill their responsibilities and the digital detection mechanism is effective, enterprises may be more inclined to assume responsibility. Similarly, when enterprises shirk and governmental governance costs are high, governments may tend to shirk responsibility; but when enterprises assume responsibility and the governance gains from active governmental fulfillment are sufficiently high, governments may be more inclined to fulfill their responsibilities. The stability of the final equilibrium points should be further determined through the replicator dynamic equations, the Jacobian matrix, and numerical simulations.

3.4. Parameter Definitions and Payoff Matrix

Based on the model assumptions above, this study defines the parameters of the evolutionary game model as shown in Table 1. The parameters are normalized theoretical variables rather than direct monetary measures. They represent the relative magnitude of economic benefits, governance utility, responsibility costs, legitimacy gains, role-deviation losses, penalty intensity, and digital governance capacity. This setting enables the model to capture both material incentives and role-based institutional pressures in digital environmental governance.

Table 1. Parameter definitions.

Symbol	Definition	Interpretation and Model Role
R_1	Long-term basic benefit obtained by enterprises when assuming ecological responsibility	Represents long-term gains from green production, compliant operation, pollution control, green innovation, and environmental management. It increases the payoff of enterprises choosing responsibility fulfillment.
R_2	Short-term benefit obtained by enterprises when shirking ecological responsibility	Represents short-term gains from reducing environmental investment, avoiding pollution treatment, weakening information disclosure, and lowering compliance costs. It increases the payoff of enterprises choosing responsibility shirking.
C_E	Cost of enterprise ecological responsibility fulfillment	Includes costs of environmental equipment, green technology upgrading, pollution treatment, environmental information disclosure, and compliance management. It reduces the payoff of enterprises choosing responsibility fulfillment.
$C_G(\theta)$	Effective governmental governance cost under digital governance	Includes costs of environmental supervision, administrative coordination, enforcement inspection, data processing, platform operation, and regulatory implementation. It decreases as digital governance capacity θ improves.
D	Governance benefit obtained by governments when enterprises assume ecological responsibility	Represents environmental improvement, better governance performance, higher public satisfaction, and fewer environmental complaints. It increases governmental governance utility.
E	Governance loss caused by enterprise shirking	Represents pollution, ecological damage, governance failure, public dissatisfaction, and accountability risk. It reduces governmental payoff when enterprises shirk responsibility.

Table 1. Cont.

Symbol	Definition	Interpretation and Model Role
F	Penalty intensity imposed on enterprises that shirk ecological responsibility	Includes fines, administrative sanctions, credit punishment, market access restrictions, public exposure, and other regulatory penalties. When shirking is detected, it reduces the expected payoff of enterprises by $Fp(\theta)$; in the governmental payoff, it reflects enforcement, deterrence, or accountability-relief effects generated by successful punishment.
L_E	Role legitimacy or reputational benefit obtained by enterprises when assuming responsibility	Represents reputation, legitimacy, stakeholder trust, and social recognition obtained when enterprises conform to their expected roles as sustainability contributors, green innovators, and environmental information disclosers.
L_G	Role legitimacy and governance-performance benefit obtained by governments when fulfilling responsibility	Represents public recognition, governance performance, institutional legitimacy, and administrative credibility obtained when governments conform to their expected roles as regulators, coordinators, and guardians of public environmental interests.
H_E	Role-deviation loss caused by enterprise shirking	Represents reputational damage, declining stakeholder trust, weakened legitimacy, and increased financing or market pressure caused by enterprise role deviation. It reduces the attractiveness of enterprise shirking.
H_G	Role-deviation and accountability loss caused by governmental shirking	Represents public criticism, accountability pressure, legitimacy loss, and damage to governance credibility caused by governmental role deviation. It reduces the attractiveness of governmental shirking.
θ	Digital governance capacity	Represents the degree to which digital monitoring infrastructure, environmental data platforms, cross-departmental data sharing, online regulatory systems, remote sensing technologies, sensor networks, and algorithmic identification tools are embedded in ecological governance. It affects both $p(\theta)$ and $C_G(\theta)$.
$p(\theta)$	Probability that enterprise shirking is detected under digital governance	Represents the detection probability of enterprise shirking under digital governance. A higher θ increases $p(\theta)$, thereby increasing the expected penalty for shirking enterprises.
α	Proportion of partial governance benefit obtained by governments when they shirk while enterprises assume responsibility	Captures the spillover effect of enterprise responsibility fulfillment or governmental free-riding. When governments shirk while enterprises assume responsibility, governments obtain only αD rather than the full governance benefit D , where $0 < \alpha < 1$.

Although the parameters in Table 1 are normalized theoretical variables rather than empirically estimated values, they are not purely abstract or unobservable. They can be linked to observable indicators in future empirical applications. For example, enterprise responsibility-fulfillment costs may be proxied by pollution-control investment, environmental protection expenditure, clean-technology upgrading costs, and environmental disclosure costs (Pokharel, 2026; Tu & He, 2026; D. Zhang et al., 2019). Governmental governance costs may be proxied by environmental enforcement expenditure, monitoring staff input, inspection frequency, data-platform operation costs, and administrative coordination costs (F. Pan et al., 2022; Z. Wu et al., 2026). Detection probability may be estimated through detected violations relative to total inspections, online-monitoring alerts, environmental enforcement records, or violation-detection rates (Svatikova & Faure, 2010; Xie et al., 2026). Role legitimacy benefits and role-deviation losses may be approximated by ESG ratings, environmental credit records, media attention, public complaints, financing constraints, corporate reputation, and administrative accountability records (Qu & Xia, 2024; Shen et al., 2025). Appendix B provides a summary of possible empirical proxies and calibration routes for the main model parameters. Therefore, while the present model remains theoretical, its parameters provide a structure that future studies can calibrate using firm-level environmental data, governmental enforcement records, environmental penalty databases, ESG disclosure data, public complaint data, and digital governance indicators.

According to the strategy settings, enterprises have two strategies: assuming ecological responsibility, denoted by A , and shirking ecological responsibility, denoted by S . Governments also have two strategies: fulfilling regulatory and coordination responsibility, denoted by I , and shirking governmental responsibility, denoted by N . The payoff matrix is constructed in Table 2. In each cell, the first payoff refers to the enterprise, and the second payoff refers to the government.

Table 2. Payoff matrix of the evolutionary game between enterprises and governments.

Enterprise Strategy	Government Fulfills Responsibility I, Probability y	Government Shirks Responsibility N, Probability $1 - y$
Enterprise assumes ecological responsibility A, probability x	$R_1 - C_E + L_E, D + L_G - C_G(\theta)$	$R_1 - C_E + L_E, \alpha D - H_G$
Enterprise shirks ecological responsibility S, probability $1 - x$	$R_2 - Fp(\theta) - H_E, Fp(\theta) + L_G - C_G(\theta) - E$	$R_2 - H_E, -E - H_G$

The payoff matrix reflects four strategic situations.

First, when enterprises assume ecological responsibility and governments fulfill regulatory and coordination responsibility, enterprises obtain the long-term benefit R_1 and the role legitimacy benefit L_E , while bearing the responsibility fulfillment cost C_E . Governments obtain the governance benefit D and the role legitimacy and governance-performance benefit L_G , while bearing the effective governance cost $C_G(\theta)$. Therefore, the payoff pair is $R_1 - C_E + L_E, D + L_G - C_G(\theta)$.

Second, when enterprises assume ecological responsibility but governments shirk responsibility, enterprises still obtain R_1 and L_E while bearing C_E . Governments do not bear active governance costs, but they obtain only a partial spillover benefit αD from enterprise responsibility fulfillment and incur the role-deviation and accountability loss H_G . Therefore, the payoff pair is $R_1 - C_E + L_E, \alpha D - H_G$.

Third, when enterprises shirk ecological responsibility but governments fulfill responsibility, enterprises obtain the short-term benefit R_2 but suffer the role-deviation loss H_E . Because governmental supervision is active, enterprise shirking is detected with probability $p(\theta)$, and the expected penalty loss is $Fp(\theta)$. Governments obtain the role legitimacy and governance-performance benefit L_G and may obtain enforcement, deterrence, or accountability-relief effects $Fp(\theta)$ from successful punishment. However, they bear the effective governance cost $C_G(\theta)$ and suffer the governance loss E caused by enterprise shirking. Therefore, the payoff pair is $R_2 - Fp(\theta) - H_E, Fp(\theta) + L_G - C_G(\theta) - E$.

Fourth, when enterprises shirk ecological responsibility and governments also shirk responsibility, enterprises obtain the short-term benefit R_2 but suffer the role-deviation loss H_E . Governments avoid active governance costs, but they suffer both the governance loss E caused by enterprise shirking and the role-deviation and accountability loss H_G caused by governmental shirking. Therefore, the payoff pair is $R_2 - H_E, -E - H_G$.

This payoff matrix links Social Role Theory with the evolutionary game model. Role-conforming behavior is represented by L_E and L_G , while role-deviation behavior is represented by H_E and H_G . Digital governance capacity is incorporated through $p(\theta)$ and $C_G(\theta)$: a higher level of θ increases the probability that enterprise shirking is detected and reduces the effective cost of governmental supervision and coordination. Therefore, the model does not treat digital governance as a general contextual background, but as a parameterized institutional condition that changes the payoff structure of government enterprise responsibility interaction.

3.5. Evolutionary Game Model and Replicator Dynamics

Based on the payoff matrix above, this section derives the expected payoffs and replicator dynamic equations of enterprises and governments. Since x denotes the proportion of enterprises choosing responsibility fulfillment A , the enterprise replicator dynamic equation is expressed as $F(x) = \frac{dx}{dt}$. Since y denotes the proportion of governments choosing responsibility fulfillment I , the government replicator dynamic equation is expressed as $F(y) = \frac{dy}{dt}$.

For enterprises, the expected payoff of choosing ecological responsibility fulfillment A is:

$$U_E^A = y(R_1 - C_E + L_E) + (1 - y)(R_1 - C_E + L_E)$$

Thus:

$$U_E^A = R_1 - C_E + L_E$$

The expected payoff of choosing ecological responsibility shirking S is:

$$U_E^S = y[R_2 - Fp(\theta) - H_E] + (1 - y)(R_2 - H_E)$$

Thus:

$$U_E^S = R_2 - H_E - Fyp(\theta)$$

Therefore, the payoff difference between enterprise responsibility fulfillment and enterprise responsibility shirking is:

$$U_E^A - U_E^S = R_1 - C_E + L_E - R_2 + H_E + Fyp(\theta)$$

The average expected payoff of the enterprise population is:

$$\bar{U}_E = xU_E^A + (1 - x)U_E^S$$

According to the standard replicator dynamic principle, the enterprise replicator dynamic equation is:

$$F(x) = \frac{dx}{dt} = x(U_E^A - \bar{U}_E)$$

Equivalently:

$$F(x) = \frac{dx}{dt} = x(1 - x)(U_E^A - U_E^S)$$

Substituting the payoff difference into the equation gives:

$$F(x) = \frac{dx}{dt} = x(1 - x)[R_1 - C_E + L_E - R_2 + H_E + Fyp(\theta)]$$

This equation indicates that enterprises are more likely to evolve toward responsibility fulfillment when the long-term benefit R_1 , role legitimacy benefit L_E , role-deviation loss H_E , detection probability $p(\theta)$, and penalty intensity F are sufficiently high, or when the responsibility fulfillment cost C_E and short-term shirking benefit R_2 are relatively low.

For governments, the expected payoff of choosing regulatory and coordination responsibility fulfillment I is:

$$U_G^I = x[D + L_G - C_G(\theta)] + (1 - x)[p(\theta)F + L_G - C_G(\theta) - E]$$

The expected payoff of choosing governmental responsibility shirking N is:

$$U_G^N = x[\alpha D - H_G] + (1 - x)(-E - H_G)$$

Therefore, the payoff difference between governmental responsibility fulfillment and governmental responsibility shirking is:

$$U_G^I - U_G^N = L_G + H_G - C_G(\theta) + x(1 - \alpha)D + F(1 - x)p(\theta)$$

The average expected payoff of the government population is:

$$\bar{U}_G = yU_G^I + (1 - y)U_G^N$$

According to the standard replicator dynamic principle, the government replicator dynamic equation is:

$$F(y) = \frac{dy}{dt} = y(U_G^I - \bar{U}_G)$$

Equivalently:

$$F(y) = \frac{dy}{dt} = y(1 - y)(U_G^I - U_G^N)$$

Substituting the payoff difference into the equation gives:

$$F(y) = \frac{dy}{dt} = y(1 - y)[L_G + H_G - C_G(\theta) + x(1 - \alpha)D + F(1 - x)p(\theta)]$$

This equation indicates that governments are more likely to evolve toward responsibility fulfillment when the role legitimacy and governance-performance benefit L_G , accountability loss H_G , governance benefit D , detection probability $p(\theta)$, and penalty intensity F are sufficiently high, or when the effective governance cost $C_G(\theta)$ is relatively low. The parameter α captures the partial spillover benefit obtained by governments when enterprises assume responsibility while governments shirk. A lower α implies that governmental shirking produces less free-riding benefit, thereby strengthening the incentive for governments to fulfill responsibility.

Combining the two replicator dynamic equations, the evolutionary dynamic system can be expressed as follows:

$$\frac{dx}{dt} = x(1 - x)[R_1 - C_E + L_E - R_2 + H_E + Fyp(\theta)]$$

$$\frac{dy}{dt} = y(1 - y)[L_G + H_G - C_G(\theta) + x(1 - \alpha)D + F(1 - x)p(\theta)]$$

Let $\frac{dx}{dt} = 0$ and $\frac{dy}{dt} = 0$. The boundary equilibrium points of the system are:

$$P_1 = (0,0), P_2 = (0,1), P_3 = (1,0), P_4 = (1,1)$$

In addition, when the internal solution satisfies $0 < x^* < 1$ and $0 < y^* < 1$, the system has a candidate internal equilibrium point:

$$P^* = (x^*, y^*)$$

where

$$x^* = \frac{C_G(\theta) - L_G - H_G - Fp(\theta)}{(1 - \alpha)D - Fp(\theta)}$$

$$y^* = \frac{R_2 - H_E - R_1 + C_E - L_E}{Fp(\theta)}$$

The candidate internal equilibrium point exists only when the denominators are non-zero and both x^* and y^* lie within the interval $(0,1)$. Otherwise, the feasible equilibrium points are located on the boundary of the strategy space. The local stability of these

equilibrium candidates should be further examined through the Jacobian matrix and numerical simulations.

3.6. Numerical Simulation Design

To verify the evolutionary mechanism derived in Section 3.5, this study conducts numerical simulations to visualize the trajectories of enterprise responsibility fulfillment and governmental responsibility fulfillment under different parameter settings. The simulations do not estimate real monetary values; instead, all parameters are treated as normalized theoretical values representing the relative magnitudes of benefits, costs, losses, penalty intensity, role legitimacy gains, role-deviation losses, and digital governance capacity. Accordingly, the simulations should be interpreted as illustrative mechanism-based simulations rather than empirical predictions or policy forecasts.

The simulation design has three objectives: first, to examine whether the system evolves toward mutual responsibility sharing or mutual shirking under the baseline parameter setting; second, to test whether different initial probabilities x_0 and y_0 affect the evolutionary trajectory; and third, to analyze how key parameters, including θ , $p(\theta)$, $C_G(\theta)$, F , L_E , L_G , H_E , H_G , C_E , α , influence the evolution of government enterprise responsibility fulfillment. The baseline parameter values are set according to the payoff matrix, the positive-value constraints, and the directional conditions proposed in Section 3.3. They are not intended to represent a specific country, region, or industry, but provide a theoretically consistent benchmark for observing the strategic evolution of government enterprise responsibility interaction. The baseline parameter setting for the numerical simulation is reported in Table 3.

Table 3. Baseline parameter setting for numerical simulation.

Parameter	Baseline Value	Interpretation
R_1	5	Long-term basic benefit obtained by enterprises when assuming ecological responsibility
R_2	5	Short-term benefit obtained by enterprises when shirking ecological responsibility
C_E	2	Cost of enterprise ecological responsibility fulfillment
L_E	1	Role legitimacy or reputational benefit obtained by enterprises when assuming responsibility
H_E	0.5	Role-deviation loss caused by enterprise shirking
F	3	Penalty intensity imposed on enterprises that shirk ecological responsibility
D	6	Governance benefit obtained by governments when enterprises assume ecological responsibility
E	3	Governance loss caused by enterprise shirking
L_G	0.8	Role legitimacy and governance-performance benefit obtained by governments when fulfilling responsibility
H_G	0.7	Role-deviation and accountability loss caused by governmental shirking
α	0.3	Proportion of partial governance benefit obtained by governments when they shirk while enterprises assume responsibility
θ	0.5	Digital governance capacity
$p(\theta)$	0.5	Probability that enterprise shirking is detected under the baseline level of digital governance
$C_G(\theta)$	5	Effective governmental governance cost under the baseline level of digital governance

Digital governance capacity is simulated through its dual effect on $p(\theta)$ and $C_G(\theta)$. A higher level of θ indicates stronger digital monitoring, data integration, online regulation, and algorithmic identification capacity. Accordingly, higher θ is associated with a higher detection probability $p(\theta)$ and a lower effective governmental governance cost $C_G(\theta)$. In addition to the baseline setting, low, medium, and high digital governance scenarios

are used to compare the evolutionary effects of different digital governance capacities. The detailed digital governance scenario settings are provided in Appendix A, Table A1. For the sensitivity analysis of digital governance capacity, this study uses normalized functional forms rather than empirically estimated functions. Specifically, $p(\theta) = \theta$, and $C_G(\theta) = C_{G0} - \beta\theta$, where $C_{G0} = 6$ and $\beta = 2$. These specifications reflect the theoretical assumption that stronger digital governance capacity increases the detection probability of enterprise shirking and reduces the effective cost of governmental responsibility fulfillment. They also preserve the baseline values $p(0.5) = 0.5$ and $C_G(0.5) = 5$.

To examine path dependence, the simulations also use different initial strategy probabilities. Here, x_0 denotes the initial proportion of enterprises choosing ecological responsibility fulfillment, and y_0 denotes the initial proportion of governments choosing regulatory and coordination responsibility fulfillment. These initial values are used to test whether different starting conditions lead to different evolutionary trajectories or convergence outcomes. The detailed initial-value settings are provided in Appendix A, Table A2.

Finally, this study conducts sensitivity analysis by varying key parameters while holding other parameters at their baseline values. The selected parameters include $\theta, F, L_E, H_E, L_G, H_G, C_E, C_G(\theta), \alpha$. These parameters are selected because they represent the core mechanisms of the model: digital governance capacity, regulatory punishment, role legitimacy incentives, role-deviation losses, responsibility fulfillment costs, and governance-benefit spillover. The detailed sensitivity-analysis ranges are provided in Appendix A, Table A3.

The simulation results will be presented in the Results section (Section 4). Specifically, the Results section will report the baseline evolutionary trajectories, the effects of different initial probabilities, and the sensitivity-analysis results of key parameters. This simulation design complements the analytical stability analysis: the Jacobian matrix-based analysis identifies the local stability conditions of equilibrium points, whereas the numerical simulations visualize the dynamic trajectories and test the robustness of the evolutionary logic under different parameter settings.

4. Results

4.1. Equilibrium Analysis

Based on the payoff matrix and the replicator dynamic equations constructed in the methodology section, the evolutionary interaction between enterprises and governments can be expressed as a two-population dynamic system. Let x denote the proportion of enterprises choosing to assume ecological responsibility, and let y denote the proportion of governments choosing to fulfill regulatory and coordination responsibilities. Accordingly, $1 - x$ represents the proportion of enterprises choosing responsibility shirking, and $1 - y$ represents the proportion of governments choosing governmental shirking.

$$\frac{dx}{dt} = x(1-x)[yp(\theta)F - C_E + R_1 - R_2 + L_E + H_E]$$

$$\frac{dy}{dt} = y(1-y)[L_G + H_G - C_G(\theta) + x(1-\alpha)D + (1-x)p(\theta)F]$$

The first equation describes the evolutionary change in enterprise responsibility fulfillment. The term inside the square brackets represents the payoff difference between enterprise responsibility fulfillment and enterprise responsibility shirking. Enterprises are more likely to evolve toward responsibility fulfillment when the governmental responsibility-fulfillment proportion y , the detection probability $p(\theta)$, the penalty intensity F , the long-term benefit R_1 , the role legitimacy benefit L_E , and the role-deviation loss H_E are sufficiently high. Conversely, a higher enterprise responsibility cost C_E or a higher short-term shirking benefit R_2 weakens the incentive for enterprises to assume ecological responsibility.

The second equation describes the evolutionary change in governmental responsibility fulfillment. The term inside the square brackets represents the payoff difference between governmental responsibility fulfillment and governmental shirking. Governments are more likely to evolve toward responsibility fulfillment when governmental legitimacy and governance-performance benefits L_G , accountability loss H_G , governance benefit D , detection probability $p(\theta)$, and penalty intensity F are sufficiently high, or when the effective governance cost $C_G(\theta)$ is relatively low. The parameter α captures the partial governance benefit obtained by governments when enterprises assume responsibility while governments shirk. A higher α therefore indicates stronger governmental free-riding incentives.

For clarity, define the enterprise payoff-difference function and the government payoff-difference function as follows:

$$A(y) = yp(\theta)F - C_E + R_1 - R_2 + L_E + H_E$$

$$B(x) = L_G + H_G - C_G(\theta) + x(1 - \alpha)D + (1 - x)p(\theta)F$$

The evolutionary direction of enterprises is determined by the sign of $A(y)$. When $A(y) > 0$, the proportion of enterprises assuming responsibility increases; when $A(y) < 0$, the proportion of enterprises shirking responsibility increases. Similarly, the evolutionary direction of governments is determined by the sign of $B(x)$. When $B(x) > 0$, the proportion of governments fulfilling responsibility increases; when $B(x) < 0$, governmental shirking becomes more likely.

The equilibrium points of the system are obtained by setting both dynamic equations equal to zero:

$$\frac{dx}{dt} = 0, \quad \frac{dy}{dt} = 0$$

Because both equations contain the terms $x(1 - x)$ and $y(1 - y)$, the system first has four boundary equilibrium points:

$$H_1 = (0,0), H_2 = (0,1), H_3 = (1,0), H_4 = (1,1)$$

These four boundary equilibria have clear governance meanings. $H_1 = (0,0)$ represents mutual shirking, in which enterprises shirk ecological responsibility and governments also shirk regulatory and coordination responsibilities. $H_4 = (1,1)$ represents mutual responsibility fulfillment, in which enterprises assume ecological responsibility and governments actively fulfill their regulatory and coordination responsibilities. $H_2 = (0,1)$ represents an asymmetric state in which governments fulfill responsibility but enterprises shirk, whereas $H_3 = (1,0)$ represents an asymmetric state in which enterprises assume responsibility but governments shirk.

In addition to the four boundary equilibria, the system may also have an interior equilibrium point when $A(y) = 0$ and $B(x) = 0$ hold simultaneously. Solving these two equations gives:

$$H_5 = (x^*, y^*)$$

where

$$x^* = \frac{C_G(\theta) - p(\theta)F - L_G - H_G}{(1 - \alpha)D - p(\theta)F}$$

And

$$y^* = \frac{C_E + R_2 - R_1 - H_E - L_E}{p(\theta)F}$$

The interior equilibrium exists only when $x^* \in (0,1)$, $y^* \in (0,1)$, and $(1 - \alpha)D - p(\theta)F \neq 0$. Substantively, x^* is the critical proportion of responsible enterprises required

for governments to increase their probability of fulfilling responsibility. y^* is the critical proportion of responsible governments required for enterprises to increase their probability of assuming ecological responsibility. Therefore, the interior equilibrium does not necessarily represent a stable final state. Instead, it functions as a threshold point that separates different evolutionary regions of the system.

Using the baseline parameter setting:

$$R_1 = 5, R_2 = 5, C_E = 2, L_E = 1, H_E = 0.5, F = 3, D = 6, L_G = 0.8, H_G = 0.7,$$

$$\alpha = 0.3, p(\theta) = 0.5, C_G(\theta) = 5$$

the interior equilibrium coordinates are:

$$x^* = 0.7407, y^* = 0.3333$$

This result indicates a clear threshold asymmetry. Enterprises begin to move toward responsibility fulfillment when the governmental responsibility-fulfillment proportion exceeds approximately 33.3%. By contrast, governments begin to move toward responsibility fulfillment only when the enterprise responsibility-fulfillment proportion exceeds approximately 74.1%. This asymmetry suggests that enterprises are relatively more sensitive to governmental regulatory fulfillment, whereas governments require a much stronger enterprise responsibility base before their own fulfillment strategy becomes self-reinforcing. Therefore, responsibility sharing in digital environmental governance is not automatic. Whether the system evolves toward mutual responsibility fulfillment or mutual shirking depends on whether the initial state and parameter conditions can push the system beyond the critical threshold represented by H_5 .

4.2. Stability Analysis Based on the Jacobian Matrix

To further identify the local stability of the equilibrium points, the Jacobian matrix of the two-dimensional replicator dynamic system is constructed. Based on the payoff-difference functions $A(y)$ and $B(x)$ defined above, the Jacobian matrix is:

$$J = \begin{pmatrix} (1-2x)A(y) & x(1-x)p(\theta)F \\ y(1-y)[(1-\alpha)D - p(\theta)F] & (1-2y)B(x) \end{pmatrix}$$

where

$$A(y) = yp(\theta)F - C_E + R_1 - R_2 + L_E + H_E$$

$$B(x) = L_G + H_G - C_G(\theta) + x(1-\alpha)D + (1-x)p(\theta)F$$

The eigenvalues of the Jacobian matrix at the boundary equilibrium points determine their local stability.

At $H_1 = (0,0)$, the eigenvalues are:

$$\lambda_1 = -C_E + R_1 - R_2 + L_E + H_E$$

$$\lambda_2 = p(\theta)F - C_G(\theta) + L_G + H_G$$

Thus, $H_1 = (0,0)$ is locally asymptotically stable when:

$$R_2 - H_E > R_1 - C_E + L_E$$

$$C_G(\theta) > L_G + H_G + p(\theta)F$$

These conditions indicate that mutual shirking becomes stable when the short-term payoff of enterprise shirking exceeds the net payoff of enterprise responsibility fulfillment, and when the effective governmental governance cost is higher than the combined effects of legitimacy benefit, accountability pressure, and expected penalty-related returns.

At $H_4 = (1,1)$, the eigenvalues are:

$$\lambda_1 = C_E - p(\theta)F + R_2 - R_1 - L_E - H_E$$

$$\lambda_2 = (\alpha - 1)D + C_G(\theta) - L_G - H_G$$

Therefore, $H_4 = (1,1)$ is locally asymptotically stable when:

$$R_1 - C_E + L_E > R_2 - H_E - p(\theta)F$$

$$L_G + H_G + (1 - \alpha)D > C_G(\theta)$$

These conditions suggest that mutual responsibility fulfillment becomes stable when enterprises obtain sufficient net returns from assuming responsibility, and when governments obtain sufficient legitimacy, accountability, and governance-performance returns to offset effective governance costs. Digital governance capacity affects this stability condition through two channels: increasing $p(\theta)$, which raises the expected cost of enterprise shirking, and reducing $C_G(\theta)$, which lowers the cost of governmental responsibility fulfillment.

Under the baseline parameter setting, the eigenvalues at $H_1 = (0,0)$ and $H_4 = (1,1)$ are both negative, indicating that these two points are locally stable. By contrast, the asymmetric equilibrium points $H_2 = (0,1)$ and $H_3 = (1,0)$ are unstable. The interior equilibrium point $H_5 = (x^*, y^*)$ is a saddle point, serving as the threshold separating the attraction basin of H_1 from that of H_4 . The local stability results of all equilibrium points are summarized in Table 4.

Table 4. Local Stability Analysis of Equilibrium Points.

Equilibrium Point	Eigenvalues	Stability Result	Stability Condition
$H_1 = (0,0)$	$\lambda_1 = -C_E + R_1 - R_2 + L_E + H_E$ $\lambda_2 = p(\theta)F - C_G(\theta) + L_G + H_G$	Stable	$R_2 - H_E > R_1 - C_E + L_E$ $C_G(\theta) > L_G + H_G + p(\theta)F$
$H_2 = (0,1)$	$\lambda_1 = p(\theta)F - C_E + R_1 - R_2 + L_E + H_E$ $\lambda_2 = C_G(\theta) - p(\theta)F - L_G - H_G$	Unstable under the baseline	—
$H_3 = (1,0)$	$\lambda_1 = C_E + R_2 - R_1 - L_E - H_E$ $\lambda_2 = (1 - \alpha)D - C_G(\theta) + L_G + H_G$	Unstable under the baseline	—
$H_4 = (1,1)$	$\lambda_1 = C_E - p(\theta)F + R_2 - R_1 - L_E - H_E$ $\lambda_2 = (\alpha - 1)D + C_G(\theta) - L_G - H_G$	Stable	$R_1 - C_E + L_E >$ $R_2 - H_E - p(\theta)F$ $L_G + H_G + (1 - \alpha)D > C_G(\theta)$
$H_5 = (x^*, y^*)$	$\det(J_{H_5}) < 0$	Saddle point	Separates the two attraction basins

This result shows that the system has a bistable evolutionary structure. Digital environmental governance does not automatically evolve toward responsibility sharing. Instead, the final evolutionary outcome depends on whether the initial state and parameter conditions push the system toward mutual shirking or mutual responsibility fulfillment.

4.3. Numerical Simulation Results

To visually verify the analytical results obtained above, numerical simulations were conducted using Python 3.12. The baseline parameter values follow the simulation design

in Section 3.6. These values are normalized theoretical parameters rather than empirical estimates, and are used to examine the evolutionary trajectories of enterprise responsibility fulfillment and governmental responsibility fulfillment under different initial probabilities.

The baseline parameter setting is as follows:

$$R_1 = 5, R_2 = 5, C_E = 2, L_E = 1, H_E = 0.5, F = 3, D = 6, E = 3, L_G = 0.8, H_G = 0.7, \alpha = 0.3, \theta = 0.5, \\ p(\theta) = 0.5, C_G(\theta) = 5$$

The following six groups of initial strategy probabilities were selected:

$$(x_0, y_0) = (0.2, 0.2), (0.4, 0.4), (0.6, 0.6), (0.8, 0.8), (0.2, 0.8), (0.8, 0.2)$$

Here, x_0 denotes the initial proportion of enterprises choosing responsibility fulfillment, and y_0 denotes the initial proportion of governments choosing responsibility fulfillment.

As shown in Figure 2, the evolutionary system presents two attraction basins. The trajectories located in the lower-left region of the phase plane converge to $H_1 = (0, 0)$, indicating mutual shirking. The trajectories located in the upper-right region converge to $H_4 = (1, 1)$, indicating mutual responsibility fulfillment. The saddle point $H_5 = (x^*, y^*)$ and the separatrix divide the strategy space into these two regions.

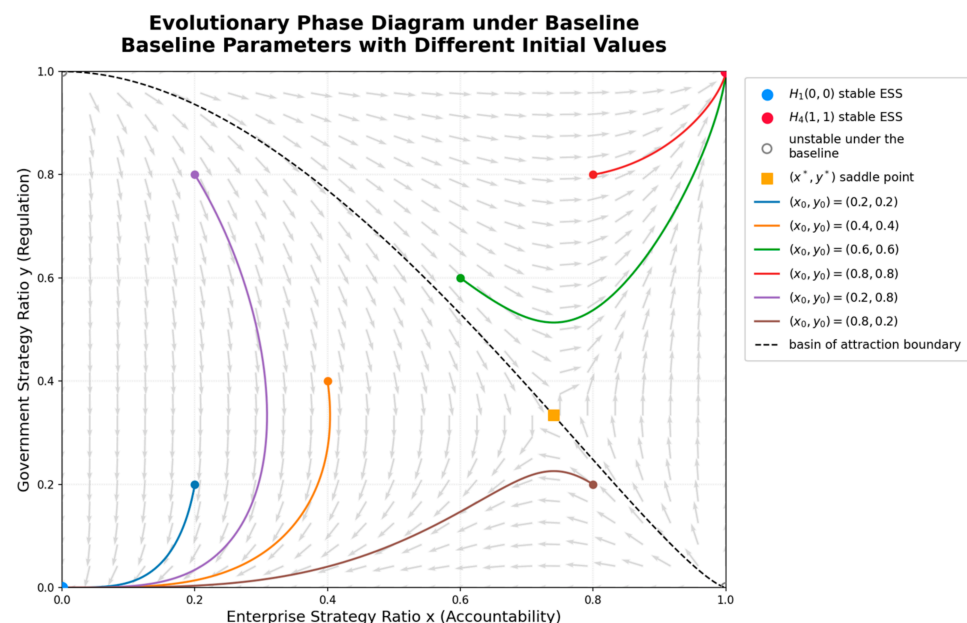


Figure 2. Phase diagram and attraction basins under the baseline parameter setting.

Under the baseline parameter setting, the trajectories starting from $(0.2, 0.2)$, $(0.4, 0.4)$, $(0.2, 0.8)$, and $(0.8, 0.2)$ converge to $H_1 = (0, 0)$. This indicates that the system may fall into a mutual-shirking equilibrium when the initial responsibility foundation is insufficient or when responsibility fulfillment is highly asymmetric. In particular, the trajectory from $(0.8, 0.2)$ shows that a high initial level of enterprise responsibility fulfillment cannot be sustained when governmental responsibility fulfillment remains too low. Similarly, the trajectory from $(0.2, 0.8)$ shows that a high initial level of governmental responsibility fulfillment alone is not sufficient to guarantee convergence toward mutual responsibility fulfillment when enterprise responsibility fulfillment is too weak.

By contrast, the trajectories starting from $(0.6, 0.6)$ and $(0.8, 0.8)$ converge to $H_4 = (1, 1)$. This result suggests that when both actors have a relatively strong initial responsibility foundation, enterprise responsibility fulfillment and governmental responsibility fulfill-

ment can reinforce each other, pushing the system toward the desirable equilibrium of mutual responsibility sharing.

Figure 3 further illustrates the time evolution of $x(t)$ and $y(t)$. For the initial values (0.2,0.2) and (0.4,0.4), both $x(t)$ and $y(t)$ decline rapidly and eventually approach 0, confirming convergence to mutual shirking. For (0.8,0.2), $x(t)$ initially remains relatively high but gradually declines as $y(t)$ fails to increase, eventually leading both variables toward 0. For (0.2,0.8), although $y(t)$ starts from a high level, it declines sharply because the enterprise responsibility foundation is too weak, and $x(t)$ also eventually falls to 0.

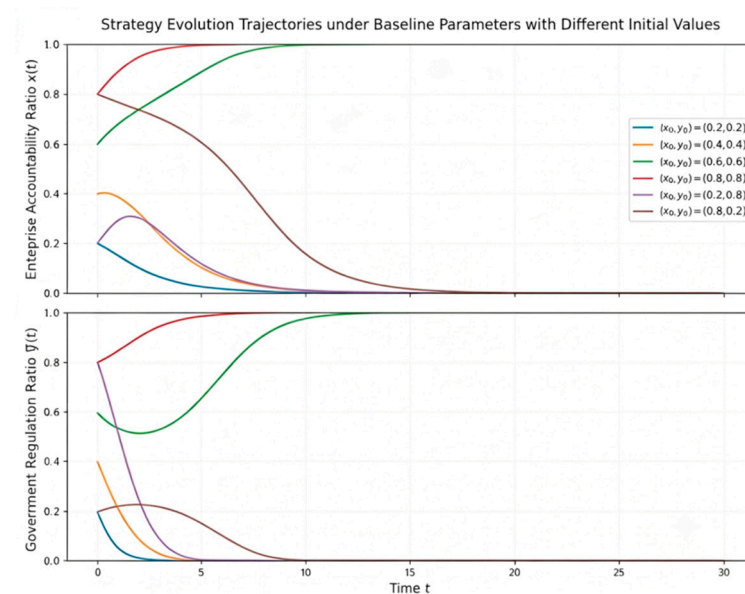


Figure 3. Evolutionary trajectories of $x(t)$ and $y(t)$ under different initial probabilities.

For (0.6,0.6) and (0.8,0.8), both variables eventually converge to 1. The trajectory from (0.6,0.6) is especially informative: $y(t)$ decreases slightly at the early stage, but as $x(t)$ continues to rise and crosses the critical threshold, governmental responsibility fulfillment is restored and the system finally converges to $H_4 = (1,1)$. This confirms that responsibility sharing is path-dependent and threshold-sensitive.

Overall, the numerical simulation results are consistent with the stability analysis. The system does not have a single deterministic evolutionary outcome. Instead, both mutual shirking and mutual responsibility fulfillment are possible. Whether digital environmental governance evolves toward the desirable equilibrium depends on the initial responsibility conditions and whether the system crosses the threshold separating the two attraction basins.

4.4. Sensitivity Analysis

To further examine how key parameters affect the evolutionary trajectory of responsibility sharing, this section conducts sensitivity analysis by changing one parameter at a time while keeping the remaining parameters at their baseline values. The analysis focuses on digital governance capacity, penalty intensity, role-based legitimacy benefits, role-deviation losses, responsibility fulfillment costs, governmental governance costs, and governmental free-riding incentives. These parameters correspond to the main incentive and constraint mechanisms embedded in the payoff matrix.

The interpretation of the sensitivity results is based on the two threshold values of the interior equilibrium:

$$x^* = \frac{C_G(\theta) - p(\theta)F - L_G - H_G}{(1 - \alpha)D - p(\theta)F}$$

$$y^* = \frac{C_E + R_2 - R_1 - H_E - L_E}{p(\theta)F}$$

A decrease in x^* or y^* expands the attraction basin of $H_4 = (1,1)$, whereas an increase in these thresholds makes the system more likely to converge to $H_1 = (0,0)$.

4.4.1. Effect of Digital Governance Capacity θ

To examine the role of digital governance capacity, this study specifies normalized functional forms for simulation purposes. Specifically:

$$p(\theta) = \theta$$

$$C_G(\theta) = C_{G0} - \beta\theta, C_{G0} = 6, \beta = 2$$

These functional forms are not empirical estimates; they are used to reflect the theoretical assumption that stronger digital governance capacity increases the detection probability of enterprise shirking and reduces the effective cost of governmental responsibility fulfillment. They also preserve the baseline values $p(0.5) = 0.5$ and $C_G(0.5) = 5$.

As shown in Figure 4, digital governance capacity has a clear threshold effect. When $\theta = 0.2$, both $x(t)$ and $y(t)$ decline rapidly and converge to 0, indicating that weak digital governance capacity cannot prevent mutual shirking. When $\theta = 0.5$, the system still converges to $H_1 = (0,0)$, suggesting that a medium level of digital governance capacity remains insufficient under the baseline initial condition. When $\theta = 0.8$, both $x(t)$ and $y(t)$ converge rapidly to 1. This result indicates that strong digital governance capacity can shift the system toward $H_4 = (1,1)$ by simultaneously increasing the expected cost of enterprise shirking and reducing the effective cost of governmental responsibility fulfillment.

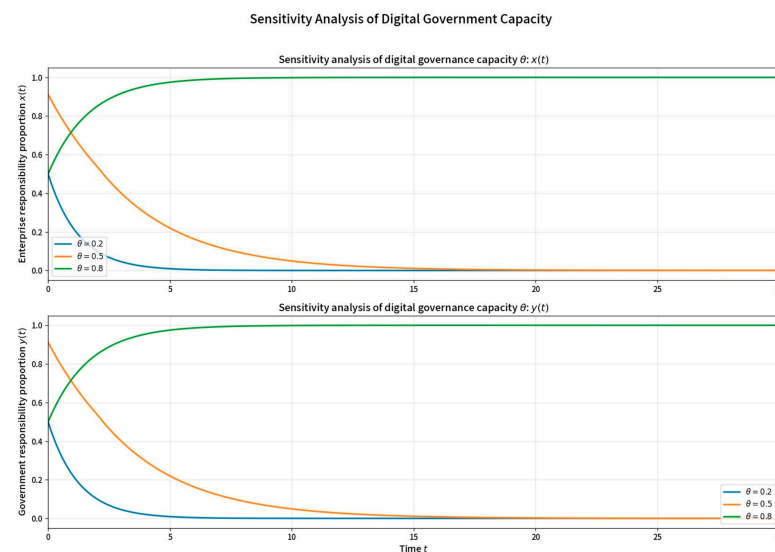


Figure 4. Sensitivity analysis of digital governance capacity θ .

4.4.2. Effect of Penalty Intensity F

Figure 5 shows that penalty intensity significantly affects the direction and speed of system evolution. When $F = 1$, the deterrent effect is insufficient, and both $x(t)$ and $y(t)$ converge to 0. When $F = 3$, the system still converges to mutual shirking under the selected initial condition, although the decline of $x(t)$ is slower. When $F = 5$, both variables converge rapidly to 1. This indicates that only sufficiently strong penalty intensity can increase the expected cost of enterprise shirking and help the system move toward mutual responsibility fulfillment.

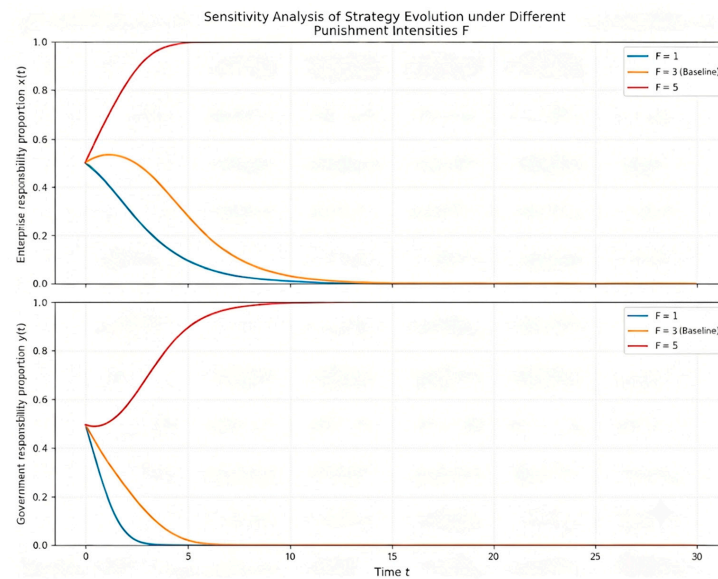


Figure 5. Sensitivity analysis of penalty intensity F .

4.4.3. Sensitivity Analysis of Enterprise Role-Based Incentives L_E and H_E

Figure 6 shows that enterprise-side role-based incentives directly affect the evolution of $x(t)$. When L_E is low or remains at the baseline level, enterprise responsibility fulfillment eventually declines to 0. When L_E increases to a high level, $x(t)$ converges rapidly to 1. Similarly, a low H_E is insufficient to sustain enterprise responsibility fulfillment, whereas a high H_E promotes convergence toward $x = 1$. These results indicate that legitimacy rewards and role-deviation losses are not merely theoretical additions, but decisive payoff components affecting enterprise strategy evolution.

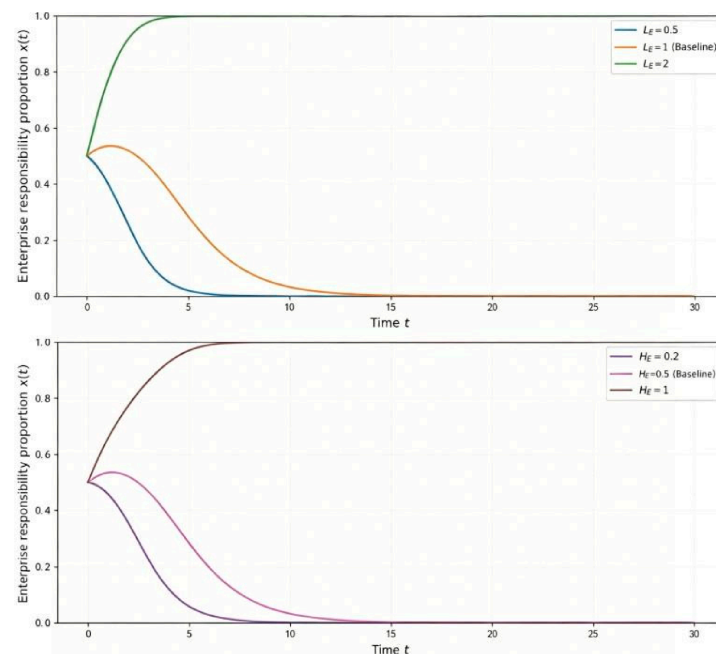


Figure 6. Sensitivity analysis of enterprise role-based incentives L_E and H_E .

4.4.4. Sensitivity Analysis of Governmental Role-Based Incentives L_G and H_G

Figure 7 presents the effects of governmental role-based incentives. When L_G or H_G is low, $y(t)$ declines toward 0, indicating that governmental responsibility fulfillment is difficult to sustain. When L_G or H_G increases to a sufficiently high level, $y(t)$ converges

rapidly to 1. This result shows that governmental responsibility fulfillment depends not only on direct governance benefits, but also on role legitimacy, performance recognition, accountability pressure, and role-deviation losses.

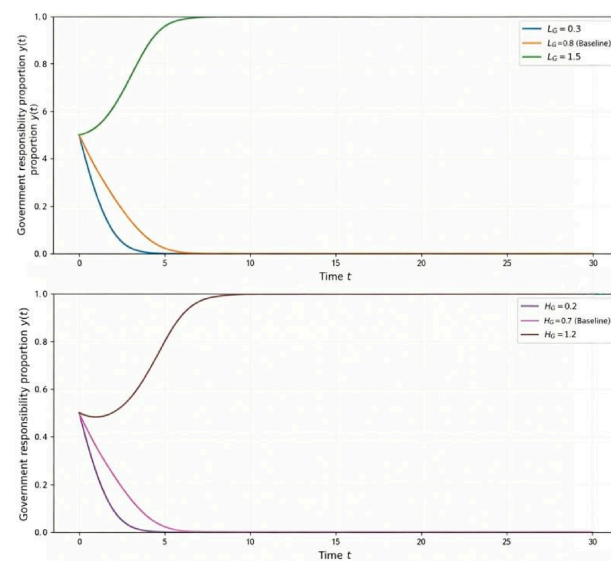


Figure 7. Sensitivity analysis of governmental role-based incentives L_G and H_G .

4.4.5. Sensitivity Analysis of Responsibility Fulfillment Costs C_E and $C_G(\theta)$

Figure 8 shows that responsibility fulfillment costs have a negative effect on responsibility sharing. When $C_E = 1$, enterprises rapidly converge toward responsibility fulfillment. However, when C_E increases to 2 or 3, $x(t)$ eventually converges to 0. This indicates that excessive enterprise responsibility costs weaken the relative payoff of assuming ecological responsibility. Similarly, when $C_G(\theta) = 4$, governmental responsibility fulfillment converges to 1. When $C_G(\theta)$ increases to 5 or 6, $y(t)$ converges to 0. Therefore, reducing enterprise compliance costs and governmental governance costs is essential for stabilizing mutual responsibility fulfillment.

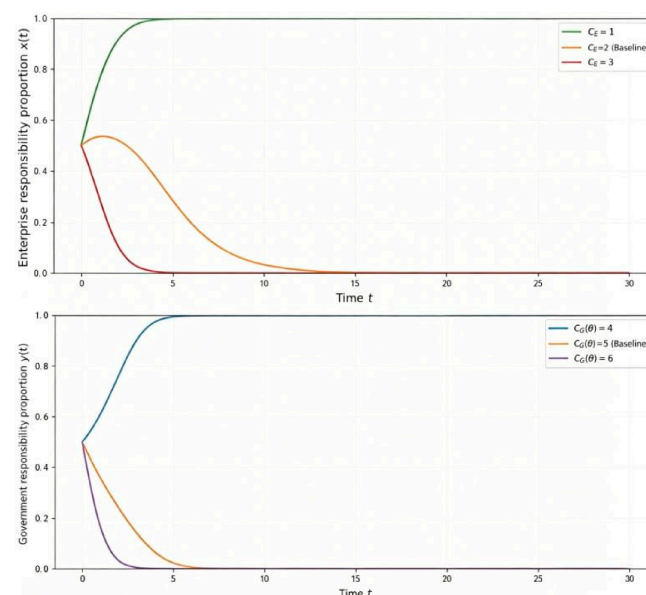


Figure 8. Sensitivity analysis of responsibility fulfillment costs C_E and $C_G(\theta)$.

5. Discussion

The results show that responsibility sharing in digital environmental governance is not an automatic outcome of digitalization or government–enterprise collaboration. The evolutionary system may converge either to mutual responsibility fulfillment or to mutual shirking, depending on the initial strategy distribution and the relative payoff of responsible versus shirking strategies. The stability analysis and numerical simulations further indicate that this process is threshold-sensitive: the interior equilibrium separates the attraction basin of mutual shirking from that of mutual responsibility fulfillment. When the threshold for responsible behavior is lower, the system is more likely to evolve toward mutual responsibility fulfillment; when the threshold is higher, it may remain trapped in mutual shirking. Therefore, the key governance issue is not simply whether incentives, penalties, or digital technologies matter, but how they change the conditions under which responsibility fulfillment becomes self-reinforcing.

5.1. Theoretical Implications

This study makes a modest but specific theoretical contribution by connecting role-based responsibility with evolutionary strategy adjustment. Social Role Theory explains why governments and enterprises are expected to assume different responsibilities in digital environmental governance, while evolutionary game theory explains how these actors adjust their strategies under bounded rationality and repeated interaction (Fan et al., 2022; Sui & Wang, 2026). By translating role fulfillment into legitimacy benefits and role deviation into legitimacy or accountability losses, the model gives role expectations a clearer behavioral meaning within the payoff structure.

The study also clarifies the role of digital governance in responsibility sharing (C. Wu et al., 2026). Digital governance should not be understood merely as a technological background. In the model, it affects the evolutionary process by increasing the probability that enterprise shirking is detected and by reducing the effective cost of governmental supervision and coordination. This treatment responds to the need to move beyond general claims about digital transformation and to specify how digital capacity changes the incentive structure of government–enterprise interaction.

Finally, the threshold result refines the theoretical understanding of collaborative environmental governance. Government–enterprise collaboration does not necessarily lead to responsibility sharing. It may also produce mutual shirking if responsibility costs are high, detection probability is low, legitimacy incentives are weak, or governmental free-riding incentives are strong. The interior equilibrium shows that responsibility sharing depends on whether the system crosses a critical boundary. This does not constitute a new grand theory, but it provides a more precise explanation of why similar collaborative arrangements may lead to different governance outcomes.

5.2. Responsibility Mechanism

Based on the model results, the VRBG mechanism can be interpreted as four channels through which the conditions of responsibility sharing are adjusted. It should not be presented as a comprehensive governance blueprint. Its function is narrower: to explain how value cultivation, responsibility identification, benefit sharing, and guarantee mechanisms can reduce the likelihood of mutual shirking and increase the likelihood of mutual responsibility fulfillment.

First, value cultivation corresponds to role-based legitimacy benefits and role-deviation losses. For enterprises, it increases the reputational and legitimacy returns of fulfilling ecological responsibility and raises the reputational cost of shirking. For governments, it strengthens the legitimacy and public-recognition benefits of active supervision

while increasing the accountability loss associated with shirking. Second, responsibility identification reduces ambiguity in role boundaries. Clear responsibility lists, disclosure duties, enforcement standards, and accountability criteria make role deviation more observable and reduce opportunities for free-riding. Third, benefit sharing improves the net payoff of responsibility fulfillment. Green finance, tax incentives, technical support, public procurement preference, and reputational recognition can reduce enterprise compliance costs and increase the long-term benefits of responsible behavior. Fourth, the guarantee mechanism strengthens digital monitoring, detection, and enforcement. Its role is to increase the probability that shirking is detected, make penalties credible, and reduce the effective cost of governmental supervision.

These four mechanisms should not be treated as independent or perfectly substitutable. Value cultivation cannot fully compensate for weak monitoring and enforcement; if violations are unlikely to be detected, moral or reputational pressure may remain symbolic. Similarly, strong enforcement cannot work well without clear responsibility boundaries, because unclear responsibilities make accountability difficult to assign. Benefit sharing can reduce the cost pressure of responsibility fulfillment, but it cannot stabilize cooperation if shirking remains profitable and undetectable. Therefore, the VRBG mechanism works only when the four elements reinforce one another: value cultivation changes role incentives, responsibility identification clarifies behavioral expectations, benefit sharing improves the payoff of responsibility fulfillment, and guarantee mechanisms make shirking detectable and costly.

5.3. Practical Implications

The findings suggest that governments should focus less on formal collaboration and more on the incentive conditions that make responsibility fulfillment self-reinforcing. Digital governance should be used to improve detection probability, data traceability, and enforcement credibility, rather than simply to signal administrative modernization. Environmental data platforms, real-time monitoring, cross-departmental information sharing, and digital disclosure systems are useful only if they reduce supervision costs and increase the expected cost of shirking.

Policy design should also reduce the cost of responsible behavior while maintaining credible penalties for shirking. Enterprises are less likely to fulfill ecological responsibility when compliance costs are high and long-term benefits are uncertain. Green finance, technical support, tax incentives, and procurement preference can improve the relative payoff of responsibility fulfillment. At the same time, penalties must be predictable and enforceable; otherwise, enterprises may still choose shirking even under formal regulatory pressure.

Finally, responsibility mechanisms should be dynamically calibrated (C. Wu et al., 2026). The key parameters in the model are not fixed. Enterprise compliance costs may change with economic cycles, energy prices, technology costs, and market pressure. Governmental governance costs may change with fiscal resources, administrative capacity, and digital infrastructure. Detection probability and penalty credibility may also vary over time. Therefore, governments should not treat responsibility lists, incentives, or penalties as once-and-for-all institutional designs. They need continuous monitoring of compliance costs, enforcement effectiveness, detection capacity, and enterprise responses, so that responsibility mechanisms can be adjusted as conditions change.

5.4. Limitations and Future Research

The main limitation of this study is the absence of empirical parameter calibration. The numerical parameter values used in the simulations were selected by the authors solely for theoretical illustration and sensitivity analysis rather than being derived from

empirical observations or formal calibration. Therefore, the simulation results should not be interpreted as empirical estimates, predictions, or policy forecasts. The model uses normalized theoretical variables to examine the logical mechanism of responsibility sharing, but it does not estimate the actual values of key parameters, such as enterprise compliance costs, governmental governance costs, detection probability, penalty intensity, legitimacy benefits, and role-deviation losses. This is the most important constraint on the external validity of the findings. Although the analytical results and numerical simulations show how parameter changes affect evolutionary outcomes, they do not demonstrate whether the assumed parameter ranges correspond to specific industries, regions, or institutional contexts. In addition, the model simplifies the governance setting by focusing only on governments and enterprises, while other actors such as citizens, NGOs, digital platforms, financial institutions, and third-party auditors may also influence monitoring, disclosure, accountability, and reputational pressure. The treatment of digital governance capacity is also stylized, as the model captures its effects mainly through detection probability and governance cost reduction, without fully considering data fragmentation, algorithmic bias, privacy risks, cybersecurity vulnerabilities, or uneven digital infrastructure. Future empirical studies can build on Appendix B by matching each theoretical parameter with observable indicators such as environmental enforcement expenditure, enterprise pollution-control investment, administrative penalty records, ESG ratings, environmental credit records, online-monitoring coverage, public complaints, and environmental quality indicators. These indicators can then be normalized or calibrated through regression analysis, expert scoring, entropy-weight methods, case-based calibration, or scenario simulation. This would allow future research to compare whether the attraction basin of mutual responsibility fulfillment differs across industries, regions, or levels of digital governance capacity. Finally, the model assumes relative homogeneity among governments and enterprises, although real actors differ in administrative capacity, fiscal resources, firm size, ownership structure, technological capability, and pollution intensity. Addressing these limitations through empirical calibration, multi-actor model extensions, and comparative analysis across regions and industries will be an important direction for our future work.

6. Conclusions

This study examined how government–enterprise responsibility sharing evolves in digital environmental governance. Integrating Social Role Theory with evolutionary game theory, it translates role expectations into legitimacy benefits, reputational gains, accountability losses, and role-deviation costs, thereby linking the normative logic of responsibility with the strategic logic of boundedly rational actors.

The results show that responsibility sharing is not an automatic outcome of digitalization or government–enterprise collaboration. The system may converge either to mutual responsibility fulfillment or to mutual shirking, depending on the relative payoff of responsible versus shirking strategies. Stronger digital governance capacity, higher detection probability, credible penalties, stronger legitimacy incentives, lower compliance and governance costs make mutual responsibility fulfillment more likely; weak monitoring, high costs, insufficient penalties, and ambiguous boundaries push the system toward mutual shirking.

The findings further reveal that responsibility sharing is threshold-sensitive. The interior equilibrium marks the critical boundary between the two attraction basins. Responsibility mechanisms should therefore aim not merely to promote collaboration, but to lower the threshold for responsible behavior and make it self-reinforcing.

On this basis, the VRBG mechanism is a focused instrument: value cultivation strengthens role-based incentives, responsibility identification clarifies boundaries, benefit sharing

improves the net payoff of responsible behavior, and guarantee mechanisms enhance detection and enforcement. These mechanisms are complementary, not independent. The conclusions are conditional on the model's assumptions, particularly its two-actor structure and normalized parameters. Future research should prioritize empirical calibration of key parameters such as compliance costs, governance costs, detection probability, penalty intensity, legitimacy benefits, and role-deviation losses.

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Appendix A

Table A1. Digital governance scenarios for numerical simulation.

Digital Governance Scenario	θ	$p(\theta)$	$C_G(\theta)$	Interpretation
Low digital governance capacity	0.2	0.2	5.6	Enterprise shirking is less likely to be detected, and governmental effective governance cost is relatively high
Medium digital governance capacity	0.5	0.5	5.0	Detection probability and governmental effective governance cost are at medium levels
High digital governance capacity	0.8	0.8	4.4	Enterprise shirking is more likely to be detected, and governmental effective governance cost is relatively low

Table A2. Initial strategy probabilities for numerical simulation.

Initial Value	Meaning	Observation Purpose
$(x_0, y_0) = (0.2, 0.2)$	Both enterprise responsibility fulfillment and governmental responsibility fulfillment are initially low	To observe whether the system falls into mutual shirking under a low-responsibility foundation
$(x_0, y_0) = (0.4, 0.4)$	Both enterprise and government responsibility fulfillment levels are relatively low	To observe whether the system can shift from a weak responsibility state toward responsibility sharing
$(x_0, y_0) = (0.6, 0.6)$	Both enterprise and government responsibility fulfillment levels are relatively high	To observe whether the system tends to evolve toward mutual responsibility sharing
$(x_0, y_0) = (0.8, 0.8)$	Both enterprise responsibility fulfillment and governmental responsibility fulfillment are initially high	To observe whether a high-responsibility foundation stabilizes the system toward mutual responsibility sharing
$(x_0, y_0) = (0.2, 0.8)$	Enterprises are initially passive, while governments are initially active	To observe whether active governmental supervision can promote enterprise responsibility fulfillment
$(x_0, y_0) = (0.8, 0.2)$	Enterprises are initially active, while governments are initially passive	To observe whether enterprise responsibility fulfillment can motivate governmental responsibility fulfillment, or whether governments develop a free-riding tendency

Table A3. Sensitivity analysis design.

Parameter	Values	Main Observation Object	Theoretical Expectation
θ	0.2, 0.5, 0.8	x, y	A higher θ increases $p(\theta)$ and reduces $C_G(\theta)$, making enterprises less willing to shirk and governments more likely to fulfill responsibility. The system is more likely to evolve toward mutual responsibility sharing.
F	1, 3, 5	x, y	A higher F increases the expected penalty for enterprise shirking. Since $Fp(\theta)$ also enters the governmental payoff under active supervision, stronger penalty intensity may also strengthen governmental responsibility fulfillment.
L_E	0.5, 1, 2	x	A higher L_E means that enterprises obtain stronger reputation, legitimacy, and social recognition from responsibility fulfillment, increasing their willingness to assume ecological responsibility.
H_E	0.2, 0.5, 1	x	A higher H_E means that enterprise shirking causes greater reputational damage, trust loss, and legitimacy loss, reducing the attractiveness of shirking.
L_G	0.3, 0.8, 1.5	y	A higher L_G means that governments obtain stronger governance performance, public recognition, and institutional legitimacy from responsibility fulfillment, increasing their willingness to fulfill responsibility.
H_G	0.2, 0.7, 1.2	y	A higher H_G means that governmental shirking generates stronger accountability pressure, credibility loss, and legitimacy loss, reducing the attractiveness of shirking.
C_E	1, 2, 3	x	A higher C_E increases the cost of enterprise responsibility fulfillment, making enterprises more likely to shirk responsibility.
$C_G(\theta)$	4, 5, 6	y	A higher $C_G(\theta)$ increases the effective cost of governmental responsibility fulfillment, making governments more likely to shirk; a lower $C_G(\theta)$ makes responsibility fulfillment easier.
α	0.1, 0.3, 0.6	y	A higher α means that governments can obtain more spillover benefits from enterprise responsibility fulfillment even when they shirk, which may strengthen the free-riding incentive and weaken governmental responsibility fulfillment.

Appendix B

Table A4. Potential empirical proxies and calibration routes for model parameters.

Parameter	Meaning in the Model	Possible Empirical Proxies for Future Calibration
R_1	Long-term enterprise benefit from responsibility fulfillment	Green revenue, green productivity improvement, improved ESG/environmental score, reduced financing cost
R_2	Short-term benefit from shirking	Avoided pollution-control expenditure, reduced environmental operating costs, short-term profit from non-compliance
C_E	Enterprise responsibility-fulfillment cost	Pollution-control investment, environmental protection expenditure, clean-technology upgrading cost, disclosure/compliance cost
L_E	Enterprise legitimacy/reputation gain	ESG ratings, environmental credit scores, positive media attention, stakeholder trust, green financing access
H_E	Enterprise role-deviation loss	Violation records, negative media attention, environmental credit punishment, increased financing constraints
F	Penalty intensity	Monetary fines, administrative penalties, production restrictions, market access restrictions, environmental credit sanctions
θ	Digital governance capacity	Online-monitoring coverage, environmental data platforms, remote-sensing use, sensor networks, cross-departmental data sharing

Table A4. Cont.

Parameter	Meaning in the Model	Possible Empirical Proxies for Future Calibration
$p(\theta)$	Detection probability	Detected violations/total inspections, online-alert conversion rate, enforcement detection rate
$C_G(\theta)$	Effective governmental governance cost	Enforcement expenditure, inspection cost, staff input, data-platform operating cost, administrative coordination cost
D	Governance benefit	Pollution reduction, environmental quality improvement, fewer complaints, improved governance performance assessment
H	Governance loss from enterprise shirking	Excess emissions, pollution incidents, ecological damage, complaints, accountability events
L_G	Government legitimacy / governance-performance gain	Public satisfaction, environmental performance assessment, public trust, administrative recognition
H_G	Government role-deviation / accountability loss	Inspection criticism, accountability records, public complaints, negative media attention
α	Partial spillover/free-riding coefficient	Share of environmental improvement attributable to enterprise action without active government intervention; expert scoring or case calibration

Note: The proxies listed in Table A4 are proposed for future empirical calibration. They do not imply that the present study empirically estimates these parameters.

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