

Article

Evolutionary Analysis of Farmers' Willingness to Participate in PPP Projects for Soil Erosion Control

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Abstract

Soil erosion control is an important aspect of promoting ecological civilization and a key support mechanism for achieving the 'dual-carbon' goals. The successful implementation of PPP (Public–Private Partnership) projects for soil erosion control requires widespread participation from farmers. Therefore, it is necessary to study the evolutionary mechanisms of farmer participation behavior and the process of their state transformation, as well as exploring how to enhance farmers' participation willingness. First, a dynamic group model of farmers' participation behavior was constructed by dividing them into five states: unknown, observing, participating, rejecting, and immune. Then, the strategic interactions between the government, social capital, and farmers under the PPP model were considered, and this was coupled with the dynamic group model. Finally, Chongqing City was taken as a typical case for numerical simulation to analyze the evolutionary patterns of farmers participation behavior. The results indicate that: (1) synergistic effective government regulation and active enterprise governance can elevate the farmer participation rate to approximately 71% and facilitate the convergence of the system toward a stable high-participation equilibrium; (2) government subsidies need to be controlled within a reasonable range to ensure policy effectiveness; (3) improving government publicity and enhancing the social atmosphere can increase farmers' participation rate to approximately 71% and 78%, respectively, significantly boosting their willingness to participate; (4) improving the social security system and reducing perceived risks can help increase farmers' participation rate. The research conclusions can provide a valuable reference for local governments in China in formulating soil erosion control policies.

Academic Editor: Xiaodong Nie

Received: 13 January 2026

Revised: 4 February 2026

Accepted: 13 February 2026

Published: 16 February 2026

Keywords: soil erosion control; PPP projects; farmers evolution; willingness; evolutionary game; SEIR model

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1. Introduction

Soil erosion represents a critical challenge to ecological security and sustainable development in China [1]. Triggered by sloping farmland cultivation, overgrazing, and unsustainable land-use practices, soil erosion not only reduces land fertility and degrades ecosystems but also leads to secondary disasters such as river siltation and reservoir sedimentation [2]. Its extensive impacts and the complexity of control efforts make soil

erosion a formidable governance task [3]. Effectively managing soil erosion is therefore of great significance for maintaining ecosystem stability, ensuring food security, supporting the achievement of dual-carbon goals, and promoting rural revitalization. In terms of governance approaches, the traditional government-led model achieved certain results in its early stages. However, as the scope and depth of governance expanded, its limitations, primarily its heavy reliance on public fiscal input, have become increasingly apparent. This model faces challenges such as insufficient funding, limited regulatory efficiency, and excessive pressure on local governments [4,5]. To alleviate these fiscal constraints and enhance governance efficiency, the introduction of social capital into ecological governance has emerged as a significant innovative direction. This shift is driven by the ongoing reform of the ecological civilization system and the guiding principle of “government steering and societal participation” [6]. Through cooperation models such as Public–Private Partnership, the government and enterprises can form complementary advantages in project financing, technological innovation, and long-term operation and maintenance. However, soil and water conservation projects generally have characteristics such as strong externalities, dispersed benefits, and long investment recovery periods, making it difficult to create sustainable incentives relying solely on administrative orders or fiscal subsidies. The issue of how to form a sustainable incentive balance between government incentives, corporate profits, and ecological benefits has become a core challenge for social capital to effectively participate in soil erosion control.

In this context, the introduction of carbon trading mechanisms provides new policy tools for soil erosion control. As one of the most market-efficient emission reduction mechanisms currently available, carbon trading can internalize the external benefits of ecological protection through price signals [7], achieving the dual goals of “promoting governance through carbon” and “generating wealth through carbon”. With forestry carbon sinks [8], agricultural soil carbon sinks [9], and other projects gradually being incorporated into the carbon market system, soil and water conservation projects possess potential advantages for participation in carbon trading because of their significant carbon sequestration and enhancement functions. In recent years, local practices of soil and water conservation carbon sink trading have been successively implemented across various regions in China: the soil and water conservation carbon sink project in Malong District, Qujing City, Yunnan Province, was successfully signed at the Fifth China Soil and Water Conservation Academic Conference; the carbon sink transaction in the Xiaonanshan watershed of Youyu County, Shanxi Province, was completed in Taiyuan; and Lingchuan County, Guilin, Guangxi Zhuang Autonomous Region, realized the first soil and water conservation carbon sink transaction in the Pearl River Basin. These practices indicate that soil and water conservation carbon sinks have transitioned from theoretical exploration to market operation stages. Under this mechanism, the government can create positive incentives for companies’ green investments by setting carbon trading rules; companies can obtain carbon benefits through governance activities, achieving a synergy of economic and ecological benefits. At the same time, carbon trading revenues can also be partially returned to the farming community, enhancing their enthusiasm for land transfer and participation in governance. In this way, carbon trading not only serves as a market-based regulatory tool in the context of environmental economics but can also become an institutional link that drives multi-party collaborative governance.

However, in stark contrast to its institutional potential and policy expectations, farmers’ participation in PPP-based soil and water conservation projects remains generally low in practice. This structural contradiction of “high potential–low participation” has become a critical bottleneck constraining the effectiveness of multi-actor collaborative governance. Consequently, the “farmer participation” link, as the most concentrated manifestation of this contradiction, constitutes the weakest component in the governance chain. To

overcome this bottleneck, it is first necessary to gain a deeper understanding of the internal logic underlying farmers' behavioral choices. Existing research often treats farmers as a homogeneous group with uniform strategies. However, in reality, they exhibit significant heterogeneity in terms of land dependency, policy awareness, and risk perception. This diversity leads to divergent behavioral choices: some farmers actively engage in conservation efforts, others remain passive, and some reject participation due to emotional attachment to land or short-term interests. These differences not only affect the coverage and sustainability of contiguous governance but also determine the actual effectiveness of policy incentives and carbon market mechanisms. Therefore, constructing a dynamic population model that accounts for this group heterogeneity to accurately characterize and analyze farmer participation behavior constitutes an important scientific issue.

At the same time, the dynamics of the farming community are not isolated, but rather the result of dynamic evolution influenced by government and corporate strategy adjustments. The government's intensity of publicity, subsidy levels, and regulatory strength can influence farmers' willingness through trust transmission and policy expectations; corporate governance attitudes can alter farmers' judgments of project benefits and risks; conversely, farmers' collective responses will feedback and impact the effectiveness of government policy implementation and corporate investment return expectations, forming a multi-level behavioral interaction and strategic synergy. This study aims to construct an analytical framework from a dynamic evolutionary perspective that reflects the mechanisms of multi-agent interaction and behavior dissemination, in order to reveal the formation logic and enhancement path of farmers' participation willingness.

2. Literature Review

2.1. *The Evolving Roles of Government, Private Sector, and Farmers in Collaborative Governance*

In recent years, the governance of soil and water conservation, both globally and in China, has been undergoing a paradigm shift from a "government-dominated, project-driven" model toward a framework of "multi-stakeholder collaboration and long-term governance." Existing research indicates that the traditional centralized model, with the government at its core, is increasingly revealing limitations in fiscal sustainability, governance efficiency, and adaptability to complex ecosystems. It struggles to meet the practical demands of soil erosion control, which are characterized by long-term commitment, uncertainty, and multiple, often competing, objectives [10]. Under this emerging paradigm, the roles and positioning of the government, private sector, and farmers have undergone significant transformation. The underlying governance logic has shifted from unidirectional administrative enforcement to a synergistic, multi-agent evolution driven by incentives and constraints [11]. The government is transitioning from a traditional "direct provider" to an "institutional designer and regulator." Studies show that by establishing governance rules, providing initial incentives, and implementing performance oversight, the government guides the participation of social capital and farmers in ecological governance. This approach aims to reduce fiscal pressure while enhancing governance efficiency [12]. The private sector is increasingly becoming a crucial investor, technology provider, and long-term operator in governance projects. Collaborative models such as Public–Private Partnerships (PPP) are recognized for introducing market efficiency and technological innovation. However, the profit-driven nature of private capital may also induce opportunistic behaviors, necessitating regulation through well-designed incentive and constraint mechanisms [13]. Farmers, as the direct implementers of conservation measures and providers of ecosystem services, constitute the micro-foundation for the long-term stability and operation of governance projects [14]. Unlike their passive role as mere executors in the traditional model, the new paradigm emphasizes farmers' active

participation decisions, which are shaped by their expected benefits, risk perceptions, and social interactions [15]. In summary, soil and water conservation governance is evolving into a multi-stakeholder collaborative framework defined by government guidance, private sector participation, and farmer involvement [16]. Within this context, systematically characterizing the strategic choices and co-evolutionary dynamics among the government, private sector, and farmers during their long-term interactions has become a central theoretical issue for understanding and advancing collaborative governance.

2.2. Influencing Factors of Farmers' Participation Willingness

Soil erosion is an important environmental issue both in China and globally. Its governance effectiveness depends not only on engineering and technological measures but more fundamentally on the behavioral responses of farmers. As key providers of land, farmers' behavioral choices directly determine the scope of governance and the long-term sustainability of outcomes. The behavior change of farmers is a multi-stage dynamic process. Policy awareness is a fundamental factor, and farmers' understanding of governance policies significantly affects their decision making and judgment [17]. Government subsidies, as the most direct economic incentive, can effectively reduce farmers' participation costs and increase their willingness to engage [18]. Emotional attachment to land [19] forms a psychological constraint, and strong emotional ties often reduce farmers' willingness to transfer land. Social atmosphere [20] has an important influence through group interactions, with a positive community atmosphere encouraging active imitation among farmers. Additionally, factors such as the proportion of non-farm household income [17], risk perception [21], environmental vulnerability [22], and participation in social insurance [22] also play significant roles. Although existing research has identified these key factors, most analyses are static, failing to reveal the dynamic transmission mechanisms of these factors within the group and their impact on the evolution of farmers' decision-making states.

2.3. Application of SEIR Model

The SEIR model originates from epidemiology and is primarily used to simulate the transmission dynamics of infectious diseases within populations. It classifies individuals into four states: Susceptible (S), Exposed (E), Infected (I), and Recovered (R). With the advancement of interdisciplinary research, the SEIR model has been widely applied across multiple fields due to its strong capability in characterizing the mechanisms of behavioral diffusion within groups.

In the field of public health, this model has not only been employed to simulate the transmission of norovirus infections in hospitals, demonstrating that timely isolation can effectively prevent outbreaks [23], but it has also been integrated with digital technologies during major epidemic responses to provide a scientific basis for developing contingency plans and allocating medical resources [24]. Moreover, scholars have analyzed the impact of media publicity and education on disease transmission by incorporating recurrence rates and nonlinear incidence rates [25]. At the same time, the application of the SEIR model has expanded to areas such as society, economy, and management: in public opinion management, some studies have used this model to analyze the transmission mechanisms of online public opinion surrounding major engineering projects [26]. In the realm of public safety, studies have simulated the self-organized spread of passenger panic during subway emergencies [27]. In organizational behavior, the model has been applied to examine the diffusion of tacit knowledge within enterprises [28]. In information science, scholars have studied the effects of user opinion evolution on information dissemination in online social networks, considering the homepage effect on the dissemination process [29]. These studies fully demonstrate the adaptability and practicality of the SEIR model

in addressing complex diffusion problems. In this study, farmers participating in soil erosion control are not isolated individuals; their decision-making behaviors are profoundly influenced by social networks such as neighbors and relatives. The diffusion process of behavioral intentions closely resembles the mechanisms underlying the spread of information and perceptions. Therefore, diffusion models are well-suited for investigating the evolutionary patterns of participation intentions among farming communities in governance initiatives.

2.4. Evolutionary Game Theory

To depict the dynamic interaction mechanisms of multiple entities in environmental governance, evolutionary game theory has been widely applied in fields such as ecological governance, pollution control, and green buildings. This theory breaks through the traditional game theory's assumption of "perfect rationality" and can illustrate the dynamic process in which participants gradually approach equilibrium through imitation, learning, and strategic adjustments under conditions of bounded rationality. It is especially suitable for analyzing governance behaviors with long-term interaction characteristics.

In public affairs management, such as ecological and environmental governance, the evolutionary game frameworks were used to analyze behavioral interactions among diverse stakeholders, including the government, private capital, and rural communities. The government guides the direction of governance through financial subsidies and administrative regulation [30]; social capital weighs governance strategies between governance costs and external incentives [31]; and farmers, as the managers of ecological resources and the implementers of governance measures, directly determine the breadth and sustainability of ecological governance through their willingness to participate and behavioral responses [32]. Related studies indicate that factors such as subsidy intensity, regulatory costs [18], and reputation mechanisms [33] are key variables for the system's evolution towards an ideal equilibrium state. With continuous innovation in governance models, the PPP model has gradually emerged as a significant pathway to enhance project operational efficiency and alleviate fiscal pressure. This model has been widely employed in areas such as water pollution control [34], infrastructure [35], public service projects [36], green waste management [37], energy [38], public rental housing [39], and building renovation [18], also providing a referable institutional framework for soil erosion governance. However, during PPP cooperation, the interest game among multiple stakeholders remains a core challenge in advancing projects. Although single policy variables can influence stakeholder strategies to some extent, whether stable collaborative governance emerges and persists fundamentally depends on the interactions and dynamic feedback mechanisms among multiple variables within the system.

Current research has made significant progress in identifying key influencing factors and macroeconomic equilibrium paths, but most models are still based on the assumption of consistent individual responses, overlooking the heterogeneity and interaction effects within the group. While this assumption facilitates theoretical analysis, it struggles to reflect the behavioral differentiation and diffusion patterns triggered by factors such as policy signals, social learning, and herd behavior in real-world governance.

2.5. Application of Carbon Trading in Environmental Governance

Carbon trading, as an efficient market-based environmental governance mechanism, has been widely applied globally to incentivize emission reduction activities. In recent years, its scope of application has gradually expanded from traditional industrial sectors to emerging fields such as ecological restoration and agricultural carbon sequestration, marking a shift in carbon trading from a purely 'end-of-pipe emission reduction' tool to a

comprehensive policy instrument that also encompasses the ‘source-based carbon sequestration’ function.

Studies show that forestry carbon trading can not only regulate the welfare effects of emission reduction policies and mitigate the negative economic impacts of policies such as carbon taxes but also enhance the enthusiasm of enterprises to participate in carbon sequestration management, facilitating the synergistic achievement of economic and ecological benefits [8,40]. Regarding grassland ecosystems, scholars point out that its carbon sequestration function is stable and can be transformed into economic value through carbon trading, providing support for regional carbon neutrality [41,42]. The carbon trading mechanism has also demonstrated significant importance in the ecological restoration of mining areas [43]. In the marine domain, related studies have explored the feasibility of incorporating fisheries carbon sinks into the trading system, suggesting that this could not only generate direct benefits for fishermen and enterprises but also incentivize their participation in ecological restoration activities such as marine ranching, forming a market-based governance pathway [44,45]. In the agricultural domain, incorporating agriculture into the carbon trading system is considered a significant driver of the green and low-carbon transformation, and it works synergistically with government subsidies, carbon taxes, and other policies, promoting the adoption and diffusion of low-carbon agricultural technologies [46].

Therefore, the carbon trading mechanism not only provides a market-based pathway for greenhouse gas emission reduction but also demonstrates broad potential in fields such as ecological restoration, agricultural carbon sequestration enhancement, and blue carbon governance. Through price signals and revenue feedback, it can effectively incentivize corporate green investment, guide governments in optimizing policy structures, and enhance public and farmer willingness to participate in ecological efforts, thereby fostering synergistic effects in environmental governance on a broader scale. However, existing research predominantly focuses on the operational mechanisms of carbon markets themselves or the behavioral analysis of single stakeholders, and it has not yet systematically embedded the carbon trading mechanism into a dynamic game-theoretic framework focused on farmer participation in PPP projects of soil erosion control.

In summary, existing studies on public participation behavior in environmental governance largely remain at a static analytical level, failing to reveal the dynamic mechanisms through which various influencing factors propagate and evolve via social networks. At the same time, the application of evolutionary game theory in environmental governance mostly assumes homogeneity within groups, overlooking the heterogeneity of public decision-making and the effect of social conformity. Furthermore, research on carbon trading mechanisms primarily focuses on the macro-market level and has not been systematically integrated into a multi-stakeholder game framework focused on farmers. This study constructs a coupled analysis framework combining evolutionary game model and the improved SEIR propagation model, revealing the interaction between the dynamic game of government–enterprise–farmer under the carbon trading mechanism and the diffusion of farmers behavior, thus uncovering the internal mechanisms that affect the evolution of governance systems. The main contributions are as follows: first, a “game-propagation” coupled model suitable for heterogeneous farmers is developed, breaking through the limitation of current research that treats farmers as a homogeneous group, and establishing an integrated analytical framework that simultaneously captures both internal group behavior spread and external strategy interactions. Second, it reveals the transmission path of dynamic multi-party games under the carbon trading mechanism. By transforming the dynamic game results of carbon sink benefits, government subsidies and other factors into behavioral transmission parameters within the farmers, it clearly unveils the internal mechanism driving the evolution of macro-participation patterns

through market signals and policy interventions. Third, it systematically simulates the dynamic trajectory of changes in the proportion of farmers in different states under various scenarios, identifying key influencing factors for farmer participation and providing quantitative references for policy design.

3. Model Construction and Solution

3.1. Analytical Framework

In the process of soil erosion control, farmers' participation willingness directly influences the implementation and effectiveness of the control measures, making it a key factor in achieving the governance objectives. The behavior of the farmers is influenced by a combination of internal and external factors. On the one hand, there is frequent information exchange and behavior imitation among individuals within the farmers, with varying levels of willingness to participate spreading through social learning and interaction within the group, resulting in dynamic cognitive evolution and behavioral change; on the other hand, external actors such as the government and enterprises, through policy design, governance actions, and economic incentives, significantly influence farmers' participation decisions. The government shapes the external policy environment through subsidies, supervision, and publicity, while enterprises influence governance expectations and economic returns through governance investments and shared income. These external game behaviors jointly affect the evolution of willingness within the farmers.

Building on this framework, it is necessary to construct a tripartite evolutionary game analysis framework from the perspective of multi-agent interaction, involving the government, enterprises, and farmers, in order to reveal the evolution mechanism of farmers' participation willingness under the joint influence of internal and external factors. This framework offers insights for enhancing farmers' participation and promoting the efficient operation of the soil erosion control system. The analytical framework is shown in Figure 1.

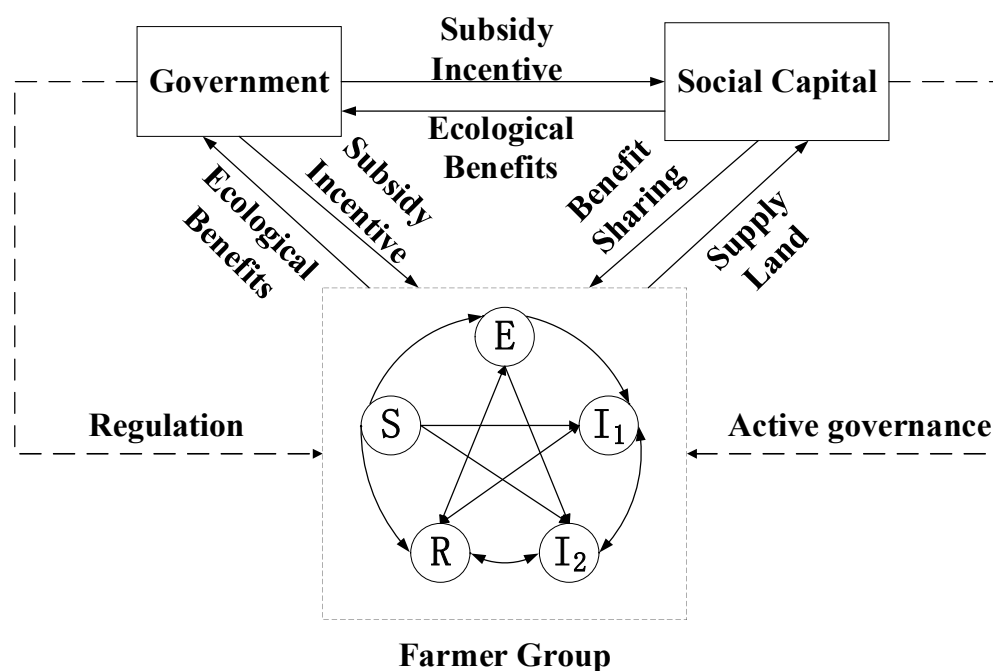


Figure 1. Framework of multi-agent interaction in PPP-based soil erosion governance.

In the figure, S represents unknown farmers, E represents neutral farmers, I₁ represents actively participating farmers, I₂ represents farmers who refuse to participate, and R represents immune farmers.

3.2. Propagation Model

To accurately depict the heterogeneous behaviors of farmers during the process of soil and water conservation, this study categorizes farmers into five types based on their information reception and decision-making status: Unknown Farmers (S) refer to those who have not yet been exposed to conservation information; Neutral Farmers (E) are those who have not yet decided on participation; Actively Participating Farmers (I₁) are those who have decided to participate and spread positive information; Refusing to Participate Farmers (I₂) are those who refuse to participate and may spread negative sentiments; Immune Farmers (R) are those who have lost interest in or no longer pay attention to the conservation projects. Based on this categorization, the basic assumptions are as follows.

3.2.1. Assumptions of the Propagation Model

Assumption 1. At time t , the proportions of unknown farmers, neutral farmers, actively participating farmers, farmers refusing to participate, and immune farmers within the total farmer population are represented by $S(t)$, $E(t)$, $I_1(t)$, $I_2(t)$, and $R(t)$ respectively, satisfying $S(t) + E(t) + I_1(t) + I_2(t) + R(t) = 1$.

Assumption 2. The dissemination and transformation of farmers are influenced by both internal and external factors. According to relevant studies [17,19,21,22,47], internal factors include Policy Cognition Level (PCL), Land Emotional Attachment (LEA), and Risk Perception (RP). External factors include Environmental Vulnerability (EV), Per Capita Arable Land Scale (PCALS), Non-Farm Income Ratio (NFIR), Government Publicity Level (GPL), Social Atmosphere (SF), Social Insurance Participation (SIP), and Soundness of the Land Transfer Service System (SLTSS). These factors work together to influence farmers' decision-making tendencies.

Assumption 3. To accurately express the cumulative effect of multiple influencing factors, a Sigmoid function is introduced to represent the combined impact of multiple factors on the state transition probability. This function effectively simulates decision-making behaviors exhibiting “diminishing marginal effects” and “factor saturation,” ensuring probability values remain within the interval (0, 1). For example, the probability of an unknown farmer (S) transitioning to an active farmer (I₁) at time t is calculated by the Sigmoid function, which integrates both internal and external factors. This probability is denoted as

$$P_{S \rightarrow I_1}(t) = \frac{1}{1 + e^{-a(\alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 + \dots - b)}}$$
, where a, b is a parameter that adjusts the shape of the function, X_i represents the internal and external influencing factors, and α_i denotes the weight coefficients for each factor. Following reference [48], a is set to 10 and b to 0.5.

Assumption 4. At time t , influenced by both internal and external factors, the probability of an

unknown farmer S converting to a neutral farmer E is
$$\beta_2 \frac{1}{1 + e^{-10(\alpha_7 \text{GPL} + \alpha_2 \text{SF} + \alpha_3 \text{PCL} - 0.5)}}$$
, the probability

of converting to an actively participating farmer I₁ is
$$\beta_1 \frac{1}{1 + e^{-10(\alpha_4 (1 - \text{EV}) + \alpha_5 (1 - \text{PCALS}) + \alpha_6 \text{NFIR} - 0.5)}}$$
, the

probability of converting to a rejecting farmer I₂ is
$$\beta_3 \frac{1}{1 + e^{-10(\alpha_7 \text{LEA} + \alpha_8 (1 - \text{SIP}) + \alpha_9 \text{EV} + \alpha_{10} (1 - \text{NIRI}) + \alpha_{11} \text{RP} - 0.5)}}$$
,

and the probability of converting to an immune farmer R is $\beta_4 \frac{1}{1 + e^{-10(\alpha_{12}LEA + \alpha_{13}(1-SIP) + \alpha_{14}RP - 0.5)}}$. Among these, the success rate of the conversion of the unknown farmer S to an actively participating farmer I₁ and a neutral farmer E is β_1, β_2 , and the success rate of the conversion of the unknown farmer S to a rejecting farmer I₂ and an immune farmer R is β_3, β_4 .

Assumption 5. Influenced by their surrounding environment, a neutral farmer (E) transitions to an actively participating farmer (I₁) with probability Z_1 , to a resistant farmer (I₂) with probability Z_2 , and to a recovered farmer (R) with probability $1 - Z_1 - Z_2$. Resistant farmers (I₂) and recovered farmers (R) can be influenced by government supervision and the active governance strategies of social capital, transitioning to actively participating farmers (I₁) with probabilities m_{2xy} and m_{3xy} respectively. Conversely, Actively participating farmers (I₁) and recovered farmers (R) may be influenced by the spread of negative information, or by government inaction and the passive governance strategies of social capital, transitioning to Resistant farmers (I₂) with probabilities $m_1(1-x)(1-y)$ and $m_4(1-x)(1-y)$, respectively. Actively Participating farmers (I₁) and Resistant farmers (I₂) may lose interest in soil erosion control, transitioning to Recovered farmers (R)

with probabilities $\frac{1}{1 + e^{-10(\alpha_{15}(1-SF) + \alpha_{16}(1-SIP) + \alpha_{17}RP + \alpha_{18}(1-SLTSS) - 0.5)}}$ and $\frac{1}{1 + e^{-10(\alpha_{19}LEA + \alpha_{20}(1-SIP) + \alpha_{21}(1-GPL) + \alpha_{22}(1-SF) - 0.5)}}$ respectively. A Recovered farmer (R) transitions back to an Exposed farmer (E) with probability $\frac{1}{1 + e^{-10(\alpha_{23}GPL + \alpha_{24}SF + \alpha_{25}SLTSS + \alpha_{26}(1-RP) - 0.5)}}$. Here, m_1 denotes the trust level of I₁ farmers towards I₂ farmers, m_2 denotes the trust level of I₂ farmers towards I₁ farmers, m_3 and m_4 denote the trust levels of R farmers towards I₁ and I₂ farmers, respectively.

3.2.2. Model Formulation

The improved SEIR diffusion model is illustrated in Figure 2. It captures the state transition dynamics among different individuals within the farmer population, connecting them into an interactive system through their interrelationships.

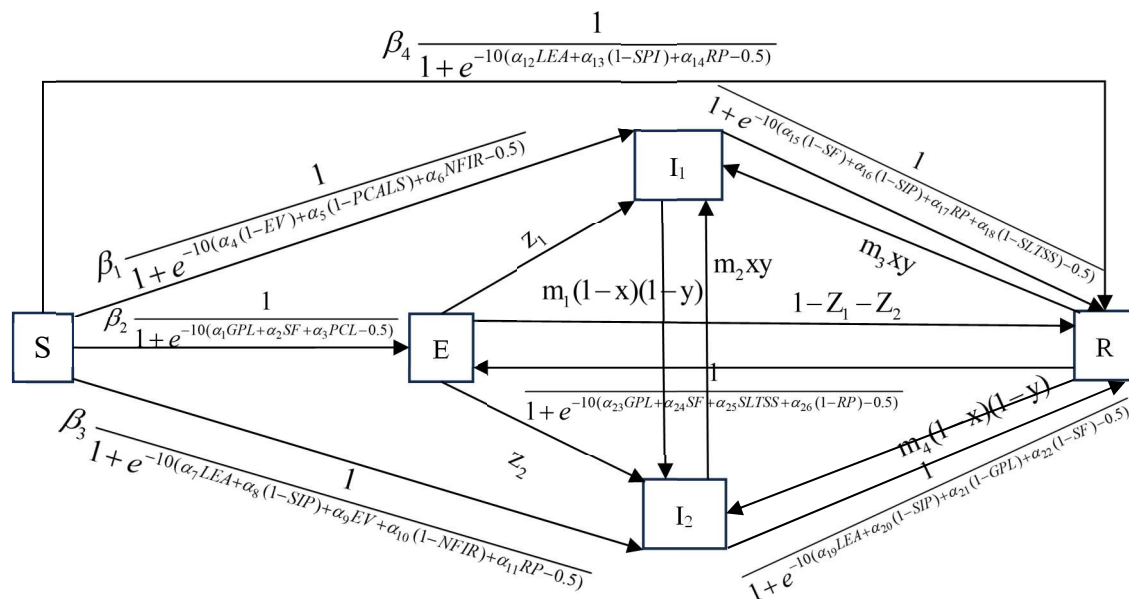


Figure 2. Improved SEIR model.

Based on the assumptions outlined above, the dynamic differential equations governing the behavioral diffusion among farmers are formulated as follows:

$$\begin{aligned}
 \frac{dS(t)}{dt} &= -\beta_1 \frac{1}{1 + e^{-10(\alpha_4(1-EV) + \alpha_5(1-PCALS) + \alpha_6 NFIR - 0.5)}} S(t) - \beta_3 \frac{1}{1 + e^{-10(\alpha_7 LEA + \alpha_8(1-SIP) + \alpha_9 EV + \alpha_{10}(1-NFIR) + \alpha_{11} RP - 0.5)}} S(t) \\
 &\quad - \beta_4 \frac{1}{1 + e^{-10(\alpha_{12} LEA + \alpha_{13}(1-SIP) + \alpha_{14} RP - 0.5)}} S(t) - \beta_2 \frac{1}{1 + e^{-10(\alpha_1 GPL + \alpha_2 SF + \alpha_3 PCL - 0.5)}} S(t) \\
 \frac{dE(t)}{dt} &= \beta_2 \frac{1}{1 + e^{-10(\alpha_1 GPL + \alpha_2 SF + \alpha_3 PCL - 0.5)}} S(t) + \frac{1}{1 + e^{-10(\alpha_{23} GPL + \alpha_{24} SF + \alpha_{25} SLTSS + \alpha_{26}(1-RP) - 0.5)}} R(t) - z_1 E(t) - z_2 E(t) - (1 - z_1 - z_2) E(t) \\
 \frac{dI_1(t)}{dt} &= \beta_1 \frac{1}{1 + e^{-10(\alpha_4(1-EV) + \alpha_5(1-PCALS) + \alpha_6 NFIR - 0.5)}} S(t) + m_3 xy R(t) + m_2 xy I_1(t) I_2(t) + z_1 E(t) - m_1 (1-x)(1-y) I_1(t) I_2(t) \\
 &\quad - \frac{1}{1 + e^{-10(\alpha_{15}(1-SF) + \alpha_{16}(1-SIP) + \alpha_{17} RP + \alpha_{18}(1-SLTSS) - 0.5)}} I_1(t) \\
 \frac{dI_2(t)}{dt} &= \beta_3 \frac{1}{1 + e^{-10(\alpha_7 LEA + \alpha_8(1-SIP) + \alpha_9 EV + \alpha_{10}(1-NFIR) + \alpha_{11} RP - 0.5)}} S(t) - \frac{1}{1 + e^{-10(\alpha_{19} LEA + \alpha_{20}(1-SIP) + \alpha_{21}(1-GPL) + \alpha_{22}(1-SF) - 0.5)}} I_2(t) \\
 &\quad + z_2 E(t) + m_1 (1-x)(1-y) I_1(t) I_2(t) + m_4 (1-x)(1-y) R(t) - m_2 xy I_1(t) I_2(t) \\
 \frac{dR(t)}{dt} &= \frac{1}{1 + e^{-10(\alpha_{15}(1-SF) + \alpha_{16}(1-SIP) + \alpha_{17} RP + \alpha_{18}(1-SLTSS) - 0.5)}} I_1(t) + \frac{1}{1 + e^{-10(\alpha_{19} LEA + \alpha_{20}(1-SIP) + \alpha_{21}(1-GPL) + \alpha_{22}(1-SF) - 0.5)}} I_2(t) + (1 - z_1 - z_2) E(t) \\
 &\quad - m_3 xy R(t) - m_4 (1-x)(1-y) R(t) + \beta_4 \frac{1}{1 + e^{-10(\alpha_{12} LEA + \alpha_{13}(1-SIP) + \alpha_{14} RP - 0.5)}} S(t) - \frac{1}{1 + e^{-10(\alpha_{23} GPL + \alpha_{24} SF + \alpha_{25} SLTSS + \alpha_{26}(1-RP) - 0.5)}} R(t)
 \end{aligned}$$

3.3. Evolutionary Game Model

In the governance of soil and water conservation, the government, enterprise, and farmers function as the core participating entities. Traditional game theory, based on assumptions of “complete rationality” and “static equilibrium,” is inadequate for modeling their long-term interactions, as these actors operate under constraints such as incomplete information, uncertain returns, and fluctuating policy continuity. In particular, farmers’ decision making is characterized by bounded rationality: they cannot precisely calculate long-term ecological or carbon sequestration benefits. Instead, their strategy adjustments rely on two learning mechanisms: experiential learning (perceiving actual benefit changes from government and enterprise actions) and social learning (imitating seemingly more successful strategies of peers). Thus, their choice between active and passive participation

is a dynamic, iterative process of adaptation through trial-and-error and comparison. Evolutionary Game Theory (EGT) provides a framework designed to analyze the long-term behavioral evolution of such boundedly rational populations. It abandons the search for one-time optimal solutions, focusing instead on dynamic changes in the proportion of strategies within a group. Its core mechanism—replicator dynamics—formalizes this learning process: the growth rate of a strategy depends on its payoff relative to the population average, which corresponds to the real-world social diffusion where farmers imitate more successful strategies. Therefore, EGT captures the “learning–adaptation–iteration” evolution of multi-agent interactions more realistically than static models. Based on this, our study constructs a tripartite evolutionary game model to reveal the logic of strategy co-evolution and collaborative governance under incentive mechanisms.

In this model, the government, as a provider of institutions and a guardian of public interests, aims to achieve a balance between ecological, economic, and social benefits. Through subsidies, regulation, and policy advocacy, the government guides enterprises and farmers to participate in governance. However, when regulatory costs exceed the ecological benefits derived from governance, the government may tend to adopt a “laissez-faire” strategy. Conversely, if active regulation can effectively improve governance performance and enhance public trust, the government will choose “active regulation” to promote the achievement of policy objectives. Enterprises, as the implementers and investors in governance, seek to maximize their own economic benefits. However, when subsidies are insufficient or regulation is lax, enterprises may resort to “passive governance” or even “perfunctory governance” to reduce short-term costs, reflecting opportunistic tendencies. Farmers, as land providers and potential beneficiaries of ecological services, are influenced by a variety of factors, including policy awareness, dependence on land, and the social atmosphere. When government regulation is robust, enterprises engage actively in governance, and subsidy and benefit-sharing mechanisms are reasonable, farmers are more willing to provide land. However, in cases of unstable policy implementation or uncertain profits, farmers may choose to withdraw.

Consequently, the government, enterprises, and farmers form an evolutionary game relationship driven by dynamic feedback. The government’s regulatory intensity and subsidy levels influence the expected returns of enterprises and farmers, thereby guiding their strategic adjustments. In turn, enterprises’ governance attitudes and investment levels affect both government policy performance and farmers’ payoff perceptions. Critically, within the large population of farmers, strategies propagate through social learning as individuals imitate those yielding higher perceived returns. This population-level learning and diffusion process constitutes the core micro-mechanism of system evolution, which is formally captured by the replicator dynamics. As the game iterates, the strategy mix of each group dynamically adjusts and may converge to a stable state. The simultaneous realization of synergistic benefits occurs only when the system stabilizes at an equilibrium characterized by active government regulation, proactive enterprise governance, and widespread farmer participation—a state where the interrelations among all actors evolve from conflict toward stable, mutualistic cooperation.

Assumptions of the Evolutionary Game Model

Assumption 6. *The government, social capital, and farmers are all assumed to be rational agents. The government’s strategy set is {regulate, not regulate}, the strategy set of enterprise is {active governance, passive governance}, and the strategy set of farmers is {participate and disseminate positive information, not participate and disseminate negative information, not pay attention and not disseminate}. The probability that the government chooses regulation is x , and conversely is $1 - x$. The probability that enterprise chooses active governance is y , and conversely is $1 - y$.*

The probabilities that farmers choose to participate and disseminate positive information, not participate and disseminate negative information, and not pay attention and not disseminate are Z_1 , Z_2 , and $1-Z_1-Z_2$, respectively.

Assumption 7. The change in the soil erosion modulus before and after governance can serve as a criterion for judging whether enterprise implements active governance. Let the soil erosion modulus before governance be E_0 . Active governance by enterprise is characterized by its full effort to implement control measures, significantly reducing regional erosion intensity by increasing investment in funds, technology, and management. In this case, the governance cost is C_{e1} , and the post-governance soil erosion modulus is reduced to $E_1 (E_1 < E_0)$. In contrast, when enterprise adopts a passive governance strategy, it typically addresses governance tasks with low input, formalized or perfunctory methods. Its governance cost is lower, denoted as $C_{e2} (C_{e2} < C_{e1})$, but the post-governance soil erosion modulus only decreases to E_2 , with $E_2 > E_1$, indicating significantly inferior effectiveness compared to active governance.

Assumption 8. The soil erosion control project can only be completed with farmer participation. Assuming enterprise employs terracing measures for soil erosion control, this governance approach combines carbon sequestration benefits with crop economic benefits. When farmers participate, enterprise shares the carbon sink revenue and crop revenue with farmers at a proportion ω . Both parties can obtain carbon sink revenue and crop revenue. Under active governance by enterprise, the shareable carbon sink revenue is $(E_0 - E_1) \cdot S \cdot G_T \cdot P_C$, and the obtainable crop economic revenue is $(Y_0 + k \cdot (E_1 - E_0)) \cdot S \cdot P_N$. Here, S is the land area, G_T is the soil organic carbon mass fraction, P_C is the carbon price, Y_0 is the pre-governance crop yield per unit area, k is the coefficient representing the impact of post-governance soil erosion modulus change on yield, and P_N is the crop price. In this scenario, the government gains ecological benefit $k_e \cdot (E_0 - E_1) \cdot S \cdot G_T$, where k_e is the coefficient representing the impact of carbon sequestration on government ecological benefit. If enterprise chooses passive governance, the obtainable carbon sink revenue is $(E_0 - E_2) \cdot S \cdot G_T \cdot P_C$, and the crop economic revenue is $(Y_0 + k \cdot (E_2 - E_0)) \cdot S \cdot P_N$. The government gains ecological benefit $k_e \cdot (E_0 - E_2) \cdot S \cdot G_T$. If farmers do not participate, enterprise still incurs preliminary research and preparation costs C_{s1} for active governance, $C_{s2} (C_{s1} > C_{s2})$ for passive governance. However, without farmer participation, enterprise cannot complete the soil erosion control task, rendering the project and carbon sink trading incapable of generating substantive benefits.

Assumption 9. Government regulation entails providing a subsidy D_1 to enterprise and a subsidy D_2 to farmers when enterprise engages in active governance and farmers participate. If enterprise adopts passive governance, the government imposes a penalty U on it. The government also bears a regulatory cost C_g . In cases where farmers actively participate and enterprise undertakes active governance, but the government fails to provide timely positive incentives such as subsidies, both farmers and enterprise may exert pressure on the government through appeals or other means. Consequently, the government faces collective pressure and negotiation costs, denoted

as H_2 . Furthermore, when farmers participate while enterprise chooses passive governance, the enterprise incurs a reputation loss H_1 . If the government opts for non-regulation under such circumstances, it suffers a credibility loss H_3 , reflecting diminished trust in its fulfillment of social responsibilities and policy execution. Conversely, if enterprise implements active governance with farmer participation, it gains a reputation enhancement R and is required to pay land transfer rent R_L to the farmers.

Assumption 10. When farmers choose to participate, they incur a participation cost C_f . If enterprise fails to conduct active governance despite farmer participation, its opportunistic behavior undermines the farmers' expected benefits. To compensate for the income loss arising from this governance failure, either the government or enterprise must pay compensation for damages B to the farmers. If farmers choose not to participate, the project cannot proceed effectively, leading to the persistence or exacerbation of regional soil erosion. This results in negative impacts L_f on farmers due to ecological degradation. Additionally, if farmers disseminate positive information during the governance process, they gain an additional social influence benefit V ; if they spread negative information, they bear a reputation loss W .

Based on the assumptions outlined above, the payoff matrix for the game among the government, enterprise, and farmers is derived, as presented in Table 1.

Table 1. Payoff Matrix of Government, Enterprise and Farmers.

Farmer	Government Regulation of Subsidies x		No Government Regulation and No Subsidy 1 – x	
	Enterprise Proactive Governance y	Enterprise Passive Governance 1 – y	Enterprise Proactive Governance y	Enterprise Passive Governance 1 – y
Participation in and dissemination of positive information z_1	$k_e \cdot (E_0 - E_1) \cdot S \cdot G_T - D_1 - D_2 - C_g$	$k_e \cdot (E_0 - E_2) \cdot S \cdot G_T - D_2 - C_g - B + U$	$k_e \cdot (E_0 - E_1) \cdot S \cdot G_T - H_2$	$k_e \cdot (E_0 - E_2) \cdot S \cdot G_T - H_3$
	$\{(E_0 - E_1) \cdot S \cdot G_T \cdot P_C + (Y_0 + k \cdot (E_1 - E_0)) \cdot S \cdot P_N\} \cdot (1 - \omega) + D_1 - C_{e1} - R_L S + R$	$\{(E_0 - E_2) \cdot S \cdot G_T \cdot P_C + (Y_0 + k \cdot (E_2 - E_0)) \cdot S \cdot P_N\} \cdot (1 - \omega) - C_{e2} - U - R_L S - H_1$	$\{(E_0 - E_1) \cdot S \cdot G_T \cdot P_C + (Y_0 + k \cdot (E_1 - E_0)) \cdot S \cdot P_N\} \cdot (1 - \omega) - C_{e1} - R_L S + R$	$\{(E_0 - E_2) \cdot S \cdot G_T \cdot P_C + (Y_0 + k \cdot (E_2 - E_0)) \cdot S \cdot P_N\} \cdot (1 - \omega) - C_{e2} - B - R_L S - H_1$
	$\{(E_0 - E_1) \cdot S \cdot G_T \cdot P_C + (Y_0 + k \cdot (E_1 - E_0)) \cdot S \cdot P_N\} \cdot \omega + D_2 - C_f + R_L S + V + W$	$\{(E_0 - E_2) \cdot S \cdot G_T \cdot P_C + (Y_0 + k \cdot (E_2 - E_0)) \cdot S \cdot P_N\} \cdot \omega + D_2 - C_f + B + R_L S + V + W$	$\{(E_0 - E_1) \cdot S \cdot G_T \cdot P_C + (Y_0 + k \cdot (E_1 - E_0)) \cdot S \cdot P_N\} \cdot \omega - C_f + R_L S + V + W$	$\{(E_0 - E_2) \cdot S \cdot G_T \cdot P_C + (Y_0 + k \cdot (E_2 - E_0)) \cdot S \cdot P_N\} \cdot \omega - C_f + B + R_L S + V + W$
Non-participation in and non-dissemination of negative information z_2	0	0	0	0
	$-C_{s1}$	$-C_{s2}$	$-C_{s1}$	$-C_{s2}$
Non-attention and non-dissemination $1 - z_1 - z_2$	$V - W - L_f$	$V - W - L_f$	$V - W - L_f$	$V - W - L_f$
	0	0	0	0
	$-C_{s1}$	$-C_{s2}$	$-C_{s1}$	$-C_{s2}$
	$-V - L_f$	$-V - L_f$	$-V - L_f$	$-V - L_f$

3.4. Game Stability Analysis

3.4.1. Construction of Replicated Dynamics Equations

The expected payoff for the government when adopting the regulation strategy is denoted as G_{11} , and the expected payoff when adopting the non-regulation strategy is denoted as G_{12} . The corresponding equations are presented as follows:

$$G_{11} = yz_1(k_e \cdot (E_0 - E_1) \cdot S \cdot G_T - D_1 - D_2 - C_g) + (1-y)z_1(k_e \cdot (E_0 - E_2) \cdot S \cdot G_T - D_2 - C_g - B + U) \quad (1)$$

$$G_{12} = yz_1(k_e \cdot (E_0 - E_1) \cdot S \cdot G_T - H_2 - P_g) + (1-y)z_1(k_e \cdot (E_0 - E_2) \cdot S \cdot G_T - H_3 - P_g) \quad (2)$$

The replicated dynamics equation for the government when choosing the regulation strategy is as follows:

$$F(x) = x(1-x)[yz_1(H_2 - D_1 - H_3 + B - U) + z_1(H_3 - D_2 - C_g - B + U)] \quad (3)$$

Similarly, the replicated dynamics equation for enterprise when choosing the active governance strategy is as follows:

$$F(y) = y(1-y)[xz_1(D_1 + U - B) + z_1(((E_2 - E_1)SG_T P_c + k(E_1 - E_2)SP_N)(1-\omega) + C_{e2} - C_{e1} - C_{s2} + C_{s1} + R + B + H_1) + C_{s2} - C_{s1}] \quad (4)$$

When farmers choose to participate and spread positive information, the replicated dynamics equation is as follows:

$$F(Z_1) = Z_1[(1-Z_1)\{y[(E_2 - E_1)S \cdot G_T \cdot P_c + k \cdot (E_1 - E_0) \cdot S \cdot P_N]\omega - B\} + xD_2 + (((E_0 - E_2)S \cdot G_T \cdot P_c + (Y_0 + k \cdot (E_2 - E_0)) \cdot S \cdot P_N)\omega - C_f + B + 2V + W + L_f + R_L S)\} - Z_2(2V - W)] \quad (5)$$

When farmers choose not to participate and spread negative information, the replicated dynamics equation is as follows:

$$F(Z_2) = Z_2\{(1-Z_2)(2V - W) - Z_1\{y[(E_2 - E_1)S \cdot G_T \cdot P_c + k \cdot (E_1 - E_0) \cdot S \cdot P_N]\omega - B\} + xD_2 + [((E_0 - E_2)S \cdot G_T \cdot P_c + (Y_0 + k \cdot (E_2 - E_0)) \cdot S \cdot P_N)\omega - C_f + B + 2V + W + L_f + R_L S]\}\} \quad (6)$$

3.4.2. Stability Analysis of Evolutionary Equilibria

By setting $F(x) = F(y) = F(z_1) = F(z_2) = 0$, 23 equilibrium points of the tripartite evolutionary game system can be obtained. Among these, 15 equilibrium points satisfy the stability conditions for evolutionary dynamics, which are:

$$\begin{aligned} & E_1(0,0,0,0), E_2(1,0,0,0), E_3(0,1,0,0), E_4(0,0,1,0), E_5(0,0,0,1), E_6(1,1,0,0), E_7(1,0,1,0), E_8(0,1,1,0), E_9(1,0,0,1), \\ & E_{10}(0,1,0,1), E_{11}(1,1,1,0), E_{12}(1,1,0,1), \\ & E_{13}\left(\frac{C_f - L_f - 2V - W - R_L S - P_N S Y_0 \omega - 2E_2 G_t P_c S \omega + 2E_1 G_t P_c S \omega + 2E_0 P_N S k \omega - 2E_1 P_N S k \omega}{D_2}, 1, 0, 0\right), \\ & E_{14}\left(\frac{C_f - B - L_f - 2W - R_L S - P_N S Y_0 \omega + E_1 G_t P_c S \omega - E_2 G_t P_c S \omega + E_0 P_N S k \omega - E_1 P_N S k \omega}{D_2}, 0, 0, 1\right), \\ & E_{15}\left(\frac{C_f - L_f - 2W - R_L S - P_N S Y_0 \omega + 2E_1 G_t P_c S \omega - 2E_2 G_t P_c S \omega + 2E_0 P_N S k \omega - 2E_1 P_N S k \omega}{D_2}, 1, 0, 1\right), \\ & E_{16}\left(\frac{C_{e1} - C_{e2} - B - H_1 - R + E_1 G_t P_c S - E_2 G_t P_c S - E_1 P_N S k + E_2 P_N S k}{D_1 - B + U}, \frac{H_3 + U - B - C_g - D_2}{D_1 - B - H_2 + H_3 + U}, 1, 0\right). \end{aligned}$$

These locally stable equilibrium points are not necessarily stable for the entire system. Their evolutionary stability can be determined by evaluating the Jacobian matrix of the system, as shown in Equation (7). A more intuitive analysis can be facilitated through numerical simulation.

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x}, \frac{\partial F(x)}{\partial y}, \frac{\partial F(x)}{\partial z_1}, \frac{\partial F(x)}{\partial z_2} \\ \frac{\partial F(y)}{\partial x}, \frac{\partial F(y)}{\partial y}, \frac{\partial F(y)}{\partial z_1}, \frac{\partial F(y)}{\partial z_2} \\ \frac{\partial F(z_1)}{\partial x}, \frac{\partial F(z_1)}{\partial y}, \frac{\partial F(z_1)}{\partial z_1}, \frac{\partial F(z_1)}{\partial z_2} \\ \frac{\partial F(z_2)}{\partial x}, \frac{\partial F(z_2)}{\partial y}, \frac{\partial F(z_2)}{\partial z_1}, \frac{\partial F(z_2)}{\partial z_2} \end{bmatrix} \quad (7)$$

$$\frac{\partial F(x)}{\partial x} = x \left(z_1 (B + C_g + D_2 - H_3 - U) + y z_1 (D_1 - B - H_2 + H_3 + U) \right) + (z_1 (B + C_g + D_2 - H_3 - U) + y z_1 (D_1 - B - H_2 + H_3 + U)) (x - 1)$$

where:

$$\frac{\partial F(x)}{\partial y} = x z_1 (x - 1) (D_1 - B - H_2 + H_3 + U)$$

$$\frac{\partial F(x)}{\partial z_1} = x (x - 1) (B + C_g + D_2 - H_3 - U + y (D_1 - B - H_2 + H_3 + U)) \quad , \quad \frac{\partial F(x)}{\partial z_2} = 0$$

$$\frac{\partial F(y)}{\partial x} = -y z_1 (y - 1) (D_1 - B + U)$$

$$\frac{\partial F(y)}{\partial y} = - (y - 1) \left(C_{s2} - C_{s1} + z_1 \left(B - C_{e1} + C_{e2} + C_{s1} - C_{s2} + H_1 + R + (G_t P_c S(E_1 - E_2) - P_N S_k(E_1 - E_2))(\omega - 1) \right) + x z_1 (D_1 - B + U) \right) - y (C_{s2} - C_{s1} + z_1 \left(B - C_{e1} + C_{e2} + C_{s1} - C_{s2} + H_1 + R + (G_t P_c S(E_1 - E_2) - P_N S_k(E_1 - E_2))(\omega - 1) \right) + x z_1 (D_1 - B + U))$$

$$\frac{\partial F(y)}{\partial z_1} = -y (y - 1) (B - C_{e1} + C_{e2} + C_{s1} - C_{s2} + H_1 + R + x (D_1 - B + U) + (G_t P_c S(E_1 - E_2) - P_N S_k(E_1 - E_2))(\omega - 1)) \quad , \quad \frac{\partial F(y)}{\partial z_2} = 0$$

$$\frac{\partial F(z_1)}{\partial x} = -D_2 z_1 (z_1 - 1) \quad , \quad \frac{\partial F(z_1)}{\partial y} = z_1 (B + \omega (G_t P_c S(E_1 - E_2) + P_N S_k(E_0 - E_1))) (z_1 - 1)$$

$$\frac{\partial F(z_1)}{\partial z_1} = -z_1 \left(B - C_f + L_f + 2V + W + R_L S + D_2 x + \omega (P_N S(Y_0 - k(E_0 - E_1)) - G_t P_c S(E_1 - E_2)) - y (B + \omega (G_t P_c S(E_1 - E_2) + P_N S_k(E_0 - E_1))) \right) - (z_1 - 1) \left(B - C_f + L_f + 2V + W + R_L S + D_2 x + \omega (P_N S(Y_0 - k(E_0 - E_1)) - G_t P_c S(E_1 - E_2)) - y (B + \omega (G_t P_c S(E_1 - E_2) + P_N S_k(E_0 - E_1))) \right) - z_2 (2V - W)$$

$$\frac{\partial F(z_1)}{\partial z_2} = -z_1 (2V - W) \quad ; \quad \frac{\partial F(z_2)}{\partial x} = -D_2 z_1 z_2$$

$$\frac{\partial F(z_2)}{\partial y} = z_1 z_2 (B + \omega (G_t P_c S(E_1 - E_2) + P_N S_k(E_0 - E_1)))$$

$$\frac{\partial F(z_2)}{\partial z_1} = -z_2(B - C_f + L_f + 2V + W + R_L S + D_2 x + \omega(P_N S(Y_0 - k(E_0 - E_1)) - G_t P_c S(E_1 - E_2)) - y(B + \omega(G_t P_c S(E_1 - E_2) + P_N S k(E_0 - E_1)))) ,$$

$$\frac{\partial F(z_2)}{\partial z_2} = -(2V - W)(z_2 - 1) - z_2(2V - W) - z_1 \left(B - C_f + L_f + 2V + W + R_L S + D_2 x + \omega(P_N S(Y_0 - k(E_0 - E_1)) - G_t P_c S(E_1 - E_2)) - y(B + \omega(G_t P_c S(E_1 - E_2) + P_N S k(E_0 - E_1))) \right) .$$

4. Results and Discussion

Taking the Municipality of Chongqing, China, as an example because of the typicality of its soil and water conservation, the following data are all determined by referring to the relevant literature and official data of Chongqing.

All numerical simulations were implemented in MATLAB (R2022b). With reference to [18,49], the initial proportions of farmers are assumed as follows: $S(t)=0.9$, $E(t)=0$, $I_1(t)=0.05$, $I_2(t)=0.05$, $R(t)=0$. The initial values for x and y

are set to 1/2, and for z_1 and z_2 to 1/3. According to [50], the soil erosion intensity before

governance is assumed to be moderate, with a soil erosion modulus $E_0 = 3.75t/(hm^2 \cdot a)$.

After active governance, the intensity becomes slight, with a modulus of $E_1 = 0.2t/(hm^2 \cdot a)$.

After passive governance, the intensity is light, with a modulus of $E_2 = 1.35t/(hm^2 \cdot a)$.

The area for soil erosion control is assumed to be $S = 1hm^2$. Referring to [51], the soil organic carbon mass fraction is $G_t = 5.4g/kg$.

Based on recent soil and water conservation carbon sink trading projects, the carbon price P_c is set at 0.0000081 (10,000 CNY/t). Referring to [52], vegetables are selected as the agricultural product. According to [53], and considering the representativeness of sloping farmland soil erosion

in Municipality of Chongqing, the pre-governance vegetable yield per unit area Y_0 is set to the average vegetable yield of Chongqing in 2023, 43,803.3 kg/hm². According to [54],

the vegetable price P_N is set to the average farmgate price in 2023, 0.000369 (10,000 CNY/kg). Based on transaction announcements published on the official website of the

Chongqing Land Exchange, the land transfer rent R_L is set at 0.33 (10,000 CNY/hm²). Referring to [55], the parameter ω is set to 0.2. According to the relationship between soil erosion modulus and soil erosion depth (Soil erosion thickness = Soil erosion modulus/Soil bulk density) and literature [56], the coefficient k is set to −0.013.

With reference to relevant literature, the parameters for the payoff matrix of each agent in the evolutionary game, as well as the influencing factors and their weights affecting farmer behavior transition, are established. The weight coefficients have been standardized to eliminate dimensional effects. The specific numerical values are presented in Table 2.

Table 2. Parameter Values.

Parameter Category	Parameter Value	References
Utility-Related Parameters	$H_2 = 10; H_3 = 5.5; D_1 = 4; D_2 = 3;$	[18]
	$B = 1; U = 3; V = 0.5; W = 0.5;$	

Farmer Trust Parameters	$m_1=0.5; m_2=0.2; m_3=0.3; m_4=0.3;$	[18]
Cost Parameter	$C_g = 4; C_{e1} = 20; C_{e2} = 12;$ $C_f = 7; C_{s1} = 2; C_{s2} = 1;$	[18]
Reputation Loss Parameter	$H_1 = 2.5;$	[57]
Ecological and Environmental Damage Parameter	$L_f = 1;$	[58]
Reputation Gain Parameter	$R = 3;$	[59]
Factors Influencing Farmers' Collective Behavior	$EV = 0.218; GPL = 0.6375;$ $PCALS = 0.1425; SIP = 0.32;$	[22]
Factors Influencing Farmers' Collective Behavior	$NFIR = 0.812; PCL = 0.625;$	[17]
Social Atmosphere	$SF = 0.8;$	[59]
Land Emotional Attachment	$LEA = 0.7841;$	[19]
Soundness of the Land Transfer Service System	$SLTSS = 0.2441;$	[47]
Risk Perception	$RP = 0.385;$	[21]
Weight Coefficient	$\alpha_1 = 0.506; \alpha_2 = 0.348; \alpha_3 = 0.146; \alpha_4 = 0.489;$ $\alpha_5 = 0.359; \alpha_6 = 0.152; \alpha_7 = 0.102; \alpha_8 = 0.034;$ $\alpha_9 = 0.615; \alpha_{10} = 0.192; \alpha_{11} = 0.058; \alpha_{12} = 0.526;$ $\alpha_{13} = 0.175; \alpha_{14} = 0.298; \alpha_{15} = 0.409; \alpha_{16} = 0.190;$ $\alpha_{17} = 0.323; \alpha_{18} = 0.078; \alpha_{19} = 0.323; \alpha_{20} = 0.108;$ $\alpha_{21} = 0.337; \alpha_{22} = 0.232; \alpha_{23} = 0.424; \alpha_{24} = 0.291;$ $\alpha_{25} = 0.055; \alpha_{26} = 0.230;$	[17,19,21,22,47]

By inputting the above parameters into the simulation model, the dynamic evolution trajectory of the tripartite strategies of government, enterprise, and farmers, as well as the density changes of different states of farmers, can be obtained, as shown in Figure 3a,b. The results indicate that the system ultimately stabilizes at the evolutionary equilibrium point $E^*(1,1,1,0)$, meaning the government chooses active regulation, enterprise engages in active governance, and farmers participate in soil erosion control by providing land. This suggests that, under the combined effect of external policy incentives and internal behavioral feedback, the tripartite game system achieves a stable cooperative equilibrium. In the initial stage of the model, the strategies of the government and enterprise are still in a period of observation and adjustment, with “unknown farmers (S)” dominating the farmer population. As the government’s publicity efforts increased and subsidy policies were gradually implemented, governance information diffused among the farmers, and individual cognitive levels continuously improved. The densities of “Neutral farmers (E)” and “Active participants farmers (I₁)” increased significantly, while “Immunized farmers (S)” rapidly declined and approached zero. Concurrently, some farmers, influenced by factors such as strong land attachment and heightened risk perception, exhibited resistance. The density of “Resistant farmers (I₂)” increased slightly in the initial phase. However, as government regulation strengthened and enterprise pursued active governance, negative signals were gradually mitigated, and the proportion of this group slowly declined over time, eventually stabilizing. Throughout the evolutionary process, the dissemination of positive and negative signals coexisted and interacted. The government’s policy publicity and the active governance behavior of enterprise enhanced the diffusion capacity of positive signals. Furthermore, through the externality and amplifying effect of governance outcomes, the spread of negative signals was further suppressed. Consequently, the overall behavioral intention of farmers showed a clear trend toward positive

transition. “Active participants (I_1)” rapidly became dominant, with their density curve significantly higher than those of other states in the figure and tending to stabilize. In contrast, the densities of “Neutral farmers (E)” and “Resistant farmers (I_2)” experienced brief fluctuations before gradually declining and stabilizing at relatively low levels. The density of the “immune (R)” group, which refers to individuals who gradually lose attention to governance affairs, slowly increases over time and remains stable at a lower level.

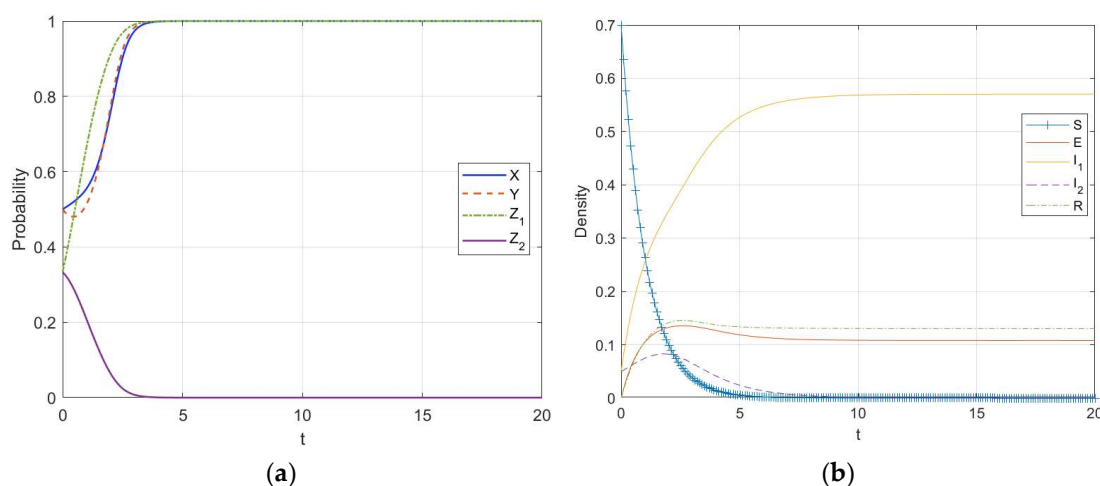
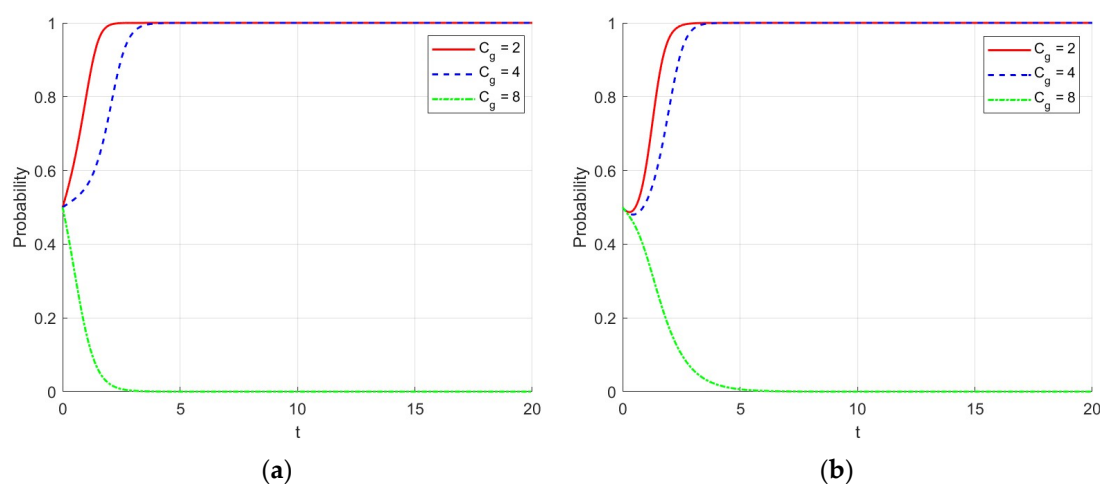


Figure 3. Dynamic game strategies and farmer participation: (a) Strategic choices of game players; (b) Change curve of farmers density.

In summary, the simulation results shown in Figures 3 and 4 demonstrate that, under the dual impetus of active government regulatory incentives and active enterprise governance, the positive feedback mechanism within the governance system is continuously strengthened. The behavioral evolution at the individual level and strategic coordination at the macro level mutually reinforce each other, forming a virtuous cycle of policy incentives and behavioral responses. The system ultimately achieves dynamic convergence from an “externally driven incentive” state to an “endogenous steady-state participation.” This establishes a stable governance structure focused on the active participation of farmers, providing theoretical foundation and practical reference for multi-agent collaboration and incentive mechanism optimization in soil erosion control.



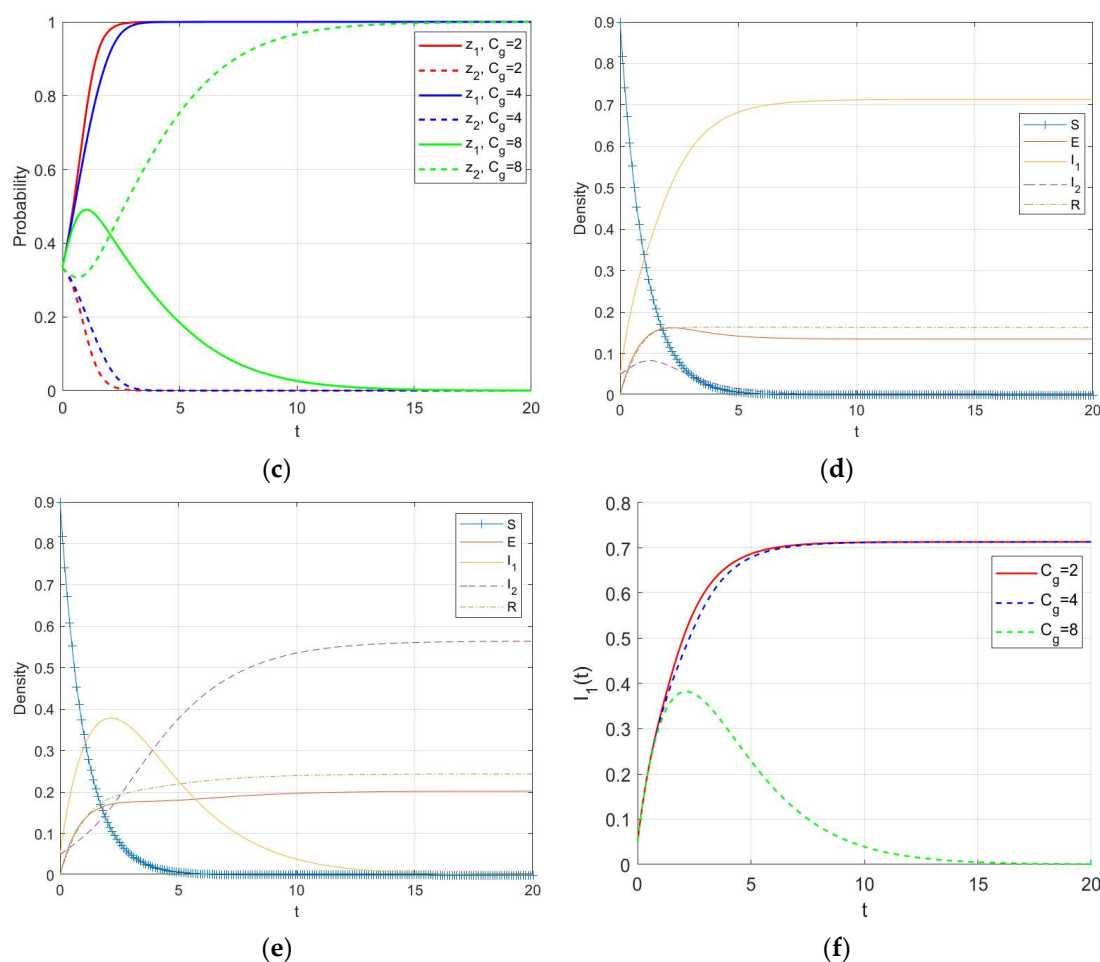


Figure 4. Dynamic game strategies and farmer participation: (a) Impact on government strategy selection; (b) Impact on enterprise strategy selection; (c) Impact on farmer strategy selection; (d) Curves of farmer densities in various states when $C_g = 2$; (e) Curves of farmer densities in various states when $C_g = 8$; (f) Effect of C_g on $I_1(t)$.

4.1. Impact of Government Regulatory Costs on Tripartite Strategy Selection and Farmers' Participation Willingness

By setting $C_g = 2, C_g = 4, C_g = 8$, the evolutionary trajectories of the game agents and the density variation curves of farmers in different states were simulated, as shown in Figure 4a–f. When regulatory costs are low, the government tends to adopt an active regulatory strategy, effectively promoting the implementation of soil erosion control projects by providing subsidies to enterprise and farmers. This proactive stance further incentivizes enterprise to actively engage in soil erosion control, while also enhancing farmers' participation willingness, thereby driving the game system to gradually converge toward the ideal equilibrium state (1, 1, 1) and forming a virtuous governance cycle. In this process, the density of actively participating farmers (I_1) quickly reaches its peak. However, the time to reach this peak shortens as the speed of stabilization in government and social capital strategies increases, reflecting the role of low regulatory costs in enhancing system coordination and governance efficiency. Nevertheless, when government regulatory costs increase, the evolutionary path of the system undergoes a significant shift. The peak density of actively participating farmers (I_1) decreases markedly, and its density curve rapidly approaches zero, while the size of the resistant farmers (I_2) increases substantially. This is because, as regulatory costs rise, the returns from government regulation fall below those of non-regulation, leading the government to tend toward a non-regulatory strategy and

to cease subsidies for social capital and farmers. In the absence of effective government constraints and incentives, social capital opts for passive governance, resulting in a decline in governance quality and a lack of progress. The passive behaviors of both the government and enterprise further undermine farmers' trust in the governance project, increasing the probability that originally active (I_1) or neutral (E) farmers convert into resistant participants (I_2). As a result, the size of the resistant group continues to expand, eventually surpassing that of the active participants, thereby hindering the effective implementation of the soil erosion control project. This demonstrates that higher government regulatory costs are increasingly detrimental to the advancement of soil erosion control initiatives. To improve governance effectiveness, it is recommended to establish a collaborative governance mechanism involving the government, enterprise, and farmers, and to introduce technologies such as remote sensing, drones, video surveillance, and intelligent monitoring to reduce regulatory costs. This approach would enhance the willingness of all parties to participate and ensure the effective implementation of soil erosion control projects.

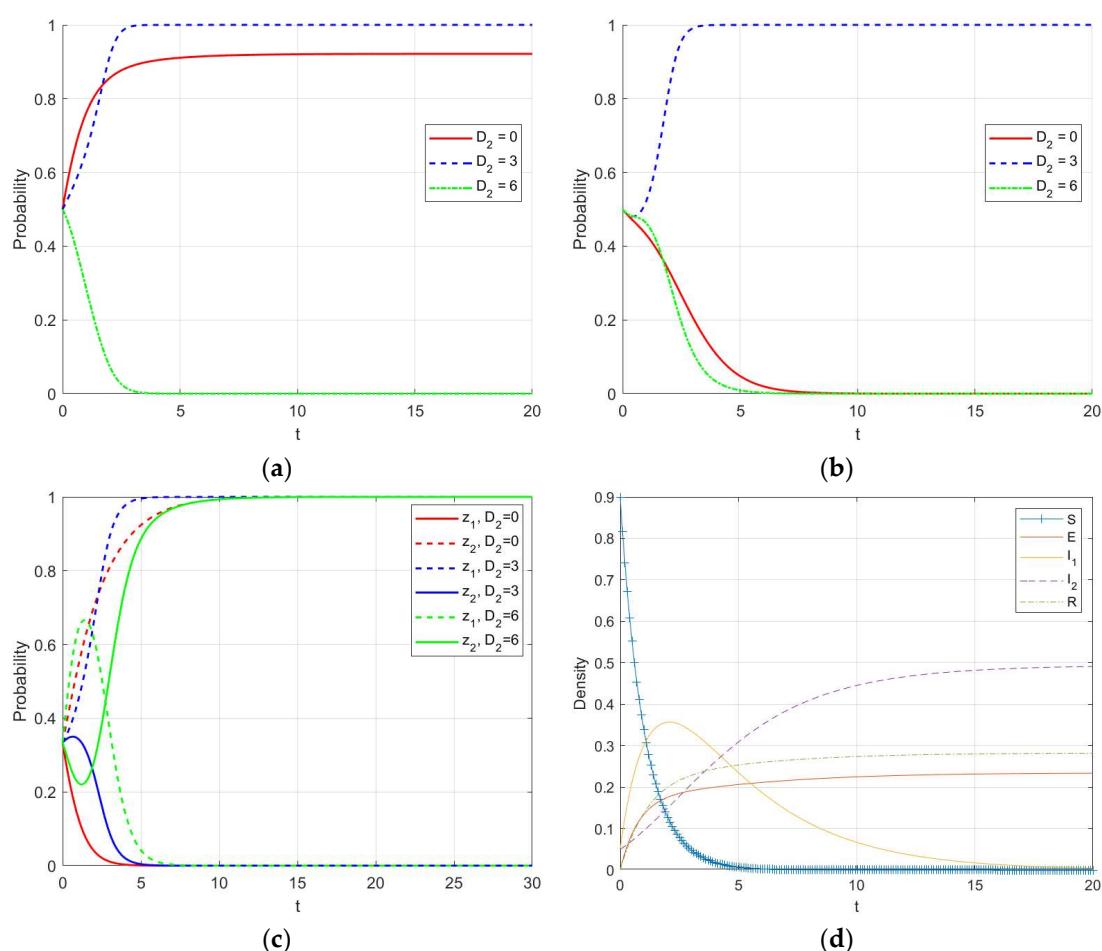
4.2. Impact of Government Subsidies Provided to Farmers on Tripartite Strategy Selection and Farmers' Participation Willingness

By setting $D_2 = 0$, $D_2 = 3$, $D_2 = 6$, the evolutionary trajectories of the game agents and the density curves of farmers in different states were simulated, as shown in Figure 5a–f. The simulation results indicate that the level of government subsidies provided to farmers is a critical determinant of the governance system's stability. When the government offers a high level of subsidies to farmers, it initially boosts farmers' participation willingness due to strong incentives, significantly increasing the density of actively participating farmers in the short term. It also creates an imbalance in the cost–benefit structure of regulation, prompting the government to adjust its strategy to 'no regulation, no subsidies' as the substantial subsidies lead to accumulated financial pressure on the government. The withdrawal of government strategy further triggers a decline in enterprise governance enthusiasm, reducing the momentum for governance, which in turn worsens farmers' expected benefits. This ultimately results in a chain of degradation along the path of 'unsustainable subsidies—government not regulating or subsidizing—negative governance by enterprise—disintegration of farmer participation'. In this process, the density of actively participating farmers exhibits a trend of rapid initial increase followed by an accelerated decline towards zero. Conversely, the density of resistant farmers (I_2) rises quickly over time, eventually dominating the population. The system converges to a negative equilibrium characterized by governance stagnation.

As shown in Figure 5d, when $D_2 = 0$, farmers show a clear lack of willingness to participate at the early stages of evolution because of the lack of direct economic incentives. Their strategy quickly shifts toward refusal to participate. The widespread non-participation of farmers makes it difficult for enterprise to form stable land cooperation relationships and long-term governance expectations, leading its governance strategy to evolve into a passive state characterized by perfunctory and low-investment approaches. Under these circumstances, although the absence of subsidy weakens the government's ability to guide the behavior of farmers and enterprise through economic incentives, the pressures from governance failure and accumulating ecological risks within the system do not disappear. After weighing the costs of regulation and potential ecological losses, the government did not choose to completely withdraw from regulation but instead maintained a high yet constrained level of oversight. Consequently, the overall system exhibits an evolutionary pattern of "low incentive—low participation—weak governance," rather than a state of complete governance abandonment. Specifically, the density of actively participating farmers (I_1) remains at a moderate level initially but gradually declines due

to the lack of sustained incentives. Correspondingly, the density of farmers refusing to participate (I_2) began to rise from the early stages of evolution and eventually dominated the steady-state phase. This result indicates that, under conditions of insufficient incentives, the system struggles to effectively stimulate and sustain the continuous participation of farmers. As a result, farmers' decisions gradually converge towards a risk-averse orientation, which in turn leads to the long-term inefficiency of soil erosion control efforts.

As we can see, a scenario with moderate subsidies achieves a better balance between incentive strength and fiscal sustainability. The government can maintain a stable regulatory strategy, enterprise forms reliable revenue expectations, and farmers gradually build sustained participatory trust over time. The system ultimately converges to a stable mode of “moderate subsidies–strong regulation–active participation,” with the governance process advancing steadily. Moderate subsidies help maintain the government's regulatory willingness within the limits of fiscal affordability, enhancing farmers' trust in and engagement with governance projects, and promoting a balanced and positive evolution of the system toward ‘government regulation–active governance by enterprise–farmer participation’. Thus, it is crucial for the government to implement reasonably moderate subsidies and positive incentives to effectively stimulate farmers' enthusiasm for participation.



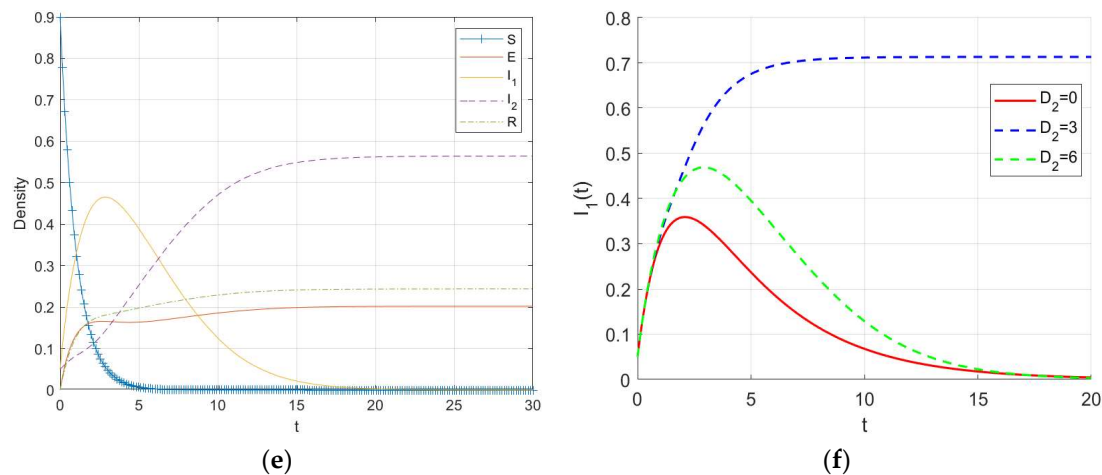


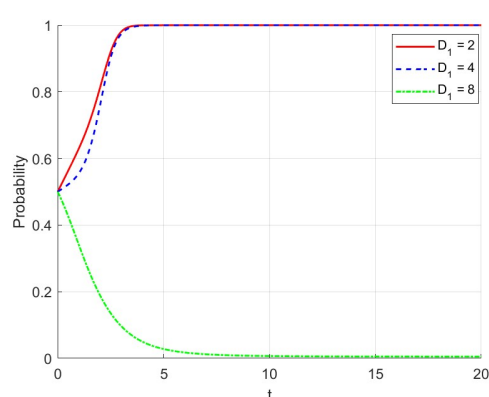
Figure 5. Dynamic game strategies and farmer participation: (a) Impact on government strategy selection; (b) Impact on enterprise strategy selection; (c) Impact on farmer strategy selection; (d) Curves of farmer densities in various states when $D_2=0$; (e) Curves of farmer densities in various states when $D_2=6$; (f) Effect of D_2 on $I_1(t)$.

4.3. Impact of Government Subsidies Provided to Enterprise on Tripartite Strategy Selection and Farmers' Participation Willingness

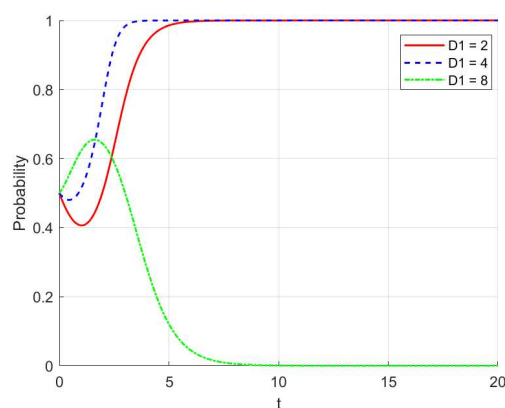
By setting $D_1 = 2, D_1 = 4, D_1 = 8$, the evolutionary trajectories of the game agents and the density curves of farmers in different states were simulated, as shown in Figure 6a–f. The simulation results demonstrate that the level of government subsidies directly determines the evolutionary paths of the government's regulatory willingness and the governance behavior of enterprise. As shown in Figure 6b, when $D_1 = 2$, the government faces relatively minor fiscal pressure, but its incentive effect on enterprise is limited, resulting in a slow increase in the probability of enterprise adopting active governance. As shown in Figure 6a,b, when $D_1 = 4$, the probability of enterprise engaging in active governance increases significantly under the drive of economic benefits, while the government can maintain a relatively stable regulatory strategy. However, when the subsidy level is excessively high, enterprise responds rapidly to strong economic incentives, leading to a quick rise in the probability of active governance in the short term. The reason is substantial subsidies directly improve the expected returns of the governance project, stimulating short-term enthusiasm from enterprise. Nevertheless, the government gradually withdraws from regulation due to mounting fiscal pressure, ultimately pushing the entire governance system into a state of failure. The subsidy policy, by influencing the behavior of the government and enterprise, further transmit their effects to the farmer population, triggering systematic changes in their participation behavior. Under a scenario of moderate subsidies, government regulation and enterprise governance behaviors form a stable complementarity, resulting in a continuous increase in farmers' confidence in governance projects. This is reflected in the steadily rising density of actively participating farmers (I_1), which maintains a high level, while the density of farmers refusing to participate (I_2) ultimately trends towards zero over time. The system has successfully constructed a governance pattern characterized by widespread participation. In contrast, excessively high subsidies initially lead to a rapid increase in farmers' participation willingness due to strong incentives, but the ensuing issues of fiscal unsustainability result in a lack of government oversight and the alienation of social capital behaviors. This leads to a significant reversal in farmers' participation: the density of actively participating farmers rises quickly but then declines rapidly towards zero, while the density of farmers refusing to

participate rises quickly over time, ultimately dominating the group. This evolutionary path reveals that an excessive reliance on subsidy incentives, while neglecting fiscal sustainability, can undermine the long-term stability of the governance system.

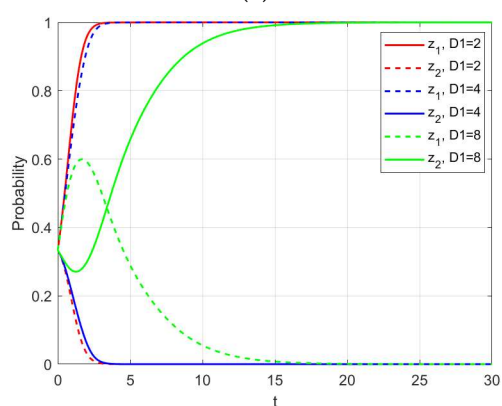
In conclusion, subsidy policies serve as both a key lever for incentivizing cooperation and a double-edged sword that affects the stability of the multi-actor governance system for soil erosion control. An appropriate subsidy level can establish a stable balance of interests and behavioral synergy among the government, enterprise, and farmers, thereby promoting the long-term healthy functioning of the governance system. However, excessive subsidies may lead to weakened regulation and governance failure due to fiscal pressure and behavioral distortion. Therefore, when formulating subsidy policies, the government should seek the optimal balance between incentivizing effectiveness and fiscal sustainability, ensuring the governance system achieves the best balance between efficiency and stability.



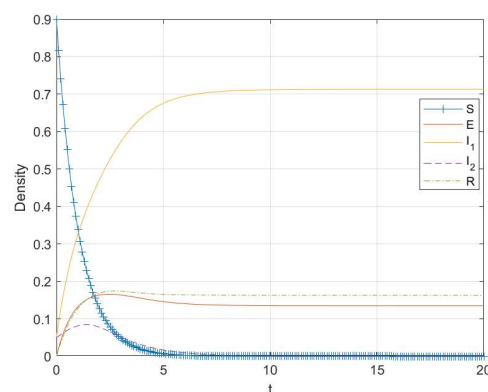
(a)



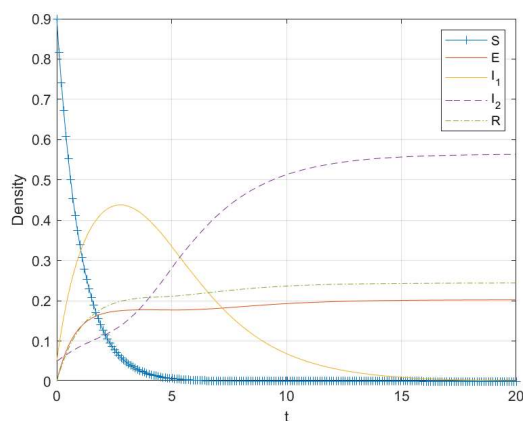
(b)



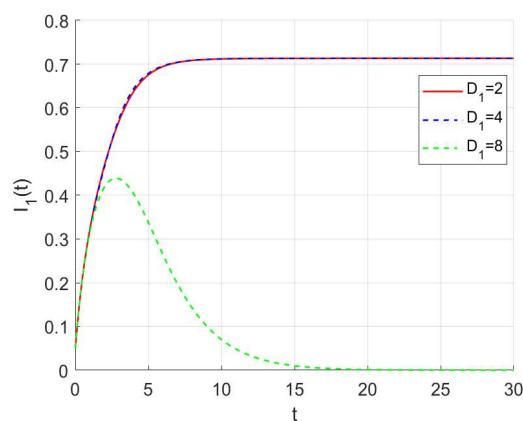
(c)



(d)



(e)



(f)

Figure 6. Dynamic game strategies and farmer participation: (a) Impact on government strategy selection; (b) Impact on enterprise strategy selection; (c) Impact on farmer strategy selection; (d) Curves of farmer densities in various states when $D_1 = 2$; (e) Curves of farmer densities in various states when $D_2 = 8$; (f) Effect of D_1 on $I_1(t)$.

4.4. Impact of Penalties on Tripartite Strategy Selection and Farmers' Participation Willingness

By setting $U = 1, U = 3, U = 6$, the evolutionary trajectories of the game agents and the density variation curves of farmers in different states were simulated, as shown in Figure 7a–f. The simulation results indicate that the intensity of penalties imposed by the government on enterprise profoundly alters the evolutionary path of farmers' states by influencing the government's regulatory strategy and the governance behavior of enterprise. When the punitive measures are relatively weak, enterprise tends to adopt passive governance strategies due to the low costs of facing punishment, directly resulting in ineffective soil erosion control efforts. At this time, although the government can continue to supervise by investing human and material resources, the inability of regulation to effectively change enterprise behavior leads to the long-term regulatory benefits being less than the costs. As rational decision makers, the government ultimately tends to choose to withdraw from regulation. This series of chain reactions ultimately transmits to the farmer level: the density of actively participating farmers (I_1) only experiences a brief increase at the beginning of governance, followed by a rapid decline due to ineffective governance. Concurrently, the density of resistant farmers (I_2) continues to increase over time, eventually occupying a dominant position and leading to a phenomenon of "participation collapse". In contrast, when the punitive measures are elevated to a higher level, the system presents a completely different evolutionary trend. Under strong punitive constraints, the incentives for active governance by enterprise are enhanced, and the benefits of government regulation significantly increase, thereby forming a virtuous cycle of 'effective regulation–active governance'. In this environment, farmers' trust in the effectiveness of governance increases, leading to a rapid rise in the density of actively participating farmers (I_1), which stabilizes at a high level, while the density of resistant farmers (I_2) gradually decreases and approaches zero, resulting in a system that achieves a collaboratively stable governance equilibrium.

As we can see, in order to effectively restrain the governance behavior of enterprise, the government must establish a punishment mechanism with sufficient deterrent power. Reasonable punishment standards should be enough to significantly lower the speculative profit expectations of enterprise, making it not worth the risk. Only in this way will enterprise be forced to shift towards active governance, thus promoting the formation of a virtuous cycle in the system: 'effective government regulation–enterprise's responsible governance–broad farmer participation'. Conversely, any punishment that is insufficient to restrain will likely encourage speculative behavior, ultimately leading to the systemic collapse of the governance system.

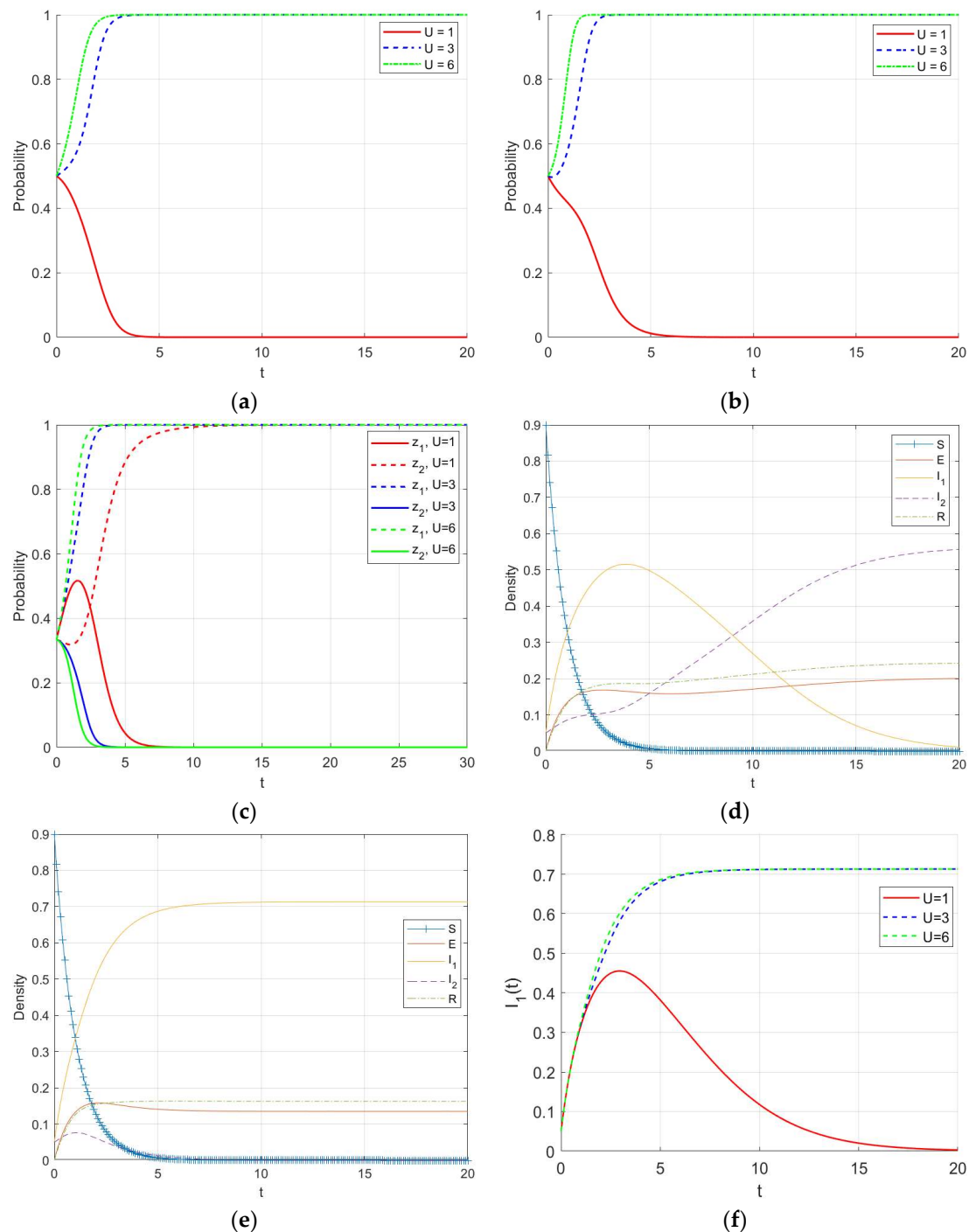


Figure 7. Dynamic game strategies and farmer participation: (a) Impact on government strategy selection; (b) Impact on enterprise strategy selection; (c) Impact on farmer strategy selection; (d) Curves of farmer densities in various states when $U=1$; (e) Curves of farmer densities in various states when $U=6$; (f) Effect of U on $I_1(t)$.

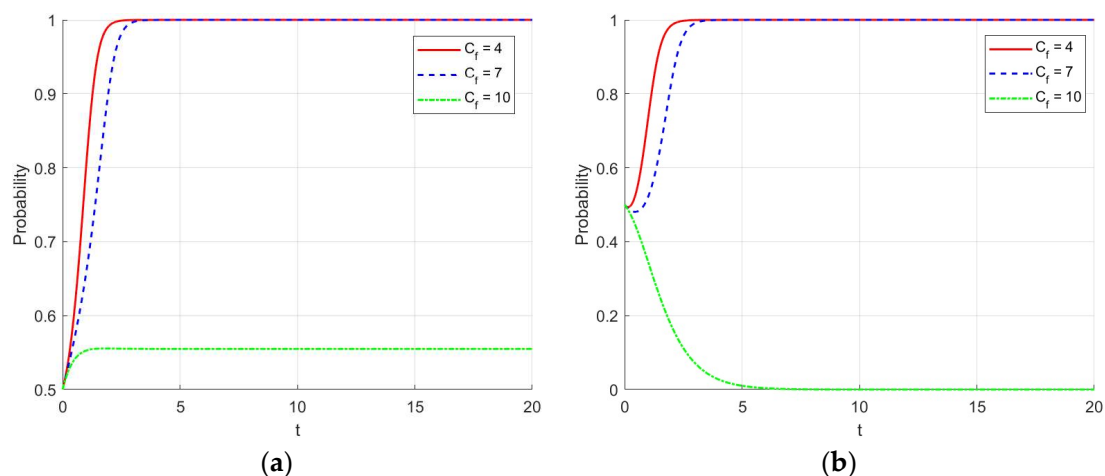
4.5. Impact of Farmers' Costs on Tripartite Strategy Selection and Farmers' Participation Willingness

With the parameters set as $C_f=4, C_f=7, C_f=10$, as shown in Figure 8a–f, the simulation produces the evolutionary trajectories of the agents and the density dynamics of farmers for different states. The results indicate that farmers' participation costs are a key factor determining the stability of the governance system. As illustrated in Figure 8a–d, when

$C_f = 4$, farmers are more inclined to actively participate, with their participation levels increasing rapidly and stabilizing at a high value. Consequently, the density of active participants rises significantly, while the proportions of hesitant and non-participating farmers decline, shifting the population toward a “high-participation” state. Active engagement by farmers provides social capital with a stable cooperative foundation and stable expected returns, thereby incentivizing proactive corporate governance. Improved corporate performance, in turn, enhances policy effectiveness, enabling the government to achieve objectives with lower marginal costs while maintaining high levels of regulation and incentives. Through this positive feedback, the strategies of the three parties reinforce one another, ultimately driving the system to converge toward an ideal equilibrium characterized by active government regulation, proactive corporate governance, and widespread farmer participation—forming a stable, virtuous governance cycle.

However, as shown in Figure 8a–c,e, when $C_f = 10$, the evolutionary path of the system undergoes a fundamental reversal, triggering a series of negative chain reactions. First, the excessively high participation cost significantly diminishes farmers’ expected returns, leading them to rationally shift toward passive or outright non-participation. The density of active participants peaks at a low level in a short time and then declines rapidly, eventually approaching zero. Second, the widespread non-participation of farmers undermines the implementation foundation of soil erosion control projects, making it difficult for enterprise to secure stable returns through collaborative governance. In the absence of farmer cooperation, enterprises tend to adopt passive governance strategies to avoid high investment and uncertain risks. Finally, faced with the simultaneous adoption of passive strategies by both farmers and enterprise, governments anticipate that continuing strict regulation and subsidy policies will yield limited substantive outcomes and may even result in sunk fiscal costs. Consequently, the rational choice for the government also gradually shifts toward reducing enforcement intensity, manifested as relaxed or symbolic supervision.

This demonstrates that farmer participation cost is a key constraint influencing the success or failure of collaborative soil erosion control under the PPP model. To break the governance deadlock in high-cost scenarios, policy efforts should focus on effectively reducing farmers’ actual participation costs through measures such as fiscal subsidies, technical support, organizational coordination, and institutional safeguards. Doing so can reactivate farmers’ participation willingness, drive positive adjustments in the governance behavior of enterprise and the regulatory strategies of the government, and ultimately steer the system from a low-efficiency equilibrium toward a high-efficiency, collaborative governance state.



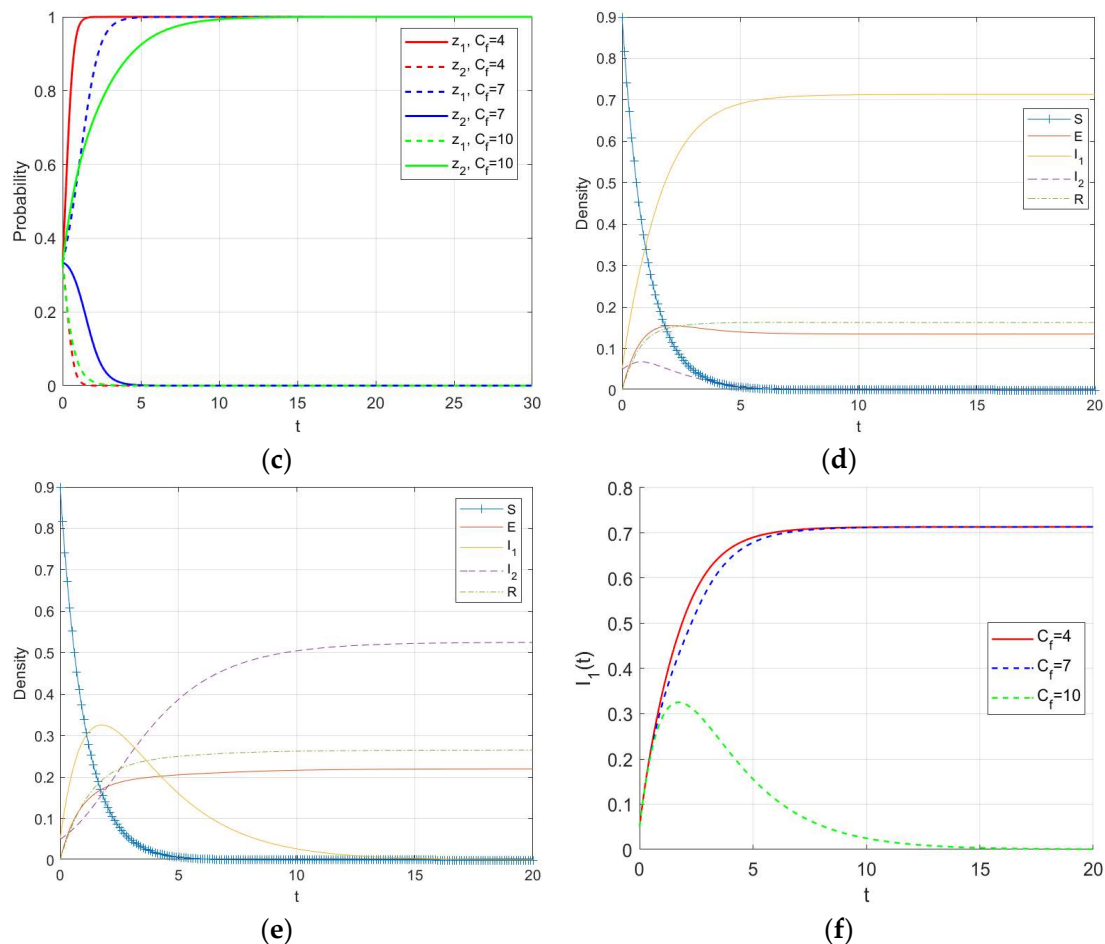


Figure 8. Dynamic game strategies and farmer participation: (a) Impact on government strategy selection; (b) Impact on enterprise strategy selection; (c) Impact on farmer strategy selection; (d) Curves of farmer densities in various states when $C_f=4$; (e) Curves of farmer densities in various states when $C_f=10$; (f) Effect of C_f on $I_1(t)$.

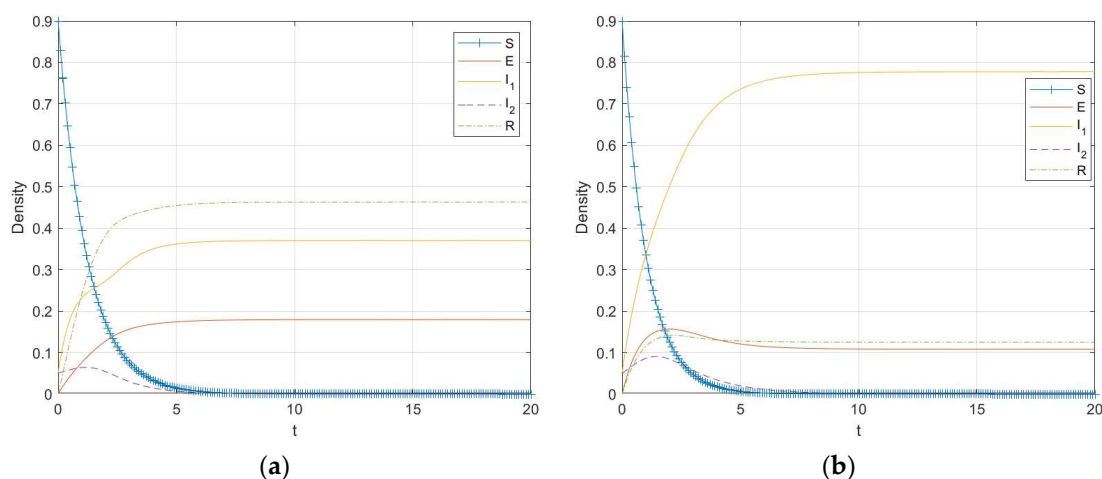
4.6. Impact of Social Atmosphere on Farmers' Willingness

By setting $SF = 0.1$, $SF = 0.5$, $SF = 0.9$, the density change curves of farmers in various states were simulated, as shown in Figure 9a–d. The results indicate that the social atmosphere plays a significant moderating role in the diffusion process of farmers' participation in soil erosion control. As shown in Figure 9a, when $SF = 0.1$, although there is a certain increase in the density of actively participating farmers (I_1) in the early stages of the system, the growth rate is limited and quickly stabilizes. In contrast, the density of immune farmers (R) remains consistently high, indicating that most farmers exhibit "information immunity" or "behavioral apathy" toward governance policies and social advocacy. This suggests that in the absence of positive public opinion and group identity, it is difficult for farmers to form attention and trust in governance projects, leading individuals to withdraw from the diffusion chain of governance behavior and resulting in low overall participation in the system. Meanwhile, the proportion of neutral farmers (E) remains at a certain level, further reflecting the weak diffusion of governance willingness under insufficient social atmosphere. As shown in Figure 9b, when $SF = 0.9$, the density of actively participating farmers (I_1) rises rapidly and becomes the dominant group within a relatively short period, while the density of immune farmers (R) decreases significantly. This indicates that a favorable social atmosphere can enhance the transmission of trust and the imitation effect among individuals, significantly increasing farmers' recognition and

enthusiasm for participation in governance projects, ultimately stabilizing the system at a high participation rate state.

It is worth noting that the social atmosphere's role in promoting farmers' participation behavior exhibits a significant nonlinear characteristic. As shown in Figure 9c, the increase in the density of active participants when the social atmosphere rises from a lower level to a moderate level is smaller than the increase when it rises further from the moderate level to a higher level. This indicates that the influence of the social atmosphere on farmers' decision-making participation is not a linear accumulation but instead shows a clear amplification effect once a certain intensity threshold is reached. From the perspective of behavioral diffusion mechanisms, during the stage when the social atmosphere evolves from weak to moderate levels, public opinion support and social advocacy have gradually emerged, but they are still insufficient to transform into stable group consensus and behavioral norms. Farmers remain highly sensitive to the uncertainties and potential risks associated with participating in governance. However, as the social atmosphere further strengthens and matures, group identity and demonstration effects begin to dominate. Non-participation in governance gradually comes to be seen as a deviation from group norms, significantly reducing farmers' tendencies to wait and see or remain passive, thereby promoting the accelerated diffusion of proactive participation behaviors within the system.

On the whole, the enhancement of the social atmosphere has not only improved the efficiency of governance policy signal transmission but, more importantly, weakened individuals' tendency towards 'immunization' by strengthening social recognition, thereby driving the governance system to evolve from a state of low participation and fragmentation to one characterized by high participation and collaboration. This mechanism reveals the role path of the social atmosphere as a key informal institution—it shapes group cognition and behavioral norms, providing an indispensable social foundation for multi-agent collaborative governance. Therefore, in the process of promoting soil erosion control, the phased role of building the social atmosphere should be given full attention: in the early stages of governance, it is necessary to continuously strengthen the foundation of social mobilization and public opinion guidance, creating conditions for the formation of group identity; while once the social atmosphere reaches a certain level, the amplified effect on farmers' participation can be unleashed through strengthening the demonstration effect and collective recognition behaviors, thus enhancing the overall stability and sustainability of the governance system.



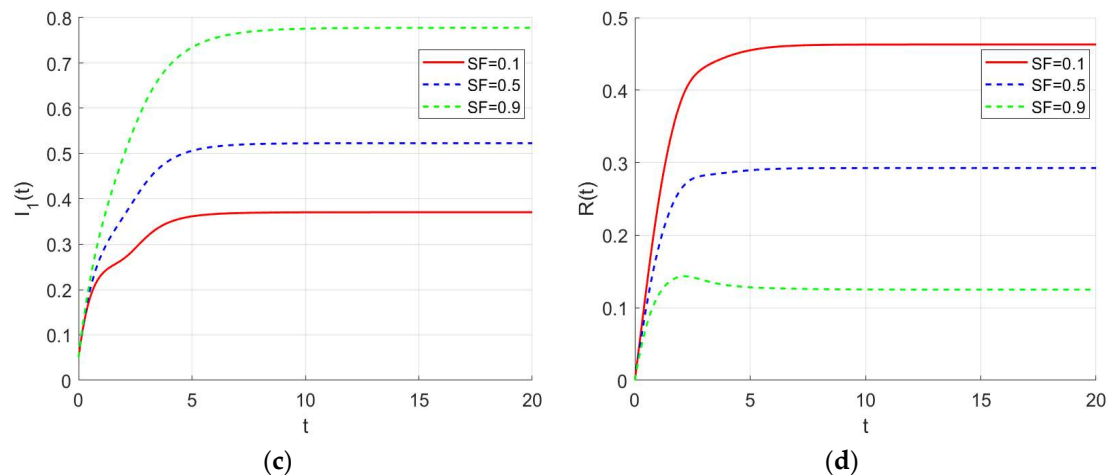


Figure 9. Evolution of Farmers: Impact of Social Atmosphere. (a) Change curves of farmer densities in various states when $SF = 0.1$; (b) Change curves of farmer densities in various states when $SF = 0.9$; (c) Effect of SF on $I_1(t)$; (d) Effect of SF on $R(t)$.

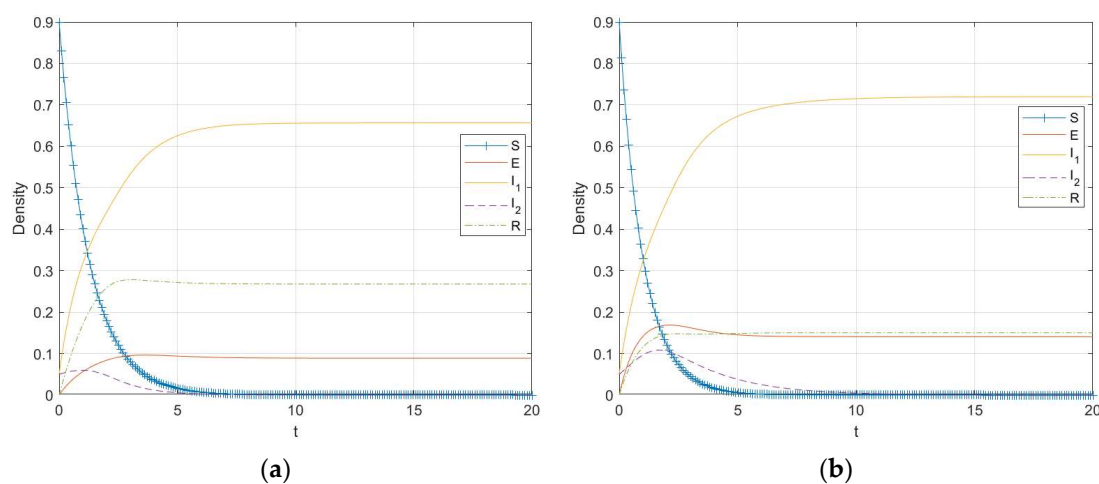
4.7. Impact of Government Publicity Level on Farmers' Willingness

By setting $GPL = 0.1$, $GPL = 0.5$, $GPL = 0.9$, the density change curves of farmers in various states were simulated, as shown in Figure 10a–d. As shown in Figure 10a, when $GPL = 0.1$, the system exhibits characteristics of “low transition–high immunity.” Since the conversion rate from unknown farmers (S) to neutral farmers (E) is directly and positively influenced by the level of government publicity, a lower intensity of publicity significantly suppresses this conversion channel, keeping the density of neutral farmers (E) at a consistently low level. At the same time, limited publicity fails to effectively correct farmers' negative perceptions, leading some farmers who refuse to participate (I_2) to further convert into immune farmers (R). As a result, the system primarily evolves along the path of $S \rightarrow I_2 \rightarrow R$ with the cumulative proportion of immune farmers (R) rising to a higher level, while the growth of actively participating farmers (I_1) is constrained due to the lack of ‘new blood’ from the neutral (E) group. As shown in Figure 10b, when $GPL = 0.9$, the system exhibits a ‘high conversion–low immunity’ virtuous cycle. Strong policy promotion significantly improves the conversion efficiency from S to E , resulting in a distinct peak in the neutral farmers (E) group in the early stages. It provides a sufficient source for the formation of actively participating farmers (I_1) to drive the rapid increase in the density of actively participating farmers (I_1) to a higher level. At the same time, high-level publicity effectively weakened the negative and rigid tendencies of farmers refusing to participate (I_2) by strengthening positive awareness and policy trust, thus suppressing the transition from I_2 to R and ultimately leading to a decrease in the proportion of immune farmers.

Further analysis reveals that the role of government publicity exhibits a characteristic of ‘significant in the early stages, slowing down later’. As shown in Figure 10c–d, when the level of publicity is raised from low to moderate, the increase in the density of actively participating farmers and the suppressive effect on the density of immune farmers are significantly stronger than when the level is further raised from moderate to high, reflecting the law of diminishing marginal returns in government publicity effectiveness. The reason is that at the initial stage of publicity, there are many farmers in the community who are either uninformed or in a wait-and-see state. Initial publicity can efficiently cover and convert these ‘susceptible farmers’, quickly filling the knowledge gaps and building basic trust, thus achieving significant effects. However, as the level of publicity rises, the remaining unconverted farmers are mostly those with limited information, deep biases,

or low trust in the government, making their conversion significantly more difficult. Additionally, publicity mainly addresses the cognitive bottleneck, helping farmers understand the policies and form basic awareness. But once most farmers have developed this awareness, their behavioral decisions are more constrained by factors such as expected benefits, risk perception, and trust in the policy. At this point, simply increasing the intensity of publicity is unlikely to significantly raise the proportion of farmers who actively participate, thus diminishing the marginal effect of publicity on the level of system participation.

In summary, the government's promotional efforts play a crucial role in regulating the path of farmers' participation evolution: on one hand, they determine whether potential participants (S) can smoothly enter the decision-making pool (E); on the other hand, they affect whether the group that rejects participation (I_2) will continue to refuse or be converted into immune individuals (S). Therefore, improving the level of promotion is not only a prerequisite for expanding policy awareness and guiding potential participants, but also helps to consolidate the foundation of farmers' participation to prevent the loss of potential governance forces, thus promoting the formation of a sustainable and stable collaborative governance pattern. This regulatory effect, combined with the diminishing returns in promotional effectiveness, provides clear implications for policy design: in the early stages of governance, resources should be concentrated on high-intensity promotion to quickly break through information barriers and establish a foundation for widespread participation; once public awareness reaches a moderate level, the promotional strategy should shift from expanding 'quantity' to deepening 'quality', and work in synergy with incentive mechanisms and institutional support measures, thereby systematically overcoming 'decision-making bottlenecks', continuously promoting farmers' participation towards higher levels and better structures, ultimately facilitating a stable and collaborative governance pattern.



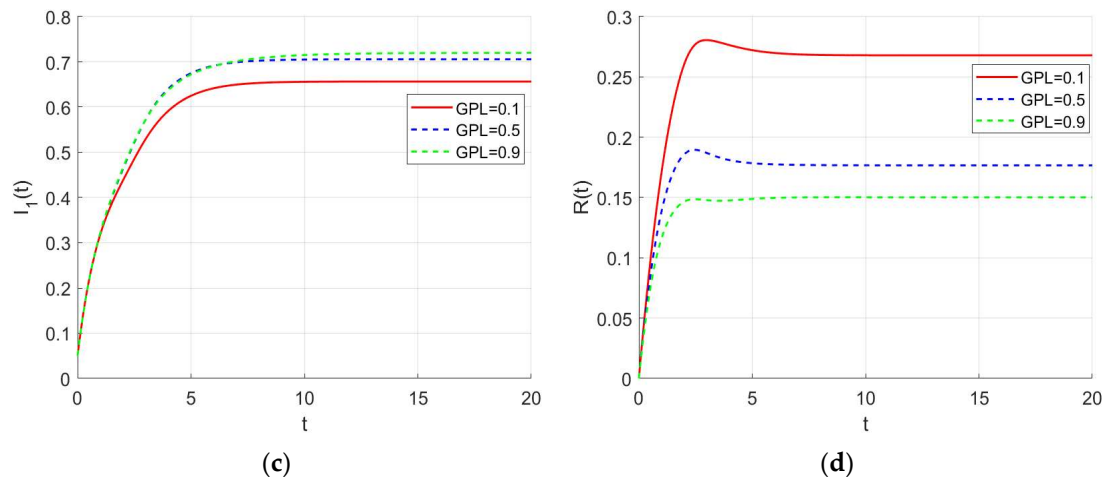


Figure 10. Evolution of Farmers: Impact of Government Publicity Level. (a) Change curves of farmer densities in various states when $GPL = 0.1$; (b) Change curves of farmer densities in various states when $GPL = 0.9$; (c) Effect of GPL on $I_1(t)$; (d) Effect of GPL on $R(t)$.

4.8. Impact of Social Insurance Participation on Farmers' Willingness

By setting $SIP = 0.1$, $SIP = 0.5$, $SIP = 0.9$, the density variation curves of farmers in different states were simulated, as shown in Figure 11a–d. The results indicate that the participation rate in social insurance (SIP) serves as a key social security factor, significantly influencing farmers' decision-making behavior in governance projects through a risk-buffering mechanism. As shown in Figure 11a, when $SIP = 0.1$, farmers exhibit a strong tendency to avoid risks due to the lack of comprehensive social security, leading to a slow growth in the density of actively participating farmers (I_1) that ultimately stabilizes at a relatively low level; meanwhile, the density of immune farmers (R) remains consistently high, reflecting that some farmers choose to withdraw from governance participation due to concerns about livelihood risks. As shown in Figure 11b, when $SIP = 0.9$, the comprehensive social security effectively reduces the participation risks for farmers, resulting in a rapid rise in the density of actively participating farmers (I_1) that maintains at a high level, while the density of immune farmers (R) is significantly suppressed to a lower range. This trend demonstrates that social insurance, by providing risk protection, can effectively enhance farmers' confidence in participation and reduce their tendency to withdraw from governance, thereby creating favorable conditions for the successful implementation of soil erosion control projects. Therefore, it should pay attention to the complementary construction of the social security system in the process of advancing ecological governance. By increasing participation in social insurance, the risk resilience of farmers can be strengthened, thereby promoting the sustainable advancement of governance projects.

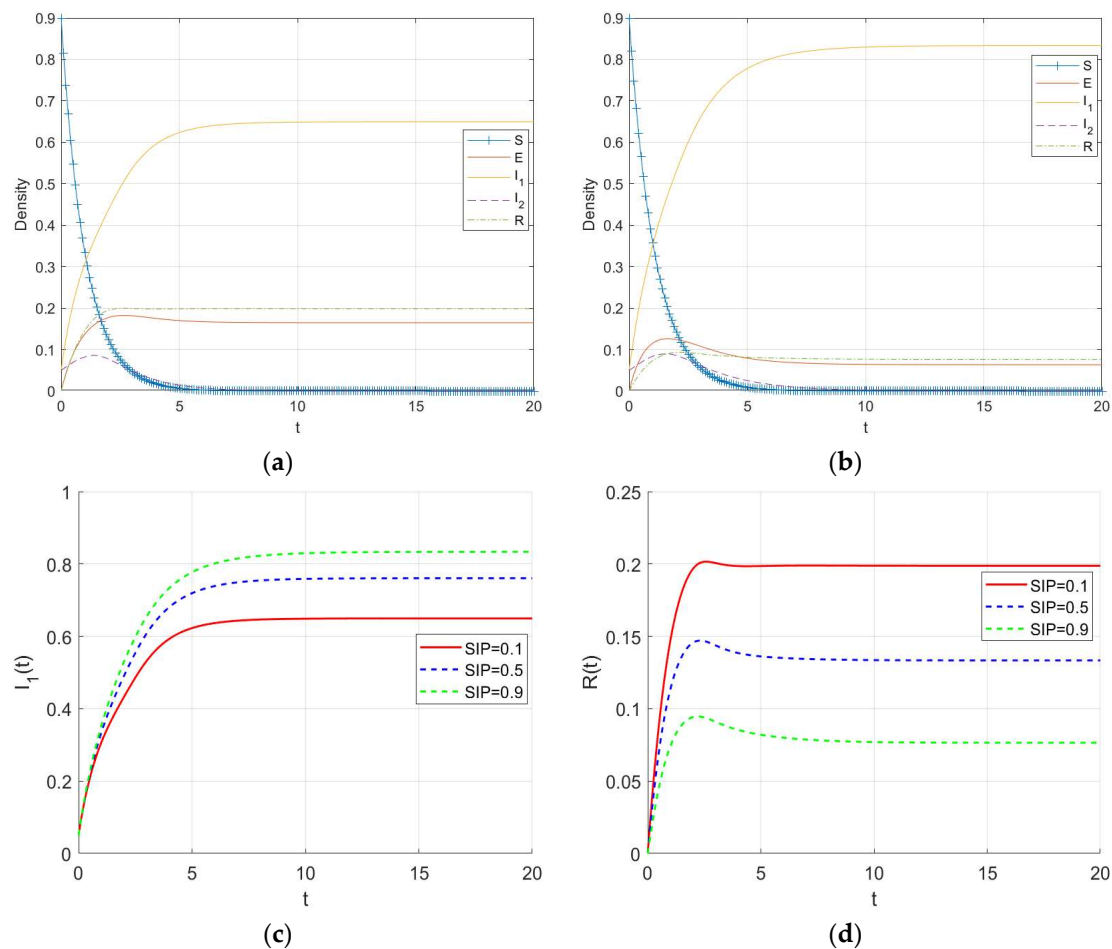


Figure 11. Evolution of Farmers: Impact of Social Insurance Participation. (a) Change curves of farmer densities in various states when $SIP = 0.1$; (b) Change curves of farmer densities in various states when $SIP = 0.9$; (c) Effect of SIP on $I_1(t)$; (d) Effect of SIP on $R(t)$.

4.9. Impact of Risk Perception on Farmers' Willingness

By setting $RP = 0.1$, $RP = 0.5$, $RP = 0.9$, the density variation curves of farmers in different states were simulated, as shown in Figure 12a–d. The results indicate that risk perception (RP) plays a significant moderating role in farmers' decision-making processes. It influences farmers' risk expectations and cost perceptions of conservation outcomes, thereby shaping the evolutionary path of their participation behavior. As shown in Figure 12a, when $RP = 0.1$, farmers generally perceive the risks of conservation activities to be small and have high confidence in policy returns, leading to a strong willingness to act. The simulation curves show that the density of actively participating farmers (I_1) rises rapidly and reaches a high level within a short period, while the density of immune/recovered farmers (R) remains low. This suggests that, in an environment of low risk perception, farmers are more likely to focus on the benefits of governance with less psychological hindrance from potential losses, thus fostering a stronger collective participation drive. However, as shown in Figure 12b, when $RP = 0.9$, farmers' concerns about the uncertainty of conservation benefits and potential losses significantly increase, suppressing the formation of participation behavior. At this point, the density of actively participating farmers (I_1) rises slowly, remains at a lower level and the peak significantly decreases, while the density of immune farmers (R) continues to increase and occupies a higher proportion, reflecting that farmers with high risk perceptions tend to adopt a wait-and-see or withdrawal strategy. This psychological defensive effect suppresses the group

diffusion process of governance participation and weakens the overall mobilization capacity of the system.

In summary, risk perception determines farmers' willingness to engage in soil erosion control by affecting their risk–benefit trade-off process. Low risk perception helps form a 'benefit-oriented' participation mechanism, while high risk perception may trigger 'defensive exit' behavior, leading to a decrease in governance participation rates. Therefore, it is essential to improve project risk communication mechanisms and benefit guarantee systems to reduce farmers' subjective risk perception, help them form rational expectations and stable confidence, and thereby facilitate a shift from "passive avoidance" to "active participation."

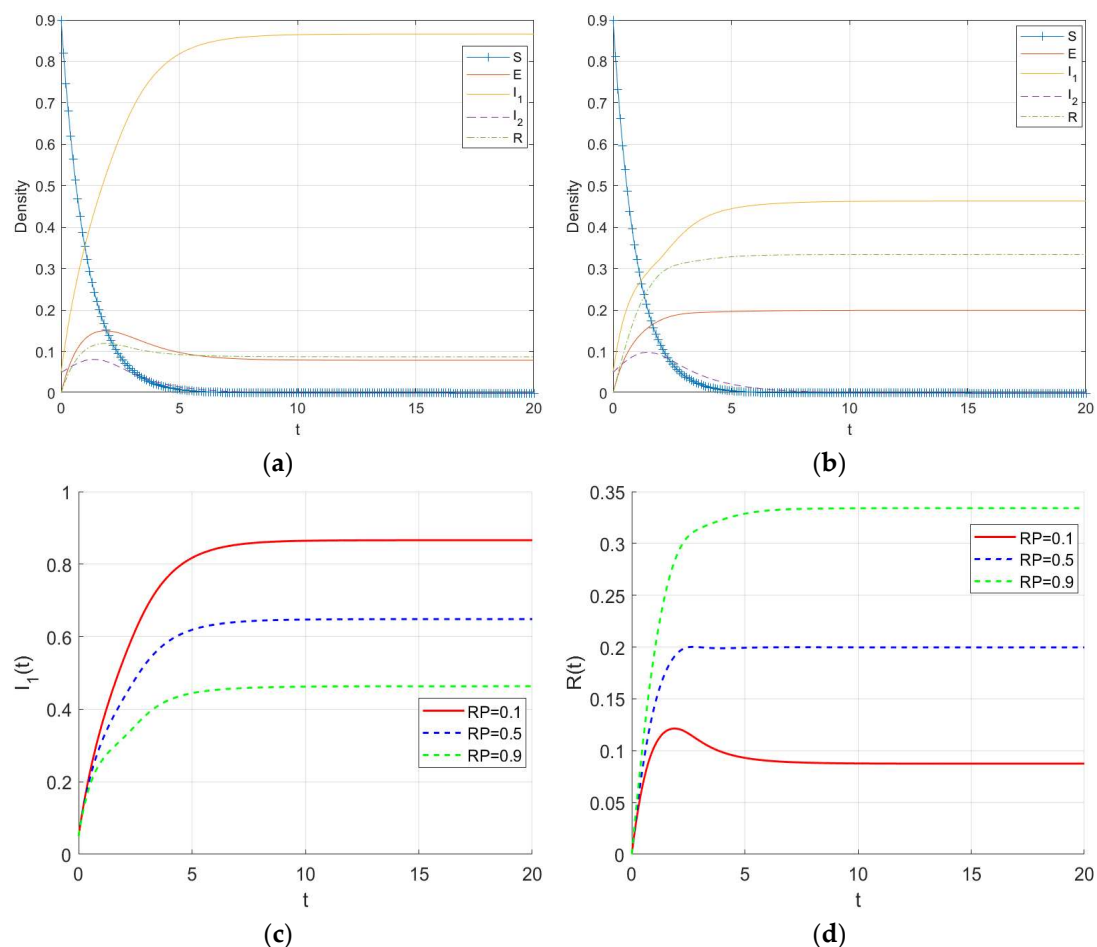


Figure 12. Evolution of Farmers: Impact of risk perception. (a) Change curves of farmer densities in various states when $RP = 0.1$; (b) Change curves of farmer densities in various states when $RP = 0.9$; (c) Effect of RP on $I_1(t)$; (d) Effect of RP on $R(t)$.

Our simulations reveal that the equilibrium outcomes of the system are highly sensitive to several key parameters. More importantly, these sensitivity patterns are not accidental artifacts of numerical settings but are endogenously rooted in the specific behavioral logics implied by the bounded rationality assumption.

- (1) Social diffusion parameters (social atmosphere and government publicity). These parameters exhibit particularly high sensitivity because farmers rely heavily on social learning and imitation under bounded rationality. Rather than making fully rational payoff comparisons, farmers update their decisions by observing the behaviors of neighboring agents. When the social atmosphere improves or government publicity increases, the information diffusion rate within the social network accelerates, which

readily generates an amplification effect through behavioral imitation. Consequently, even small increases in these parameters may trigger a pronounced jump in farmers' participation rate during the evolutionary process.

- (2) Farmers' economic perception parameters (government subsidies, social insurance participation, and risk perception). These variables function as psychological thresholds that regulate farmers' participation decisions. Under bounded rationality, farmers exhibit short-sightedness and loss aversion and thus respond more strongly to immediate and certain costs and risks than to distant and uncertain benefits. Government subsidies, social insurance participation, and risk perception jointly shape farmers' subjective evaluation of participation uncertainty and determine whether the perceived payoff crosses a critical action threshold. Simulation results indicate that these parameters primarily affect the system convergence speed and participation magnitude, rather than the fundamental evolutionary direction of the system.
- (3) Government–enterprise institutional incentive parameters (regulatory cost, enterprise subsidies, and penalties). For the government and social capital, bounded rationality is manifested in the pursuit of observable short-term performance and net benefits under conditions of informational complexity. Regulatory cost directly affects the government's supervision willingness, while enterprise subsidies and penalties reshape the payoff structure of social capital. These parameters therefore act as key levers driving strategy switching among governance actors. Although their variation does not overturn the basic stability structure of the system, it directly determines the degree of multi-actor coordination and the final level of farmer participation.

Overall, the parameter sensitivities observed in this model are not numerical coincidences, but endogenous outcomes of bounded-rational decision-making mechanisms across heterogeneous actors.

5. Discussion

By constructing and analyzing a tripartite evolutionary game model involving the government, private sector, and farmers, this study provides an in-depth exploration of the dynamic evolutionary patterns of multi-agent collaborative governance for soil erosion under the combined mechanism of PPP and carbon trading. The findings of this research resonate profoundly with the existing literature on farmer behavior and collaborative governance, while also making significant extensions in terms of dynamic mechanism characterization and system barrier diagnosis.

First, regarding the influence of government–private sector synergy on farmers' participation, prior studies have widely indicated that government regulation and market incentives are crucial external factors affecting farmers' land-use decisions and engagement in governance. For example, based on evolutionary game analysis, Chen et al. found that government policy interventions significantly influence farmers' land abandonment behavior [32]; Zhou et al. and He et al. further emphasized that, in the context of agricultural green production and non-point source pollution control, strategic coordination between the government and enterprises is a key condition for promoting farmer participation. The simulation results of this study build upon this finding by showing that effective government regulation and proactive governance by private sector, do not function in isolation; rather, they form a positive feedback mechanism through synergistic evolution, thereby significantly enhancing the stability of farmers' participation in soil erosion control and improving overall system governance performance.

Second, in terms of costs and incentive mechanisms, existing studies often examine from a static or single-agent perspective how high governance costs and unreasonable incentives may suppress farmers' participation willingness [32]. By introducing

government regulatory costs and subsidy structures, this study further reveals the internal mechanism of rational government withdrawal from regulation when regulatory costs are excessively high or subsidy arrangements are imbalanced, as well as the subsequent diffusion of passive governance by enterprises and negative behaviors among farmers. This provides a dynamic evolutionary perspective on the formation pathway of multi-agent coordination failure.

Regarding penalty mechanisms, He et al. pointed out that insufficient penalties weaken the enthusiasm of enterprises for governance, thereby affecting governance outcomes. The results of this study further indicate that, when penalty intensity fails to effectively alter the expected returns of social capital, the system falls into a “constraint failure” state, characterized by increased speculative behavior by enterprises, withdrawal of government regulation, and a sustained decline in farmers’ participation willingness, forming a hard-to-reverse cycle of governance failure.

Furthermore, concerning the role of information dissemination and socio-psychological factors, Yang et al. analyzed the influence of publicity and social atmosphere on residents’ green behavior by using a coupled dissemination–game model. Building on this, the present study finds that although government publicity and social atmosphere operate through different pathways, both contribute to stabilizing farmers’ participation by enhancing cognitive levels and social trust, thereby suppressing the diffusion of an “immunized” state and promoting the system’s evolution toward a high-participation, high-coordination governance equilibrium.

Finally, regarding risk factors, Liu et al. and Wang et al. used empirical evidence to demonstrate that risk perception and social security levels significantly influence farmers’ land transfer and participation decisions [21,22]. The results of this study are consistent with the direction of these studies and further reveal, from an evolutionary mechanism perspective, how social insurance participation and moderate risk perception jointly constitute a risk mitigation mechanism, thereby strengthening farmers’ confidence and long-term stability in participating in governance.

The dynamic patterns and key-parameter sensitivities revealed by the model provide an integrated theoretical framework for diagnosing the real-world barriers to farmer participation in under the PPP governance model. Within this framework, it becomes clear that farmers do not face a single constraint, but rather a multidimensional system of interwoven obstacles. First, high participation and opportunity costs significantly weaken farmers’ willingness to engage, especially under uncertain returns. Second, when government regulatory costs are excessive or subsidy schemes are poorly designed, the institutional credibility of PPP projects is undermined, eroding farmers’ confidence in long-term cooperation. Moreover, insufficient penalty intensity may induce opportunistic behavior by private sector, further weakening farmers’ trust in the governance system. At the same time, inadequate policy communication and a weak social atmosphere constrain the diffusion of positive information, while low levels of social security and heightened risk perceptions amplify farmers’ exposure to uncertainty during the participation process. Taken together, these factors constitute the major barriers to farmer participation within the PPP framework. The discussion results indicate that insufficient participation does not stem from any single cause, but rather from the interactive effects of economic incentives, institutional credibility, and the socio-psychological environment. This further highlights the importance of systemic institutional design and multi-dimensional policy coordination in the governance of soil erosion under PPP arrangements.

6. Conclusions and Recommendations

6.1. Conclusions

In addressing the issue of farmers' participation willingness in soil erosion control under the Public–Private Partnership (PPP) model, this study integrates a dynamic group model with a tripartite evolutionary game model involving the government, enterprise, and farmers. It systematically analyzes the strategic interactions among these agents and the dynamic evolution of farmers' participation behavior. The main findings are as follows:

- (1) Effective government regulation coupled with proactive governance by enterprise significantly increases the proportion of farmers participating in soil erosion control. Conversely, the absence of government oversight and passive governance by enterprise result in a continuous decline in farmers' participation willingness and a rise in the proportion of non-participants, considerably weakening governance effectiveness.
- (2) Lower government regulatory costs and moderate subsidies to enterprise and farmers help enhance farmers' participation willingness. Excessively high regulatory costs or subsidy expenditures may undermine the government's regulatory motivation, triggering passive governance by enterprise and reduced farmers participation, thereby lowering the operational efficiency of the governance system.
- (3) When penalty intensity is insufficient to constrain the behavior of enterprise, a tendency toward passive governance emerges. This weakens the government's incentive to regulate and leads to a sustained decline in farmers' participation willingness, making it difficult to sustain stable and effective governance.
- (4) Enhanced government publicity and a favorable social atmosphere significantly increase farmers' participation willingness in soil erosion control, promoting the system's evolution toward a positive pattern characterized by "high awareness, strong trust, and broad participation."
- (5) A well-developed social security system and a moderate level of risk perception help establish a risk mitigation mechanism for farmers' participation. These factors significantly raise the proportion of active participants and contribute to a relatively stable state of high engagement within the system.

6.2. Recommendations

In promoting soil erosion control, the government plays a crucial leading role. To achieve governance objectives, the government can systematically advance in the following key areas:

- (1) Establish a precise and efficient regulatory system that integrates government oversight with public supervision. Utilize technological means to enhance procedural transparency and accountability, effectively curbing opportunistic behavior while optimizing regulatory costs.
- (2) Implement performance-based, differentiated subsidy policies. Shift fiscal support from "universal distribution" toward "results-oriented incentives," avoiding the crowding-out effect of excessive subsidies on regulatory motivation and overall governance efficiency.
- (3) Foster a positive social environment for participation. Strengthen policy communication and community guidance to raise farmers' awareness and social trust, leveraging social learning effects to encourage the spontaneous diffusion of participatory behavior.
- (4) Improve risk-sharing social security mechanisms. Link social insurance programs with governance projects, and design reasonable risk-compensation and sharing

arrangements to stabilize farmers' long-term income expectations and reduce participation hesitancy.

- (5) Encourage technological innovation and management optimization by social capital. Through technological advances and improved management models, continuously reduce governance costs and enhance ecological outputs, thereby consolidating project profitability and farmers' confidence.
- (6) Establish a dynamic evaluation and adaptive adjustment mechanism. Develop a multi-dimensional governance performance assessment framework and dynamically link its outcomes with regulatory and subsidy instruments, ensuring the governance system can continuously learn and optimize.

This study analyzes the dynamic interactions, influence transmission paths, and group evolution patterns among the government, enterprise, and farmers in the collaborative soil erosion management using dynamic evolutionary game theory and dynamic group model systems. It offers insights for the formulation of soil erosion management policies, but certain limitations still exist. First, the model uses a universal analytical framework, failing to fully consider the regional differences in soil erosion types, economic development levels, and socio-cultural characteristics between the northern and southern regions of China. This has somewhat affected the applicability of the research conclusions in specific regions. Secondly, the model treats regulatory costs, social atmosphere, risk perception, and other factors as independent variables, without adequately capturing the potential nonlinear interactions between these factors, thereby simplifying the complex coupling mechanisms in the real-world system. Future research could deepen the exploration of the synergistic and offset effects among multiple factors by conducting regional comparative analysis and introducing system dynamics methods and conducting empirical validation through field surveys in representative regions such as Chongqing, further enhancing the model's explanatory power and practical guidance value.

Author Contributions: Conceptualization, Y.Y. and X.Y.; methodology, Y.Y.; software, X.Y.; validation, X.Y., J.Z. and J.D.; formal analysis, Y.Y.; investigation, X.Y.; resources, Y.Y.; data curation, X.Y.; writing—original draft preparation, Y.Y. and X.Y.; writing—review and editing, J.Z., J.D., R.W. and D.L.; visualization, X.Y.; supervision, Y.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained in the article.

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

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