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Unveiling Agricultural Shifts through Stakeholder Interactions and Strategic Dynamics in Green Rice Production

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Abstract: This study explores the strategic interactions among the government, growers, and the public within the context of green rice production, employing an evolutionary game theory framework. Recognizing the intricate dynamics of agricultural sustainability, we construct a three-party evolutionary game model to investigate the strategic decision-making processes and stability conditions of each stakeholder. The model assesses how various strategies evolve under the influence of economic incentives, regulatory measures, and public engagement. Through analytical and numerical methods, including stability analysis and MATLAB 2020b simulations, we identify the Evolutionarily Stable Strategies (ESS) that signify sustainable practices in green rice production. The results reveal that as government incentives for green production increase and fines for non-green practices are enforced, the likelihood of growers adopting sustainable practices significantly rises. Furthermore, the strategic enhancement of economic incentives and reputational factors not only bolsters governmental regulatory commitment but also reduces the necessity for public supervision, demonstrating a systemic shift towards self-regulation and market-driven sustainability. The simulations demonstrate the system's evolution towards a stable state where governmental regulation is fully enforced, growers adopt green production universally, and public supervision becomes redundant. The findings underscore the importance of designing policy interventions that harmonize economic and environmental objectives, suggesting that well-structured incentives and regulatory measures can catalyze the transition towards sustainable agricultural practices. Additionally, our study highlights the pivotal role of establishing effective incentive structures that ensure the economic benefits of green production outweigh the costs, facilitating an autonomous regulatory system. This study contributes to the understanding of how strategic interactions shaped by policy and market forces can foster agricultural sustainability.

Keywords: sustainability; agricultural practices; stakeholder strategies; incentives; evolutionary game theory

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1. Introduction

Rice is one of the major crops feeding the world population and is the most important ingredient in food composition in South Asia and Africa [1]. Reflecting its global significance, in 2022, China and India, which are among the largest consumers, also remained the top producers of rice, with China producing approximately 211 million tons and India producing 196 million tons (FAOSTAT) [2]. This substantial output not only underscores rice's pivotal role in these economies but also accentuates the critical need to integrate sustainable agricultural practices within these regions to ensure long-term viability and environmental stewardship. The urgency of transitioning towards sustainable agricultural practices is driven by the dual challenges of escalating global food demands and the imperative of environmental conservation. The complexities of ensuring food security for a projected population of 9.1 billion by 2050 pose unprecedented challenges for the sustainability of food production systems and the terrestrial and aquatic ecosystems that support them [3]. The adoption of green agricultural practices, which involves adopting practices such as soil conservation, organic farming, reduced use of chemical inputs, and enhanced biodiversity to create resilient farming systems that can sustainably produce food while providing a range of ecosystem services [4,5], is pivotal in this context. These practices not only mitigate the adverse impacts of conventional farming on biodiversity, soil health, and climate but also hold the promise of resilient food systems that can withstand and adapt to changing environmental conditions [6]. Globally, green agricultural practices are tailored to regional agricultural challenges and policy frameworks, showcasing diverse implementations across continents. For instance, the Climate-Smart Agriculture (CSA) approach in India emphasizes productivity enhancements through integrated nutrient and water management [7], while the Common Agricultural Policy (CAP) in Europe focuses on the multifunctionality of land, addressing environmental protection alongside agricultural productivity [8].

Despite the clear benefits of green agriculture, its adoption faces significant barriers, including higher initial costs for technology and knowledge transfer, market access challenges, and the need for supportive policies and incentives. Specifically, rice production has encountered yield plateaus, with limited scope for expanding cultivation areas due to resource constraints, such as arable land and water availability [9,10]. In addition, the rice sector must adapt to the challenges posed by climate change, which affects water availability, pest pressures, and crop productivity, necessitating resilient farming practices [11,12]. The importance of transitioning to sustainable agricultural practices is underscored by the environmental and health risks associated with conventional farming, which include biodiversity loss, soil degradation, water pollution, and the contribution to climate change through greenhouse gas emissions [6,13,14].

The role of governmental policies in facilitating this transition cannot be overstated [15]. The challenge of policy-making lies in designing policies that balance economic growth with environmental sustainability and social equity [16,17]. Effective policy frameworks can motivate the adoption of sustainable practices through financial support, regulatory measures, and the promotion of research and innovation in green technologies. The effectiveness of policy frameworks is pivotal in guiding farmers toward sustainable practices but is often challenged by implementation gaps and the need for alignment with local agricultural contexts [18,19].

Furthermore, the integration of sustainable agriculture into public policy reflects a growing recognition of its role in addressing broader societal challenges, including climate change, rural development, and public health [20]. Sustainable agriculture is characterized by its capacity to produce necessary quantities of high-quality food and fiber; be profitable for the grower; conserve nonrenewable resources; and harmonize with the biological, physical, and social environments [21]. In the context of green rice production, sustainable agriculture emphasizes practices that balance growers' economic needs with the preservation of environmental quality and community well-being. In parallel, the engagement of growers and the public in sustainable agriculture practices is critical. Farmers are central to the adoption of green production techniques. Their decisions are influenced by economic viability, access to resources, knowledge of sustainable practices, and the perceived benefits and risks associated with changing traditional practices [22,23]. The public, including consumers and civil society, plays a vital role in shaping the demand for sustainably produced rice and in advocating for policies that support sustainable agriculture. Their perceptions and preferences directly influence market trends, with a growing consumer preference for environmentally friendly products driving increased demand for sustainably produced rice. This shift in consumer behavior is crucial for creating a market that values environmental sustainability and for holding both the government and farmers accountable [24,25]. Moreover, public engagement in environmental issues raises awareness among farmers about the benefits of adopting green practices, not only for ecosystem health but also for market competitiveness. Effective communication and educational campaigns can further enhance this awareness, leading to more informed choices by consumers and more sustainable practices by producers. This highlights the importance of knowledge exchange, stakeholder collaboration, and supportive networks in achieving widespread adoption of green agriculture [26,27].

Evolutionary game theory, which has been increasingly applied since the 1970s, leverages the bounded rationality of stakeholders to elucidate the complex dynamics in various economic and social settings, particularly in sectors where the interplay of multiple actors shapes outcomes significantly. Hofbauer and Sigmund (2003) [28] highlight its utility in capturing the nuanced interdependencies and strategic adjustments among parties under uncertainty—a feature crucial for analyzing sectors like agriculture, where the decisions of governments, farmers, and the public intertwine to influence sustainability.

The application of this theory extends to exploring strategic interactions in green rice production, as demonstrated by Cui (2019) [29], who constructed an evolutionary game model considering the government, farmers, and agricultural enterprises to optimize green technology diffusion. Similarly, Xu et al. (2020) [30] investigated the roles of local governments, new agricultural operators, and traditional farmers in controlling agricultural non-point source pollution, offering insights into effective strategy formulation for environmental management. While these studies provide valuable frameworks for understanding strategic decision-making processes, there is a notable tendency in the existing literature, such as the works of Du et al. (2020) [31] and Luo et al. (2024) [32], to focus on dyadic interactions, often omitting a comprehensive analysis that integrates all relevant stakeholders into a unified model.

While the current body of literature provides extensive insights into sustainable agricultural practices, government policies, grower decision making, and public participation, it exhibits notable shortcomings, particularly in the context of both theoretical and empirical exploration of these integrated elements. First, existing studies often explore isolated aspects of sustainable agriculture, such as individual sustainable practices, policy impacts, or farmer behavior. However, they seldom consolidate these factors into a unified theoretical framework that captures the dynamic interplay between all stakeholders (government, growers, and the public) in the context of green rice production. Secondly, though numerous studies propose various sustainable agricultural models, there is a paucity of empirical research validating these models, especially through simulation techniques like those offered by MATLAB, which can corroborate theoretical predictions with real-world data. Thirdly, the critical role of economic incentives aligned with effective regulatory frameworks in motivating stakeholders towards sustainability is often overlooked. The nuanced understanding of how these incentives, alongside reputational factors, affect the collective move towards sustainable agricultural practices is not adequately detailed in existing literature.

This research unfolds systematically, exploring the dynamics of green production within the agricultural sector under environmental regulation. First, we delve into the strategic behaviors of growers concerning green and non-green production influenced by governmental incentives and public oversight. An evolutionary game model is constructed to encapsulate the interactions among three primary stakeholders, namely the government, growers, and the public. This model serves to elucidate the strategic stability of each party and examines how various parameters influence their strategic choices, providing a theoretical foundation for understanding the mechanisms driving sustainable agricultural practices.

Subsequently, the study progresses to a meticulous stability analysis of the strategic equilibrium points. This phase is crucial for identifying the conditions under which the agricultural system stabilizes, revealing the configurations of strategies that are likely to persist over time. By examining these equilibrium states, we gain insights into the potential long-term outcomes of different policy and behavioral scenarios, offering a predictive glimpse into the evolutionary trajectories of the system.

The final step employs MATLAB 2020b for an in-depth simulation analysis, translating the theoretical model into a dynamic representation that visualizes how the strategies evolve under various conditions. This simulation not only validates the theoretical insights but also facilitates the exploration of complex interactions that are difficult to analyze analytically. Through this computational approach, we can observe the real-time evolution of strategies and assess the impact of different policy interventions in a controlled, simulated environment.

Drawing on the conclusions derived from both the theoretical analysis and simulation results, the paper culminates in proposing specific policy recommendations. These recommendations are designed to offer actionable strategies that policymakers can implement to promote sustainable agricultural practices, enhancing the sector's environmental and economic sustainability.

The significance of this research lies in its integrative approach, combining theoretical modeling with empirical simulations to deliver a comprehensive understanding of the factors driving sustainable practices in agriculture. By elucidating the interplay between economic incentives, regulatory frameworks, and collective behavior, this study contributes valuable insights to the ongoing discourse on environmental policy and agricultural sustainability, aiming to inform effective policy-making.

2. Methodology and Materials

2.1. Basic Model Assumptions

In the proposed model, we delineate the dynamics of interaction among three principal stakeholders in the context of green rice production, namely the government (G), rice growers (R), and the public (P). Within our evolutionary game theory model, the strategic interactions among the government, growers, and the public exemplify the dynamic balance sought in sustainable agriculture. By analyzing the economic incentives for green practices, regulatory frameworks, and public engagement, our model investigates how sustainable practices can be realistically implemented and maintained. The government serves as the regulatory authority, overseeing agricultural practices to ensure they meet environmental sustainability and public health standards. Rice growers, who are at the core of rice production, face a strategic choice between adopting environmentally sustainable, green production methods and continuing with traditional, potentially harmful practices. The public, comprising consumers and the wider community, plays a crucial role in monitoring agricultural practices, driven by concerns for environmental health and food safety. The available strategic choices are twofold for each agent. The government decides between guiding rice growers towards green production and not intervening, rice growers choose between green and non-green production methods, and the public chooses to either actively supervise and report non-green practices or remain passive.

The model is premised on the concept of bounded rationality, assuming that, while agents aim to maximize their respective utilities, their decision-making is constrained by limited information and cognitive processing capabilities. It is posited that the government's regulatory actions include the authority to impose fines on non-compliant growers, reflecting an enforcement mechanism integral to promoting green agricultural practices. This model further assumes that non-green production by farmers specifically refers to practices detrimental to the environment and consumer health, highlighting the stakes involved in the strategic decision-making processes. An underlying assumption is the societal concern for food safety, quality, and environmental sustainability, which drives public engagement in the oversight of agricultural practices. Economic incentives and disincentives (such as fines, rewards, and subsidies) are considered pivotal in shaping the behaviors of the growers with respect to sustainability. Additionally, awareness of the environmental impacts associated with non-green production practices influences the strategic choices of all parties involved. Through these assumptions, the model aims to elucidate the conditions under which sustainable agricultural practices can be realized, emphasizing the interplay of regulatory policies, economic incentives, and public engagement.

The government's available strategies are to regulate (G1) growers to implement green production or not to regulate (G2) them. The strategies that growers can choose are green production (R1) and non-green production (R2). The strategies that the public can choose are to supervise and report the non-green production behaviors of growers (P1) or not to supervise and report (P2). We assume that the probability of the government choosing G1 is x (where $x \in [0, 1]$) and the probability of choosing G2 is $1 - x$. The probability that the growers choose R1 is y (where $y \in [0, 1]$), and the probability of choosing R2 is $1 - y$. The probability that the public chooses P1 is z (where $z \in [0, 1]$), and the probability of choosing P2 is $1 - z$.

The income of growers when adopting non-green production strategies is A_1. The transition to green production incurs additional costs (*Cs*), encompassing technological innovation, equipment acquisition, and the adoption of environmentally friendly farming practices. Despite these costs, the potential for increased market value (*Rs*) of green agricultural products and the availability of government incentives (*B*) motivates growers towards sustainable practices (*Cs* > *Rs*). Conversely, the model accounts for the deterrent effects of fines (*F*) and reputational losses (*Cl*) on the propensity to engage in non-green production behaviors, highlighting the economic and social pressures that influence growers' strategic choices. The total opportunity cost for growers to adopt non green production behavior is (*Cl* + *Bp* + *Fp* + *Rs*), assuming *Cs* < (*Cl* + *Bp* + *Fp* + *Rs*).

The government's income from choosing G2 is A_2. The incentives for the government to engage in regulatory actions include the potential for reputation gain (*Rg*) and the avoidance of reputational damage due to inaction (*Cm*). However, these actions are not without cost; the human and material resources (*Cr*) required for regulation, alongside the environmental management costs (*Ce*) tied to overseeing non-green production practices, represent significant considerations. Additionally, the government's regulatory strategy incorporates financial mechanisms, such as fines (*F*) for non-compliance and rewards (*B*) for adherence to green production standards. The probability of government regulation being successful is p.

The model posits that the public is motivated by both altruistic and self-interested considerations, including the direct benefits (*Rp*) associated with improved health and environmental conditions, as well as the green benefits (*Rb*) that accrue from widespread adoption of green production methods. The public's adoption of the P1 strategy requires investment cost (*Cp*), including the exertion of time, energy, and resources in the supervision and reporting activities (*Cp* > *Rp*). Furthermore, the model introduces a government-provided reward mechanism (*H*) for the public's successful reporting of non-compliance, encapsulating the reciprocal relationship between public vigilance and governmental oversight in the promotion of sustainable agricultural practices.

In our evolutionary game theory model, parameters such as economic incentives (subsidies and penalties) and the strategic choices of growers (opting for green vs. non-green production) are critically aligned with environmental goals of sustainable agriculture. These include the reduction in pesticide use and the enhancement of biodiversity. Specifically, the model incorporates how subsidies can incentivize growers to adopt environmentally friendly practices that contribute to biodiversity conservation and reduced chemical input use, while penalties discourage practices that are detrimental to environmental health. This linkage between economic mechanisms and environmental outcomes is central to our analysis of sustainable agricultural practices within the green rice production context.

The model operates through a sequence of defined steps to simulate the decision-making process among stakeholders. Initially, stakeholders are set with predefined strategies. During the decision phase, each stakeholder evaluates potential changes in strategy in response to environmental conditions and policy frameworks. Stakeholders may adapt their strategies based on the outcomes and the actions of others. Payoffs are calculated considering economic, environmental, and social metrics, leading to strategy updates via replicator dynamics. The game iterates until reaching an equilibrium where no stakeholder can better their payoff by changing strategies unilaterally.

All parameters involved in the model are shown in Table 1.

Table 1. Parameter table for three-party evolutionary game model.

Parameter	Description
A_1	Benefits accrued by growers from non-green production strategies
Cs	Costs incurred by growers in adopting green production methods, including expenses related to technology research and development, soil testing, formula fertilization, and equipment purchases
Rs	Additional value derived from green agricultural products compared to non-green ones
A_2	Gains realized by the government when choosing not to engage in regulatory strategies
Rg	Reputation gain when the government chooses a regulatory strategy
Cr	Human and material costs borne by the government in implementing a regulatory strategy
F	Fines imposed by the government on growers for non-green production behaviors
B	Rewards provided by the government to growers for adopting green production practices
p	Probability of the government's regulation being a success
Cp	Costs related to time, energy, and resources expended by the public in supervision and reporting activities
Rp	Benefits to the public from supervision and reporting, including health protection, increased availability of green products, and environmental improvement
Cl	Reputational losses suffered by growers due to non-green production behaviors identified through public supervision
Cm	Reputational damage incurred by the government due to regulatory inaction
S	Reputation benefits gained by the government when growers adopt green production behaviors
Ce	Environmental management costs faced by the government associated with non-green production practices by growers
H	Rewards received by the public from the government for reporting growers' non-green production behaviors
Rb	Green benefits to the public resulting from growers' adoption of green production practices
x	Probability that a government regulator chooses to regulate
y	Probability that a rice grower chooses green production
z	Probability that a consumer chooses to supervise and report the non-green production behaviors of growers

According to the model and parameter settings we constructed, we can obtain the payoff matrix of this game model, as shown in the Table 2.

Table 2. Payoff matrix for three-party evolutionary game model.

Government	Rice Grower	The Public: Supervise and Report	The Public: Not to Supervise and Report
Regulate	Green production	$Rg - Cr - pB + S$, $A_1 + Rs - Cs + pB$, $Rp - Cp + Rb$	$Rg - Cr - pB + S$, $A_1 + Rs - Cs + pB$, Rb
	Non-green production	$Rg - Cr + pF - Ce - (1-p)H$, $A_1 - pF - Cl$, $Rp - Cp + (1-p)H$	$Rg - Cr + pF - Ce$, $A_1 - pF$, 0
Not to regulate	Green production	$A_2 - Cm + S$, $A_1 + Rs - Cs$, $Rp - Cp + Rb$	$A_2 - Cm + S$, $A_1 + Rs - Cs$, Rb
	Non-green production	$A_2 - Cm - Ce - H$, $A_1 - Cl$, $Rp - Cp + H$	$A_2 - Cm - Ce$, A_1, 0

2.2. Solutions for Evolutionarily Stable Strategies

The expected returns of governments choosing the regulation strategy (G1) are defined as $E(G1)$, with the expected returns of non-regulation strategy (G2) denotes as $E(G2)$ and the average expected returns denoted as $\overline{E(G)}$. The specific settings are given in Equations (1)–(3) as follows:

$$E(G1) = -Ce - Cr + Fp + Rg + Cey - Bpy - Fpy + Sy - Hz + Hpz + Hyz - Hpyz \quad (1)$$

$$E(G2) = A_2 - Ce - Cm + Cey + Sy - Hz + Hyz \quad (2)$$

$$\overline{E(G)} = A_2 - Ce - Cm - A_2x + Cmx - Crx + Fpx + Rgx + Cey + Sy - Bpxy \\ -Fpxy - Hz + Hpxz + Hyz - Hpxyz \quad (3)$$

The replicator dynamics equation for the strategy choice of the governments is given in Equation (4) as follows:

$$F(x) = dx/dt = x[E(G1) - \overline{E(G)}] \\ = (1-x)x(-A_2 + Cm - Cr + Fp + Rg - Bpy - Fpy + Hpz - Hpyz) \quad (4)$$

The expected returns of the growers choosing the green production strategy (R1) are defined as $E(R1)$, with the expected returns of the non-green production strategy (R2) denoted as $E(R2)$ and the average expected returns denoted as $\overline{E(R)}$. The specific settings are given in Equations (5)–(7) as follows:

$$E(R1) = A_1 - Cs + Rs + pBx \quad (5)$$

$$E(R2) = A_1 - pFx - Clz \quad (6)$$

$$\overline{E(R)} = A_1 - pFx - Csy + Rsy + pBxy + pFxy - Clz + Clyz \quad (7)$$

The replicator dynamics equation for the strategy choice of the growers is given in Equation (8) as follows:

$$F(y) = dy/dt = y[E(R1) - \overline{E(R)}] \\ = (1-y)y(-Cs + Rs + pBx + pFx + Clz) \quad (8)$$

The expected returns of the public choosing the supervising and reporting strategy (P1) are defined as $E(P1)$, with the expected returns of the non-supervising and reporting strategy (P2) denoted as $E(P2)$ and the average expected returns denoted as $\overline{E(P)}$. The specific settings are given in Equations (9)–(11) as follows:

$$E(P1) = -Cp + H + Rp - Hpx - Hy + Rby + Hpxy \quad (9)$$

$$E(P2) = Rby \quad (10)$$

$$\overline{E(P)} = Rby - Cpz + Hz + Rpz - Hpxz - Hyz + Hpxyz \quad (11)$$

The replicator dynamics equation for the strategy choice of the public is given in Equation (12) as follows:

$$F(z) = dz/dt = z[E(P1) - \overline{E(P)}] \\ = (z-1)z(Cp - H - Rp + Hpx + Hy - Hpxy) \quad (12)$$

3. Results and Discussion

3.1. Analysis of the Stability of the Strategies of the Three Game Subjects

3.1.1. Analysis of the Stability of Government Strategies

Taking the derivation of the government's replicator dynamics equation as F(x), with respect to x, we can obtain the following Equation (13):

$$dF(x) = dF(x)/dx = (1-2x)(-A_2 + Cm - Cr + Fp + Rg - Bpy - Fpy + Hpz - Hpyz) \quad (13)$$

According to the stability theorem of the differential equation, the probability of governments choosing a regulating strategy is in a stable state and must meet $F(x) = 0$ and $dF(x)/dx < 0$. Assume that $G(y) = -A_2 + Cm - Cr + Fp + Rg - Bpy - Fpy + Hpz - Hpyz$ when $y = y^* = (-A_2 + Cm - Cr + Fp + Rg + Hpz)/(Bp + Fp + Hpz)$, $F(x) = 0$, and $dF(x)/dx \equiv 0$, the governments cannot determine a stable strategy. Since $G(y)$ is a subtraction function about y, when $y > y*$, $G(y) < 0$, and $dF(x)/dx|_{x=0} < 0$, $x = 0$ is the government's evolutionarily stable strategy (ESS). Conversely, when $y < y*$, $G(y) > 0$, and $dF(x)/dx|_{x=1} < 0$, $x = 1$ is the government's evolutionarily stable strategy (ESS). The evolution phase diagram of governments is shown in Figure 1.

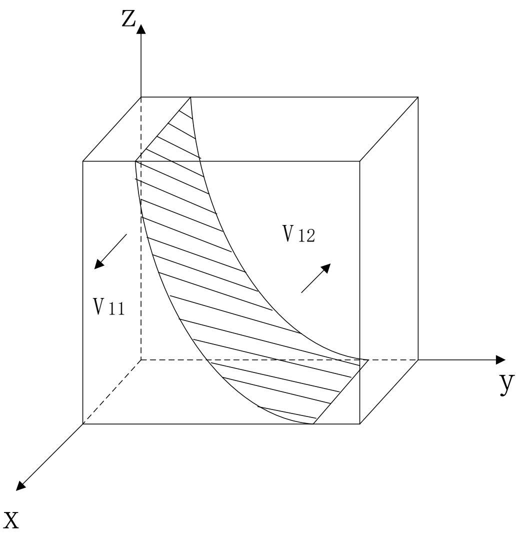

Figure 1. Evolution phase diagram of governments.

Figure 1 shows that the probabilities of governments steadily choosing the regulation strategy and the non-regulation strategy are the volumes of V_{11} and V_{12}, respectively. We can obtain Equations (14) and (15) as follows:

$$\begin{aligned} V_{11} &= \int_0^1 \int_0^1 \frac{-A_2+Cm-Cr+Fp+Rg+Hpz}{Bp+Fp+Hpz} dydz \\ &= 1 - \frac{A_2+Bp-Cm+Cr-Rg}{Hp} \log(1+\frac{H}{B+F}) \end{aligned} \tag{14}$$

$$V_{12} = 1 - V_{11} \tag{15}$$

Inference 1: The probability of governments' stable choice of regulating is positively correlated with Cm and Rg but is negatively correlated with A_2, Cr, H, B, p, and F.

Demonstration: According to the expression of the probability (V_{11}) that governments choose to regulate growers' green production, the partial derivatives of each element can be obtained as follows: $\partial V_{11}/\partial A_2 < 0$, $\partial V_{11}/\partial Cm > 0$, $\partial V_{11}/\partial Cr < 0$, $\partial V_{11}/\partial Rg > 0$, $\partial V_{11}/\partial H < 0$, $\partial V_{11}/\partial B < 0$, $\partial V_{11}/\partial p < 0$, and $\partial V_{11}/\partial F < 0$. Therefore, an increase in Cm or Rg or an decrease in A_2, Cr, H, B, p, or F can increase the probability of governments choosing the regulation strategy.

Inference 1 suggests a strong correlation between the government's regulatory decisions and the associated reputational impacts. The act of enacting and enforcing green production standards not only bolsters the government's public image, showcasing its dedication to environmental sustainability and public health, but also serves as a crucial motivator for regulatory action. This is because reputational gains align the government's actions with broader societal expectations and values.

Moreover, the potential reputational damage from selection of the non-regulation strategy strongly influences the government's regulatory stance. The threat of negative public perception and accountability for any ensuing environmental or public health repercussions push the government towards adopting a proactive regulatory approach. Conversely, the advantages of non-regulation, like reduced administrative burdens, can negatively impact the government's inclination to regulate, especially when these benefits outweigh the perceived value of regulatory enforcement.

Furthermore, the costs associated with regulatory actions, encompassing both human and material resources, play a critical role in the government's decision-making process.

The inclination to regulate diminishes as the implementation and enforcement costs escalate, particularly under financial constraints or competing resource allocation priorities.

The financial implications of rewarding compliant growers and the efficacy of regulatory supervision also have a nuanced influence on regulatory decisions. Substantial rewards to growers escalate the regulatory cost, and a high likelihood of successful supervision may indicate that sustained regulation could be excessively resource-intensive, suggesting a preference for alternative compliance strategies. Paradoxically, while fines and rewards are intended as enforcement tools, excessively high fines might trigger concerns about fairness or adverse economic impacts on growers, and significant public rewards could inflate governmental expenditures, potentially rendering regulation a less attractive option.

Inference 2: The probability that governments choose to regulate during the evolution process decreases as the probability of growers' green production and the public choosing to supervise and report increases.

Demonstration: When $y < y*$, $x = 1$ is the evolutionary stabilization strategy for governments. Thus, as y and z gradually increase, the stabilization strategy of governments evolves from regulation (G1) to non-regulation (G2).

Inference 2 elucidates a pivotal shift in the agricultural sector's regulatory dynamics, suggesting that as growers increasingly adopt green production practices and the public intensifies its vigilance in reporting non-green practices, the imperative for direct government regulation diminishes. This transition towards sustainable agricultural practices, denoted by an increased y, coupled with heightened public oversight (z), paves the way for the government to potentially recalibrate its role from direct intervention (G1) to a more supportive or facilitative stance (G2).

This shift also underscores the significant influence of trust and societal norms on regulatory frameworks and environmental governance. The voluntary move of growers towards sustainable practices, along with proactive public engagement in environmental monitoring, reflects a growing trust in these stakeholders' commitment to sustainability, reducing the reliance on stringent regulatory measures. This evolving trust suggests that adherence to environmental standards is increasingly motivated by shared social norms and values and a collective sense of environmental responsibility rather than mere compliance with regulatory mandates. Such dynamics highlight the necessity of cultivating a robust culture of environmental ethics and awareness, promoting sustainable practices not just through regulatory compulsion but by embedding them within the societal value system.

In exploring the dynamics between regulated and unregulated agricultural practices, it is essential to recognize how each contributes to sustainability goals under varying conditions. Regulated practices, typically mandated by government policies, ensure a baseline of environmental protection by enforcing standards on pesticide use, water management, and land use. However, they can be rigid and slow to adapt and often require significant bureaucratic oversight, which can stifle innovation. Conversely, unregulated practices, although not officially sanctioned, can sometimes lead to rapid adoption of innovative and adaptive techniques due to the presence of less bureaucratic inertia. These practices might include community-led conservation efforts or farmer-initiated organic farming techniques that have not yet been formally recognized by regulatory bodies. While these practices offer flexibility and grassroots solutions, they lack formal oversight, which can result in inconsistent application and effectiveness, potentially undermining broader environmental goals.

The interaction between these two approaches can be complex. For instance, in regions where regulated measures are perceived as restrictive or unresponsive to local conditions, unregulated practices may flourish, filling gaps in sustainability that formal policies fail to address. However, without integration into formal policy frameworks, these practices risk being unsustainable in the long term or failing to scale effectively.

3.1.2. Analysis of the Stability of Growers' Strategies

Taking the derivation of the growers' replicator dynamics equation ($F(y)$) with respect to y, we can obtain the following Equation (16):

$$dF(y) = dF(y)/dy = (1 - 2y)[-Cs + Rs + (B + F)px + Clz] \tag{16}$$

According to the stability theorem of the differential equation, the probability of growers choosing the green production strategy is in a stable state and must meet $F(y) = 0$ and $dF(y)/dy < 0$. Assuming that $J(z) = -Cs + Rs + (B + F)px + Clz$, when $z = z^* = (Cs - Rs - Bpx - Fpx)/Cl$, $J(z) = 0$, and $dF(y)/dy \equiv 0$, the growers cannot determine the stable strategy. Since $J(z)$ is an increasing function about z, when $z > z*$, $J(z) > 0$, and $dF(y)/dy|_{y=1} < 0$, $y = 1$ is the growers' evolutionarily stable strategy (ESS). Conversely, when $z < z*$, $J(z) < 0$, and $dF(y)/dy|_{y=0} < 0$, $y = 0$ is the growers' evolutionarily stable strategy (ESS). The evolution phase diagram of growers is shown in Figure 2.

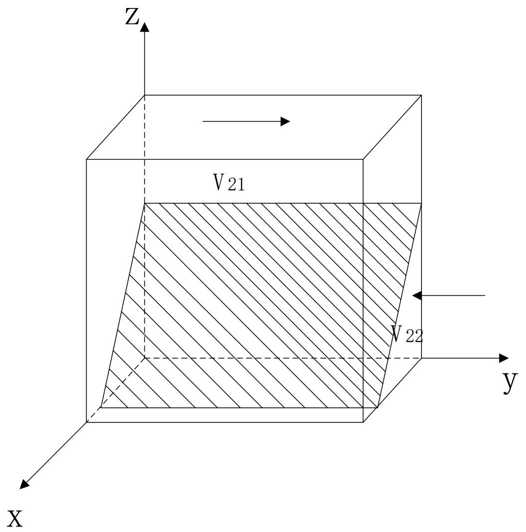

Figure 2. Evolution phase diagram of growers.

Figure 2 shows that the probability of growers steadily choosing the green production strategy and the non-green production strategy are the volumes of V_{21} and V_{22}, respectively. We can obtain Equations (17) and (18) as follows:

$$\begin{aligned} V_{22} &= \int_0^1 \int_0^1 \frac{Cs-Rs-Bpx-Fpx}{Cl} dxdz \\ &= \frac{Cs-Rs}{Cl} - \frac{(B+F)p}{2Cl} \end{aligned} \tag{17}$$

$$\begin{aligned} V_{21} &= 1 - V_{22} \\ &= 1 - \frac{Cs-Rs}{Cl} + \frac{(B+F)p}{2Cl} \end{aligned} \tag{18}$$

Inference 3: The probability of growers' stable choice of green production is positively correlated with Rs, B, F, and p but is negatively correlated with Cs.

Demonstration: According to the expression of the probability (V_{21}) that the growers choose to implement green production, the partial derivatives of each element can be obtained as follows: $\partial V_{21}/\partial Cs < 0$, $\partial V_{21}/\partial Rs > 0$, $\partial V_{21}/\partial B > 0$, $\partial V_{21}/\partial Cl$ cannot determine the positive and negative signs, $\partial V_{21}/\partial F > 0$, $\partial V_{21}/\partial p > 0$. Therefore, an increase in Rs, B, F, or p or a decrease in Cs can increase the probability of growers choosing the green production strategy.

Inference 3 delineates the economic factors as pivotal in shaping growers' decisions with respect to adopting green production practices. The analysis indicates that the costs associated with transitioning to sustainable agriculture—such as investments in eco-friendly technologies and practices like soil testing—pose significant barriers. These costs can impinge on profitability, potentially deterring growers from embracing green methods. Integrating practices such as crop rotation can mitigate some of these financial challenges. Crop rotation not only enhances soil health and reduces dependency on chemical inputs but also aligns with green transformation goals by lowering long-term operational costs and improving yield stability. Inference 3 also shows that the market premium on green agricultural products emerges as a potent incentive, aligning growers' economic interests with sustainable practices. This premium reflects a growing consumer demand for products that are both environmentally sustainable and health-conscious, enhancing the financial attractiveness of green production.

Moreover, the government's role is underscored as crucial in facilitating this transition. Through financial incentives, the government can ameliorate the burdens of initial and ongoing costs associated with green production, making it economically viable for growers. These incentives serve not only to offset costs but also to align growers' financial interests with environmental sustainability goals. Additionally, enforcement mechanisms, such as fines for non-compliance with green standards, act as a deterrent against traditional, non-sustainable practices, further nudging growers towards sustainable methods by introducing a financial risk for non-adherence.

Inference 4: The probability that the growers choose green production during the evolution process increases as the probabilities of governments choosing to regulate and the public choosing to supervise and report increase.

Demonstration: When $z < z*$, $y = 0$ is the evolutionary stabilization strategy for growers. Thus, as x and z gradually increase, the stabilization strategy of growers evolves from non-green production (R2) to green production (R1).

Inference 4 underscores a synergistic relationship whereby top-down regulatory frameworks and bottom-up public engagement collectively foster an ecosystem conducive to sustainable agricultural transitions. Government regulations establish the necessary legal scaffolding that either mandates or incentivizes sustainable practices, setting a clear operational path for growers. Concurrently, public supervision mechanisms enhance this regulatory landscape by ensuring accountability and fostering transparency, thereby solidifying the adherence to sustainable practices.

This collaborative dynamic is pivotal in creating a robust platform for growers to shift towards environmentally friendly production methods (transitioning from R2 to R1), essentially echoing an evolution in social norms and market preferences that increasingly valorize environmental stewardship. The intensification of government regulation, coupled with proactive public engagement, signals to the market a definitive shift towards sustainability. This not only aligns with compliance mandates but also resonates with growing consumer predilections for sustainable products, thereby incentivizing growers to adopt green practices through a positive reinforcement loop. The resultant market evolution suggests that regulatory frameworks and societal expectations are not merely directive but also play a reinforcing role, progressively molding market trends to champion sustainability.

3.1.3. Analysis of the Stability of the Public's Strategies

Taking the derivation of the public's replicator dynamics equation ($F(z)$) with respect to z, we can obtain the following Equation (19):

$$dF(z) = dF(z)/dz = (2z-1)(Cp - H - Rp + Hpx + Hy - Hpxy) \quad (19)$$

According to the stability theorem of the differential equation, the probability of the public choosing the supervision and reporting strategy is in a stable state and must meet $F(z) = 0$ and $dF(z)/dz < 0$. Assuming that $Q(Y) = Cp - H - Rp + Hpx + Hy - Hpxy$ when $y = y^{**} = (-Cp + H + Rp - Hpx)/(H - Hpx)$, $Q(y) = 0$, and $dF(z)/dz \equiv 0$, the growers cannot determine the stable strategy. Since $Q(y)$ is an increasing function about y, when $y > y**$, $Q(y) > 0$ and $dF(z)/dz|_{z=0} < 0$, $z = 0$ is the public's evolutionarily stable strategy (ESS). Conversely, when $y < y**$, $Q(y) < 0$, and $dF(z)/dz|_{z=1} < 0$, $z = 1$ is the public's evolutionarily stable strategy (ESS). The evolution phase diagram of the public is shown in Figure 3.

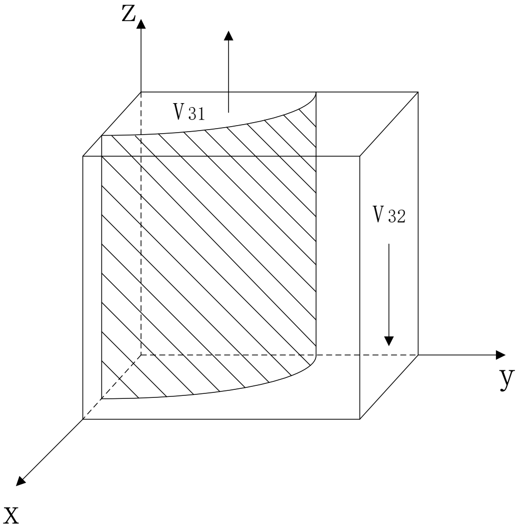

Figure 3. Evolution phase diagram of the public.

Figure 3 shows that the probabilities of the public steadily choosing the supervision and reporting strategy and the non-supervision and reporting strategy are the volumes of V_{31} and V_{32}, respectively. We can obtain Equations (20) and (21) as follows:

$$\begin{aligned} V_{31} &= \int_0^1 \int_0^1 \frac{-Cp+H+Rp-Hpx}{H-Hpx} dxdy \\ &= 1 - \frac{Cp-Rp}{Hp} \log\left(\frac{H}{H-Hp}\right) \end{aligned} \tag{20}$$

$$V_{32} = 1 - V_{31} \tag{21}$$

Inference 5: The probability of the public's stable choice of supervision and reporting is positively correlated with *Rp* and *H* but is negatively correlated with *Cp* and *p*.

Demonstration: According to the expression of the probability (V_{31}) that the public chooses to supervise and report growers' non-green production, the partial derivatives of each element can be obtained as follows: $\partial V_{31}/\partial Cp < 0$, $\partial V_{31}/\partial Rp > 0$, $\partial V_{31}/\partial p < 0$, and $\partial V_{31}/\partial H > 0$. Therefore, an increase in *Rp* or *H* or a decrease in *Cp* or *p* can increase the probability of the public choosing the supervision and reporting strategy.

Inference 5 delves into the dynamics influencing public engagement in environmental supervision and reporting, emphasizing the pivotal role of perceived benefits and costs. The benefits (*Rp*), such as enhanced environmental quality and personal health gains, serve as significant motivators for public participation. This intrinsic motivation is heightened when the public perceives their efforts as contributing meaningfully to collective well-being, thereby increasing their willingness to engage in these activities. Additionally, the governmental rewards (*H*) for effective reporting strengthen this motivation by providing a direct incentive, enhancing the appeal of active engagement in environmental vigilance. However, the analysis acknowledges that high costs (*Cp*) associated with public supervision can deter engagement. If the public perceives these costs as outweighing the benefits, their propensity to participate diminishes, highlighting the need for a balanced approach in policy design to ensure that the costs borne by the public do not eclipse the perceived benefits.

The counterintuitive negative correlation between the government's successful supervision probability (p) and public willingness to engage in reporting activities is particularly insightful. It suggests that when government supervision is perceived as highly effective, the public may deem their participation redundant, diminishing their perceived importance in the regulatory ecosystem. This perception can lead to a decreased likelihood of the public undertaking active supervision roles, underscoring the delicate balance required in public policy to maintain optimal levels of public involvement without rendering their contributions seemingly unnecessary.

Inference 6: The probability that the public chooses to supervise and report during the evolution process decreases as the probabilities of governments choosing to regulate and growers choosing green production increase.

Demonstration: When $y < y**$, $z = 0$ is the evolutionary stabilization strategy for the public. Thus, as x and y gradually increase, the stabilization strategy of the public evolves from supervising and reporting (P1) to not supervising and reporting (P2).

Inference 6 suggests that the decrease in public engagement in supervision and reporting as government regulation and green production practices become more prevalent indicates that the public perceives these activities as increasingly redundant or unnecessary. This perception likely stems from a growing confidence in the effectiveness of governmental regulation and growers' commitment to sustainable practices. As the government intensifies its regulatory efforts and growers increasingly adopt environmentally friendly practices, the rationale for public vigilance and reporting diminishes, indicating a trust in institutional mechanisms and industry self-regulation to uphold environmental standards.

This evolutionary shift in public strategy from active supervision and reporting (P1) to a passive stance (P2) highlights the adaptive nature of public engagement based on the perceived need for intervention. When government regulation and grower compliance are deemed sufficient to ensure environmental sustainability, the public may choose to allocate their resources and attention to other areas where their participation is perceived as more critical. This adaptation reflects a rational assessment of the effectiveness and efficiency of environmental governance mechanisms, where public intervention is calibrated according to the performance of regulatory and industry actors.

3.2. Stability Analysis of Equilibrium Point of Three-Party Evolutionary Game System

Now, letting $F(x) = 0, F(y) = 0, F(z) = 0$, this paper determines eight local stable equilibrium points, namely $E_1(0, 0, 0)$, $E_2(1, 0, 0)$, $E_3(0, 1, 0)$, $E_4(0, 0, 1)$, $E_5(1, 1, 0)$, $E_6(1, 0, 1)$, $E_7(0, 1, 1)$, and $E_8(1, 1, 1)$. The evolution of mixed equilibrium points is not considered here because the mixed equilibrium points must have the characteristic value of 0, which does not fit the evolutionarily stability strategy (ESS). The Jacobian matrix (J) of agricultural green production is as follows (see Equation (22)):

$$
\begin{aligned}
J &= \begin{pmatrix} J_1 & J_2 & J_3 \\ J_4 & J_5 & J_6 \\ J_7 & J_8 & J_9 \end{pmatrix} = \begin{pmatrix} \partial F(x)/\partial x & \partial F(x)/\partial y & \partial F(x)/\partial z \\ \partial F(y)/\partial x & \partial F(y)/\partial y & \partial F(y)/\partial z \\ \partial F(z)/\partial x & \partial F(z)/\partial y & \partial F(z)/\partial z \end{pmatrix} \\
&= \begin{pmatrix} \begin{array}{l}(1-2x)(-A_2+Cm-Cr+Fp \\ +Rg-Bpy-Fpy+Hpz-Hpyz)\end{array} & (1-x)x(-Bp-Fp-Hpz) & (1-x)x(Hp-Hpy) \\ (1-y)y(Bp+Fp) & \begin{array}{l}(1-2y)(-Cs+Rs \\ +Bpx+Fpx+Clz)\end{array} & (1-y)yCl \\ (z-1)z(Hp-Hpy) & (z-1)z(H-Hpx) & (2z-1)\begin{pmatrix} Cp-H-Rp \\ +Hpx+Hy-Hpxy \end{pmatrix} \end{pmatrix}
\end{aligned}
\tag{22}
$$

According to Lyapunov's first methodology, when all the eigenvalues of a Jacobian matrix (J) are negative, the equilibrium point is the asymptotic stability point; when at least one of the eigenvalues of the Jacobian matrix (J) is positive, the equilibrium point is unstable. However, when the Jacobian matrix (J) has a zero eigenvalue and all the other eigenvalues are negative, the stability of the point cannot be determined. Combined with the profit and loss variable settings and the descriptions of the three subjects, the stability analysis of the equilibrium point is shown in Table 3.

Table 3. Jacobian matrix eigenvalues.

Equilibrium Point	Eigenvalue of Jacobian Matrix		
	λ_1	λ_2	λ_3
$E_1(0, 0, 0)$	$-A_2 + Cm - Cr + Fp + Rg$	$-Cp + H + Rp$	$-Cs + Rs$
$E_2(1, 0, 0)$	$A_2 - Cm + Cr - Fp - Rg$	$-Cp + H - Hp + Rp$	$-Cs + Bp + Fp + Rs$
$E_3(0, 1, 0)$	$-A_2 + Cm - Cr - Bp + Rg$	$-Cp + Rp$	$Cs - Rs$
$E_4(0, 0, 1)$	$-A_2 + Cm - Cr + Fp + Hp + Rg$	$Cp - H - Rp$	$Cl - Cs + Rs$
$E_5(1, 1, 0)$	$A_2 - Cm + Cr + Bp - Rg$	$-Cp + Rp$	$Cs - Bp - Fp - Rs$
$E_6(1, 0, 1)$	$A_2 - Cm + Cr - Fp - Hp - Rg$	$Cp - H + Hp - Rp$	$Cl - Cs + Bp + Fp + Rs$
$E_7(0, 1, 1)$	$-A_2 + Cm - Cr - Bp + Rg$	$Cp - Rp$	$-Cl + Cs - Rs$
$E_8(1, 1, 1)$	$A_2 - Cm + Cr + Bp - Rg$	$Cp - Rp$	$-Cl + Cs - Bp - Fp - Rs$

According to the payoff matrix of the three-party game in Table 2, it can be seen that the highest possible return for the government adopting a regulatory strategy is $Rg + S - Cr - Bp$, and the highest possible return for the government adopting an unregulated strategy is $A_2 - Cm + S$. We assume that the highest possible return when the government adopts regulatory strategies is greater, and we can determine that $A_2 + Bp + Cr - Cm - Rg < 0$. Combined with other previously assumed constraints ($Cs > Rs$, $Cs < (Cl + Bp + Fp + Rs)$, $Cp > Rp$), it is not difficult to know that E_1, E_3, E_4, E_6, E_7, and E_8 all have positive eigenvalues.

Scenario 1. Under the conditions of $-Cp + H - Hp + Rp < 0$, $-Cs + Bp + Fp + Rs < 0$, E_2 is the Evolutionary Equilibrium Point (ESS). In this scenario, when the probability of successful government regulation (p) is constant, the reward given by the government to the public for supervision and reporting should be sufficiently low, and the cost of public supervision and reporting should far outweigh the benefits. In addition, the cost of green transformation for growers is higher than the added value of green rice and the rewards and fines for successful government regulation. The system's evolutionary strategy should be (regulation, non-green production, non-supervision and reporting). The emergence of E2 as the evolutionary equilibrium point under these conditions illustrates a complex scenario where regulatory efforts by the government do not translate into widespread adoption of green production practices by growers or active supervision and reporting by the public. The government's choice to regulate, despite the lack of effective public engagement and growers' adherence to non-green practices, may indicate a potential disconnect between regulatory intentions and practical outcomes. It suggests that, while regulatory intentions are present, the mechanisms for incentivizing compliance and public participation are not adequately aligned with the stakeholders' economic realities and motivations. In addition, the scenario underscores the need to adjust economic incentives and policy measures to better align the interests of growers and the public with environmental sustainability goals. For growers, this might involve enhancing the economic attractiveness of green production through subsidies, tax incentives, or higher rewards. For the public, increasing the rewards for reporting and reducing the associated costs could encourage more active participation in environmental oversight.

Scenario 2. Under the specified condition of $Cs - Bp - Fp - Rs < 0$, E_5 is the evolutionary equilibrium point (ESS). In this scenario, the cost of green transformation for growers is less than the added value of green rice and the rewards and fines for successful government regulation. This condition essentially suggests that the net cost of transitioning to green production for growers is offset by the combination of higher market values for green products, government rewards for compliance, and penalties for non-compliance, making green production economically viable and preferable. The system's evolutionary strategy should be (regulation, green production, non-supervision and reporting).

The evolutionary strategy of (regulation, green production, non-supervision and reporting) underscores the role of government regulation as a catalyst for sustainable agriculture. By implementing policies that make green production economically advantageous for growers, the government can drive the agricultural sector towards sustainability without necessitating continuous oversight by the public. This approach leverages economic incentives and disincentives to align growers' interests with environmental objectives, demonstrating the effectiveness of well-designed regulatory frameworks in achieving sustainable outcomes.

This scenario posits a model of environmental governance where the interplay of market forces, regulatory policies, and economic incentives obviates the necessity for direct public engagement in surveillance and reporting functions. This evolutionary equilibrium point (E5) has important implications for policy design and sustainability goals. It illustrates that creating an effective incentive structure for sustainable practices, where the economic benefits of compliance outweigh the costs, can lead to a self-regulating system that minimizes the need for external oversight.

3.3. Numerical Simulation and Analysis

The purpose of our numerical simulation, conducted using MATLAB 2020b, was to rigorously explore and validate the theoretical predictions of our evolutionary game model concerning green rice production. Each simulation was initiated with predefined sets of parameters reflecting different strategic conditions among the stakeholders. The process involves iteratively adjusting these parameters to observe the changes in strategies adopted by the government, growers, and the public over time. For example, one simulation scenario involves setting a high penalty for non-green production practices to see how quickly and effectively growers switch to sustainable methods. By integrating the complex interplay among government regulation, growers' production choices, and public supervision strategies into a dynamic simulation environment, we aimed to empirically assess the conditions under which different evolutionarily stable strategies (ESSs) emerge. This approach allows us to not only corroborate the analytical inferences drawn from the model but also to observe the system's behavior under a range of parameter values, providing deeper insights into the practical implications of policy interventions, economic incentives, and societal engagement in promoting sustainable agricultural practices. Through this simulation, we endeavor to bridge the gap between theoretical modeling and real-world applicability, offering a robust framework for understanding the drivers of sustainable behavior within the agricultural sector.

Further, our simulations explicitly model the temporal aspects of strategy transitions, illustrating how farmers incrementally adjust their practices in response to evolving external pressures and incentives. This gradual shift from traditional to sustainable practices is captured through phased adoption mechanisms within the simulations, which are designed to reflect realistic time scales and decision-making processes observed in the agricultural sector. By incorporating these dynamics, the simulation provides a detailed depiction of how transitions unfold over time, highlighting the role of continuous adaptation and the impact of cumulative changes in policy and market conditions on farmer behaviors.

In the empirical analysis of agricultural practices and policy impacts, particularly within the context of green agriculture, obtaining accurate, quantifiable data on certain parameters, such as the value of reputation or the exact costs of government supervision, presents significant challenges. These variables, which are critical to understanding the dynamics at play in the adoption of sustainable agricultural practices, often elude direct measurement due to their inherently qualitative nature and the complexity of the systems in which they operate.

Recognizing these limitations, this article endeavors to construct a parameter array that, while grounded in rigorous literature analysis, also incorporates insights gained from consultations with experts and scholars in the field. We set the parameters as follows: A_2 = 10, Cm = 35, Cr = 30, F = 25, p = 0.6, Rg = 20, B = 10, Cp = 10, Rp = 5, H = 10, Cs = 30, Rs = 20, and Cl = 15.

The adoption of green agricultural practices necessitates significant initial investments in technology and infrastructure yet offers substantial benefits through enhanced market value of green products. Studies have documented the economic implications of transitioning to sustainable agriculture, highlighting the balance between the costs incurred and the premium prices achievable in the market for environmentally friendly agricultural outputs [33]. Therefore, we set Cs = 30, reflecting the comprehensive investments required for green transformation, and Rs = 20, representing the premium market valuation of green agricultural products.

Governmental incentives and regulatory mechanisms are pivotal in steering the agricultural sector towards sustainability. Research by Zhang (2015) [34] underscores the effectiveness of policy frameworks in integrating environmental and agricultural objectives, yielding notable socioeconomic and environmental dividends. Consequently, we designate A_2 = 10, Rg = 20, Cr = 30, F = 25, B = 10, and p = 0.6 to encapsulate the dynamics of policy incentives (rewards and fines), the costs associated with regulatory strategies, and the probability of successful government supervision.

Public engagement in environmental governance plays a crucial role in fostering sustainable agricultural practices. Piñeiro et al. (2020) [35] emphasize the significance of public participation, driven by the benefits of supervision and reporting and incentivized through rewards for the reporting of non-compliant behaviors. This informs our selection of Cp = 10, Rp = 5, and H = 10, balancing the costs of public engagement with the benefits and rewards associated with active environmental stewardship.

The interplay of social and reputational factors significantly influences the adoption of green agricultural practices. Chengjun et al. (2021) [36] highlight the impact of societal pressures and policy enforcement in shaping the motivations behind sustainable agricultural decisions, where reputation emerges as a key driver. Accordingly, we set Cm = 35 and Cl = 15 to reflect the reputational considerations of government inaction, growers' non-green production behaviors, and the social benefits accruing from green production.

3.3.1. Impact of Initial Probabilities on Regulatory and Adoption Dynamics in Agricultural Sustainability

As illustrated in Figure 4, our simulation, which adjusts initial probabilities for government regulation (x), growers' green production (y), and public supervision/reporting (z) to 0.2, 0.5, and 0.7, respectively, uncovers a significant trend (as shown in Figure 4a), namely that x consistently reaches unity by t = 0.4, indicating a uniform shift towards comprehensive governmental regulation. This consistent convergence (particularly notable after a key intersection at t = 0.2) highlights a systemic bias towards regulatory intervention, suggesting that once regulatory frameworks are activated, they are capable of rapidly and effectively fostering sustainable agricultural practices. The model points to a pivotal moment in regulatory adoption after which the momentum towards sustainability is self-reinforcing, illustrating the critical role of robust, legitimate regulatory frameworks in accelerating the adoption of sustainable practices, resonating with the perspectives presented by Smith and Stirling (2018) [37] on the transformative potential of well-implemented policies.

The simulation results for the probability of growers adopting green production practices over time (t) (as shown in Figure 4b) exhibit distinct convergence behaviors based on varying initial probabilities (0.2, 0.5, and 0.7). Specifically, with an initial probability of 0.2, y achieves full convergence to 1 at approximately t = 0.6. When the initial probability is set to 0.5, convergence occurs sooner, at t = 0.4, and with an initial probability of 0.7, y reaches 1 even more rapidly, by t = 0.3. These findings emphasize the crucial influence of starting conditions on the adoption rate of sustainable practices, indicating that initial hesitancy or obstacles might slow down the transition, despite conducive conditions or incentives for green production. The quicker convergence observed with higher initial probabilities suggests the existence of positive feedback loops in the adoption of sustainable practices, where early successes catalyze a broader and faster transition towards green methods. This observation is in line with diffusion of innovation theories, which posit that early adopters play a critical role in precipitating widespread change [38].

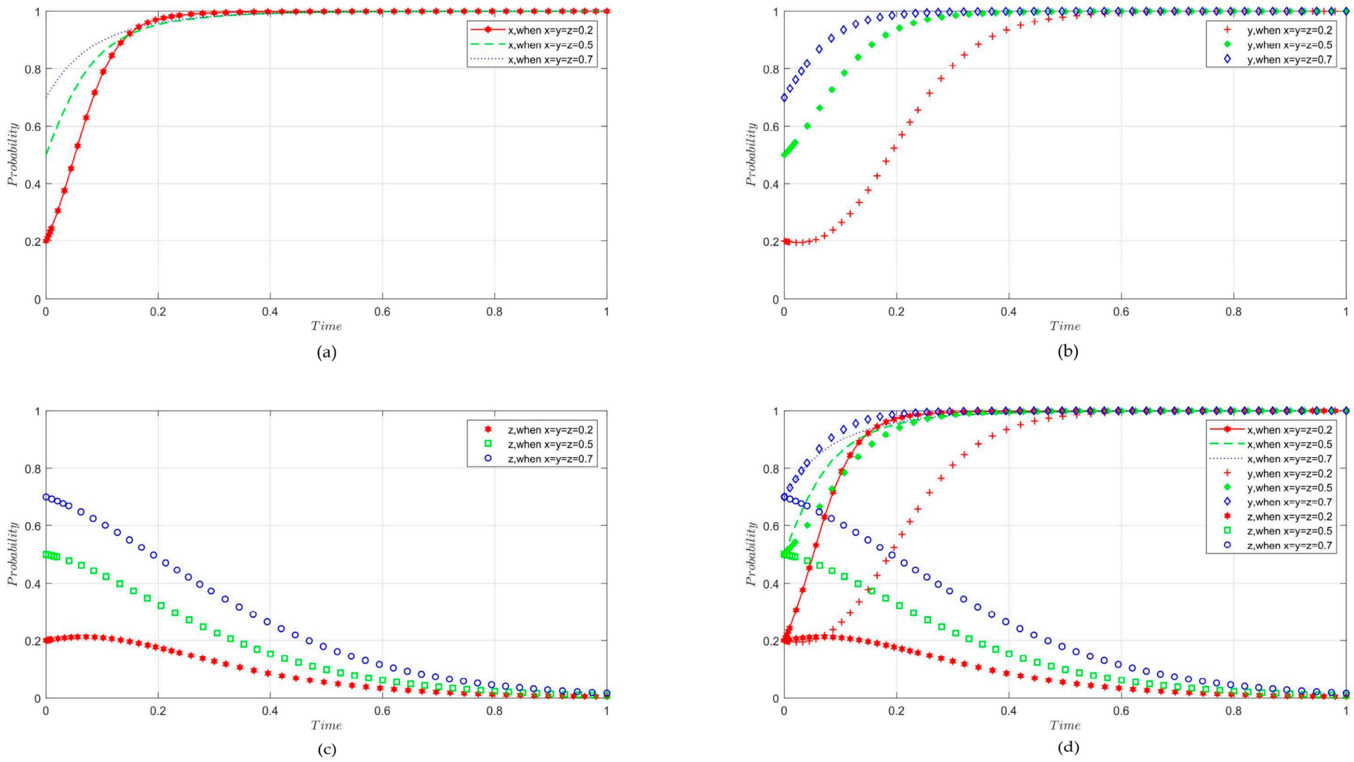

Figure 4. Dynamics of evolutionary strategies with varying initial probabilities illustrating the response of each strategy to different initial settings ($x = y = z = 0.2$; $x = y = z = 0.5$; $x = y = z = 0.7$). (**a**) Evolution of government regulation; (**b**) adjustment of growers' green production; (**c**) shift in public supervision/reporting; (**d**) a holistic view of the system's adaptation over time.

Our simulation analysis, focusing on the evolution of public supervision and reporting probability (z) over time (t) from initial probabilities of 0.2, 0.5, and 0.7, shows a consistent decrease in z, ultimately converging to 0 as it approaches $t = 1$ (as shown in Figure 4c). This trend indicates a diminishing role of public engagement in the supervision and reporting of non-green production behaviors as the agricultural system evolves towards its equilibrium states. The decreasing trajectory of z across all initial settings suggests that, in the context of our model, the necessity of active public supervision and reporting diminishes over time. This could be attributed to the increasing effectiveness of government regulation and the adoption of green production practices by growers, which collectively reduce the need for public intervention.

3.3.2. Analyzing the Influence of Incentive Structures on Sustainable Agricultural Dynamics

Our numerical simulations, designed to explore the impact of varying government rewards (B) and fines (F) on the dynamics of regulatory adoption (x), green production practices (y), and public supervision/reporting (z) over time (t), yield insightful results with respect to the mechanisms driving sustainable agricultural practices (Figure 5). Specifically, we incrementally increased the values of B and F across three scenarios ($B = 5$, $F = 20$; $B = 10$, $F = 25$; and $B = 15$, $F = 30$) to observe the resultant changes in x, y, and z.

In our simulation analysis examining the impact of government rewards (B) and fines (F) on the regulatory adoption process (as shown in Figure 5a), we specifically scrutinized the scenario where B = 15 and F = 30. This particular setting revealed a slower convergence to full regulatory commitment, with x reaching 1 at t = 0.6, which is distinctively later than in scenarios with lower values of B and F.

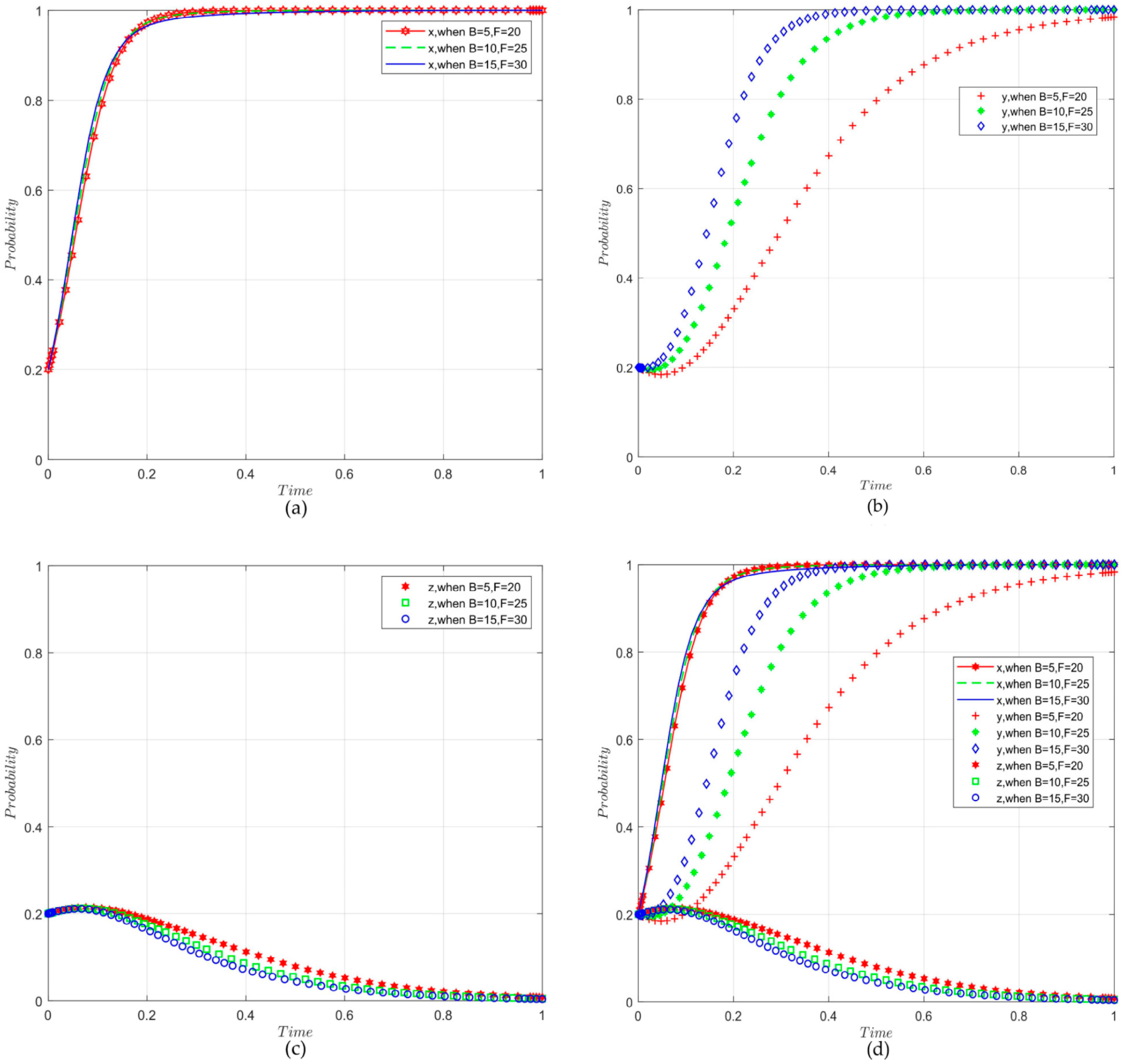

Figure 5. Response of evolutionary strategies to variations in incentives and penalties demonstrating how different configurations of government rewards (B) and fines (F) influence the system's strategic evolution, with sets of values of B = 5, F = 20; B = 10, F = 25; and B = 15, F = 30. (**a**) Evolution of government regulation under varying B and F values; (**b**) changes in growers' green production in response to B and F values; (**c**) how public supervision/reporting adjusts with the alterations in B and F; (**d**) an integrated representation of the evolutions of x, y, and z, offering a comprehensive view of the system's adaptive strategies over time.

This delayed convergence in the high-incentive scenario implies that, while increased rewards and fines typically bolster regulatory engagement, excessively high incentives might inadvertently introduce inefficiencies or complexities, decelerating the pace of total regulatory adoption. The observed lag in achieving full regulatory commitment at these elevated incentive levels points to a complex interplay of factors. It suggests that, beyond a certain threshold, heightened incentives do not linearly translate to faster regulatory commitments, possibly due to issues like incentive over-saturation, diminishing returns, or bureaucratic complexities that might emerge in larger incentive frameworks.

The simulation results (Figure 5b) for the y variable, tracking the adoption of green production practices by growers over time (t), clearly demonstrate that the likelihood of adopting sustainable methods increases significantly with higher values of government rewards (B) and fines (F). Notably, in the scenario with the lowest incentives ($B = 5$ and $F = 20$), the probability of full adoption (y reaching 1) is not realized within the timeframe up to $t = 1$, suggesting that the provided incentives and penalties are insufficient to fully catalyze the shift towards sustainable practices within the given period. This scenario illustrates that when rewards and fines fall below certain levels, they fail to provide enough motivation for growers to fully commit to sustainable practices, echoing challenges often encountered in real-world policy implementation for sustainability transitions.

Conversely, the simulation indicates that enhanced incentives (higher B and F values) lead to a quicker adoption rate of green practices, with the scenario featuring the highest incentives ($B = 15$, $F = 30$) showing the most rapid convergence to full adoption. This trend highlights the potent influence of economic incentives in promoting sustainable agricultural practices, aligning with economic theories that suggest behavioral shifts are more likely when the economic benefits of compliance, as well as the costs of non-compliance, are substantial [39]. Tian et al. (2022) [40] also determined that insufficient governmental ecological compensation, particularly when it approaches zero, is ineffective in incentivizing farmers to reduce their use of fertilizers.

Our simulation analysis (Figure 5c), examining the impact of government rewards (B) and fines (F) on public engagement in environmental supervision and reporting (z) over time (t), consistently shows a decline in z, with all scenarios converging to zero. The trajectories of z, regardless of the levels of B and F, largely overlap, indicating only marginally lower values of z in scenarios with reduced rewards and fines. This pattern suggests that while the economic mechanisms of incentives and disincentives play a substantial role in shaping the regulatory behavior of the government and the green production practices of growers, their influence on the public's willingness to engage in environmental oversight appears to be minimal. The diminishing trend in public engagement, converging uniformly to zero, implies that as the regulatory environment becomes more established and the agricultural sector adapts to sustainable practices, the perceived need or value of public intervention in monitoring and reporting fades, potentially due to increased trust in the effectiveness of the regulatory framework and the intrinsic motivation of growers to pursue sustainable compliance.

3.3.3. Impact of Reputational Factors on Evolutionary Dynamics in Agricultural Sustainability

We also conducted simulations (Figure 6) to examine the effects of varying levels of reputational damage due to government inaction (Cm), reputational gain from government regulation (Rg), and reputational losses for growers adopting non-green production behaviors (Cl). Specifically, we considered three distinct sets of values, namely $Cm = 32$, $Rg = 17$, $Cl = 12$; $Cm = 35$, $Rg = 20$, $Cl = 15$; and $Cm = 38$, $Rg = 23$, $Cl = 18$, to elucidate how reputational considerations influence x, y, and z over time (t).

The simulation outcomes (as shown in Figure 6a) consistently demonstrate an increase in the likelihood of government regulation (x), with all tested scenarios ultimately converging to full regulatory adoption ($x = 1$). This pattern becomes more pronounced with elevated values of Cm, Rg, and Cl, which are found to hasten the progression toward regulatory enforcement. In particular, the simulations indicate that under lower reputational stakes ($Cm = 32$, $Rg = 17$, and $Cl = 12$), full regulatory adoption is achieved until $t = 1$, while higher reputational implications result in quicker convergence, achieving full adoption as early as $t = 0.3$ or $t = 0.4$.

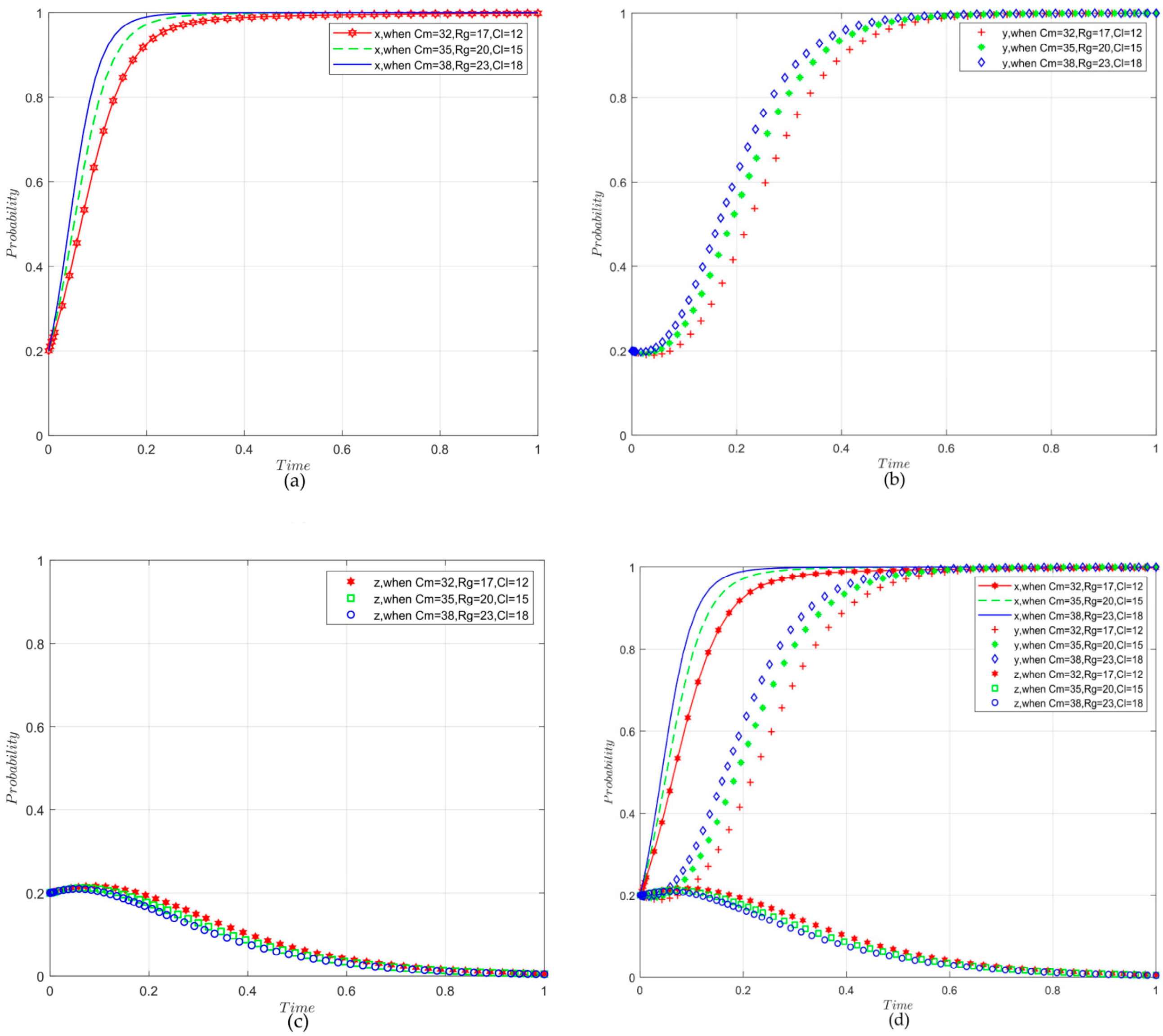

Figure 6. Response of evolutionary strategies to variations in reputational influences illustrating the simulation outcomes when adjusting the parameters of reputational damage to the government (*Cm*), reputational gain from government regulation (*Rg*), and reputational losses for growers (*Cl*). The simulations consider three distinct sets of values, namely *Cm* = 32, *Rg* = 17, *Cl* = 12; *Cm* = 35, *Rg* = 20, *Cl* = 15; and *Cm* = 38, *Rg* = 23, *Cl* = 18. (**a**) Evolution of the government regulation strategy as it responds to different levels of *Cm*, *Rg*, and *Cl*; (**b**) adjustment of the growers' strategy towards green production influenced by variations in *Cm*, *Rg*, and *Cl*; (**c**) shifts in the public's supervision/reporting strategy with the changing reputational parameters; (**d**) an integrated representation of the evolutions of x, y, and z, providing a holistic view of how each strategy adapts in the context of reputational factors, presenting a comprehensive perspective on the system's response over time.

These insights highlight the profound influence of reputational considerations on the regulatory decision-making process. Escalated reputational costs and potential gains not only incentivize the government to intensify regulatory enforcement but also suggest that such reputational factors might drive quicker alignment with sustainable practices. The faster attainment of full regulatory adoption under increased reputational stakes underscores the theory that reputational concerns, both in terms of avoiding negative consequences and achieving positive recognition, are pivotal in motivating stakeholders to pursue compliance with sustainability-oriented regulatory frameworks. This dynamic suggests that leveraging reputational influences could be a strategic approach to enhance the efficacy of regulatory policies, especially in sectors where sustainability is critical.

The simulation results (Figure 6b) demonstrate a clear trend, namely that as the values of Cm, Rg, and Cl increase, so does the probability of growers adopting green production practices (y), with all scenarios eventually converging to $y = 1$. This pattern suggests that heightened reputational considerations across the board act as significant motivators for growers to shift towards sustainable practices. Despite the variability in the rate of increase depending on the specific values of Cm, Rg, and Cl, convergence to full adoption ($y = 1$) is consistently observed near $t = 0.6$, indicating a robust tendency towards sustainability irrespective of the initial reputational pressures.

This finding underscores the pivotal role of reputational factors in influencing environmental compliance and sustainable practice adoption among growers. It is worth noting that both Cm and Rg are reputational values or reputational damage directly related to the government, but they also have an impact on the green production of growers. This correlation suggests that growers are responsive to the reputational stance of the government, with enhanced regulatory measures and the associated reputational implications acting as key motivators for the adoption of environmentally friendly practices. The simulation reveals that higher risks of reputational damage (Cm and Cl) and greater prospects for reputational gain (Rg) create a compelling case for growers to engage in green production practices. The convergence of y to 1 by $t = 0.6$ across varying levels of reputational considerations highlights the effectiveness of leveraging reputational dynamics as a mechanism to promote sustainable agricultural practices.

In our simulations (Figure 6c) examining the impact of increased government reputational considerations (Cm and Rg) and growers' reputational losses (Cl) on public supervision and reporting behavior (z) over time, we observed a consistent decline in z, with all scenarios converging to zero. The simulations revealed that higher values of Cm, Rg, and Cl led to a marginally lower z, although the differences were slight and the trajectories of z across different settings nearly coincided. This trend indicates that, while government and growers' reputational factors have a discernible impact on the dynamics of regulatory adoption and green production practices, their influence on public engagement in supervision and reporting is minimal.

3.3.4. Economic Impacts on Strategic Choices in Agricultural Sustainability Simulations

Our simulation study (Figure 7), aimed at investigating the influence of costs associated with green transformation (Cs) and the market value of green agricultural products (Rs), reveals the impact of the economic gains and losses of green transformation on the strategic choices of the three parties. Specifically, we considered three distinct sets of values, namely $Cs = 33$, $Rs = 17$; $Cs = 30$, $Rs = 20$; and $Cs = 27$, $Rs = 23$, to observe resultant changes in x, y, and z over time (t).

As shown in the diagrams of x-t (Figure 7a) and z-t (Figure 7c), by adjusting Cs downwards and Rs upwards across three distinct scenarios, we observe that the probabilities of government regulation (x) and public supervision/reporting (z) exhibit remarkably similar trajectories, with x converging to $x = 1$ and z diminishing to zero in all cases. Scenarios characterized by lower Cs and higher Rs values result in marginally lower levels of x and z. This consistency in the trajectories, irrespective of the economic adjustments, highlights that while economic factors are pivotal, they might only slightly modulate the systemic move towards a regulatory framework that ensures sustainability and reduces the reliance on public monitoring, without drastically altering the path to achieving these outcomes.

Our simulation (Figure 7b) scrutinizes the impact of economic factors (Cs and Rs) on the adoption rates of sustainable practices among growers (y). The results vividly illustrate that modifications in these economic incentives, notably by reducing Cs and enhancing Rs, substantially influence the adoption trajectory of y, which consistently culminates in full adoption ($y = 1$) across various scenarios.

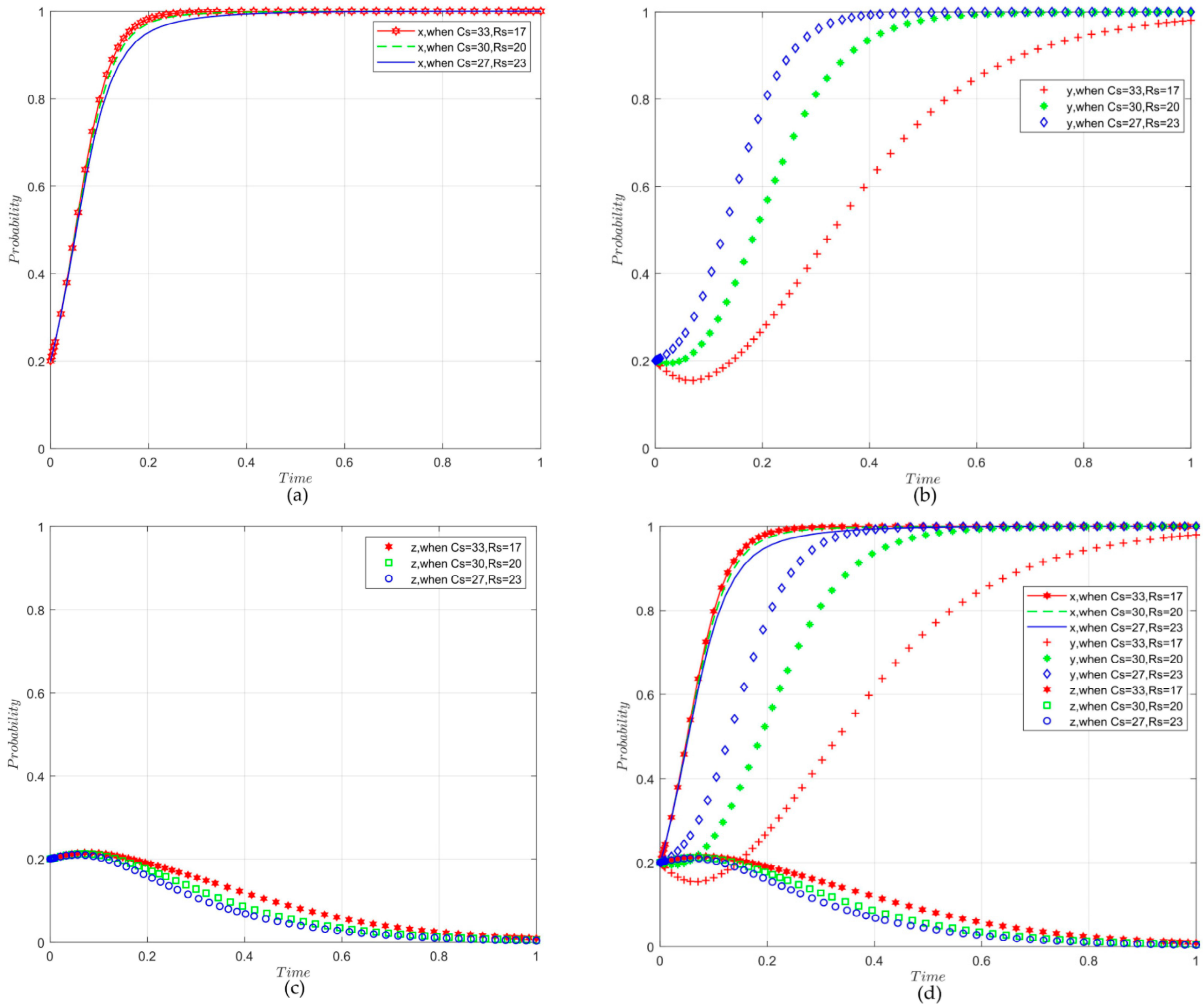

Figure 7. Strategy adjustments in response to economic incentives and costs exploring how changes in the cost of green transformation and the revenue from green products influence strategic behaviors in the evolutionary game model. The simulations are executed with varying levels of Cs and Rs, namely Cs = 33, Rs = 17; Cs = 30, Rs = 20; and Cs = 27, Rs = 23. (**a**) Evolution of the government regulation strategy as influenced by adjustments in Cs and Rs; (**b**) changes in growers' green production strategy in response to economic incentives and costs; (**c**) variation in the public supervision/reporting strategy with alterations in Cs and Rs; (**d**) a consolidated view of the simultaneous changes in x, y, and z, offering a comprehensive perspective on how the entire system adapts to the economic shifts represented by Cs and Rs.

In the scenario with Cs = 27 and Rs = 23, y exhibits a swift convergence to 1, achieving full adoption around t = 0.5, suggesting that the combination of lower costs and higher rewards effectively fast-tracks the shift toward sustainable practices. Conversely, with Cs set at 30 and Rs at 20, the convergence to 1 occurs at a slower pace, concluding around t = 0.7, which implies that while the economic conditions are conducive, they are not as optimal as the former scenario, resulting in the decelerated adoption rate. The third scenario, featuring Cs = 33 and Rs = 17, shows an initial decline in y, followed by a gradual increase, yet failing to fully converge to 1 within the simulation timeframe. This pattern indicates that less favorable economic incentives (higher costs and lower rewards) may hinder the prompt adoption of green practices, potentially leading to protracted or incomplete transitions to sustainability. This observation aligns with the findings presented by Xu et al. (2021) [30], which underscore the significance of their research in the context of our study.

The variations in the trajectory and convergence speed of y highlight the critical impact of reducing the financial barriers to green transformation and enhancing the profitability of green agricultural products. These findings suggest that policies aimed at lowering the costs associated with adopting sustainable practices and increasing the economic benefits of green products can significantly accelerate the sector's transition towards sustainability.

3.3.5. Simulating Public Supervision Costs and Benefits in Agricultural Sustainability

In our evolutionary game model designed to elucidate the dynamics of sustainable agricultural practices, we introduce simulations (Figure 8) to examine the effects of modifying the costs associated with public supervision and reporting (Cp) alongside the benefits derived from these activities (Rp). Specifically, we consider three distinct sets of values, namely $Cp = 12$, $Rp = 3$; $Cp = 10$, $Rp = 5$; and $Cp = 8$, $Rp = 7$, to observe resultant changes in x, y, and z over time (t).

The simulation diagram of x-t (Figure 8a) indicates that modifications in the public supervision and reporting costs (Cp) and benefits (Rp) do not significantly impact the probability of government regulation (x), as the trajectories for x essentially overlap across different values. This suggests that the dynamics of regulatory commitment are largely independent of the variations in public engagement costs and benefits within the modeled scenarios.

The simulation (Figure 8b) reveals a discernible impact on y, the probability of growers adopting green production practices, which slightly increases as Cp decreases and Rp increases, ultimately converging to $y = 1$. This pattern suggests that reducing the burdens associated with public supervision and reporting, coupled with enhanced perceived benefits of these activities, can marginally influence growers to pursue more sustainable practices.

The slight increase in y in response to more favorable conditions for public engagement (lower Cp and higher Rp) indicates that, while the primary drivers of green production adoption among growers may be more directly related to economic incentives and regulatory pressures, the ambient environment of public supervision and the cultural valuation of environmental stewardship also play supportive roles. This dynamic points to an agricultural system where the direct influencers of growers' adoption of green practices are primarily economic incentives and regulatory frameworks, yet the ambient environment fostered by public engagement also contributes positively to sustainability.

The simulation results for z-t (Figure 8c) reveal a nuanced response to the adjusted values of Cp and Rp. Specifically, we observe that as Cp decreases and Rp increases, there is a general trend of rising z, indicating enhanced public engagement in monitoring and reporting. However, distinct behaviors are noted for each set of values. With $Cp = 12$ and $Rp = 3$, z exhibits a continuous decline, followed by a convergence to zero nearing $t = 0.7$, suggesting that higher costs and lower benefits eventually dampen public engagement, leading it to its ceasing over time. When Cp is set to 10 and Rp to 5, z also converges to 0 but does so at a later point compared to the first scenario, indicating that a moderate balance of costs and benefits prolongs active public engagement before it diminishes. Interestingly, for $Cp = 8$ and $Rp = 7$, z initially rises, reflecting increased public engagement due to lower costs and higher benefits, but then stabilizes at around 0.2 instead of dropping to zero, suggesting sustained public involvement over time, albeit at a reduced level.

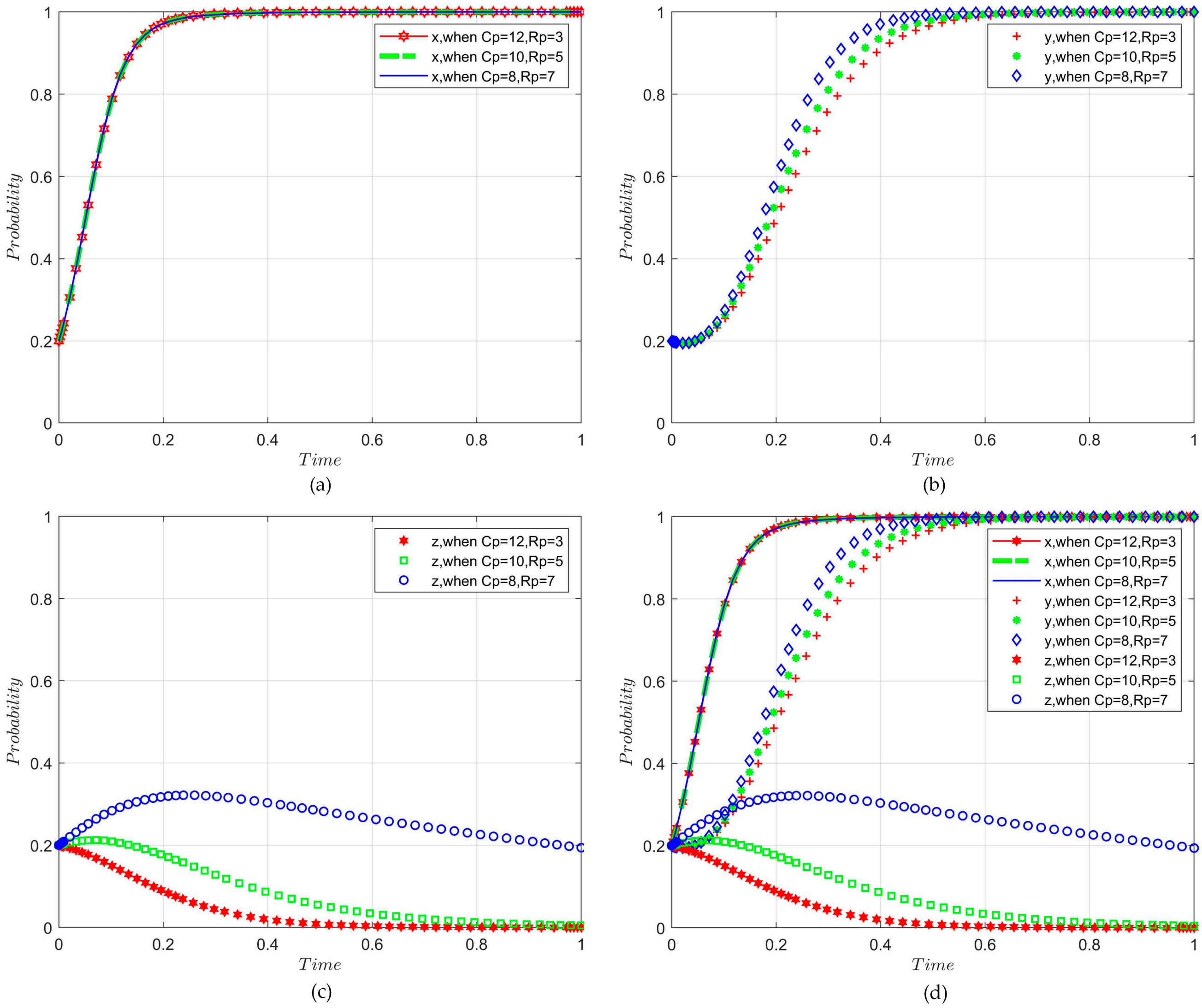

Figure 8. Strategy adjustments in response to adjusted supervision costs and reporting benefits exploring the effects of modifying the costs associated with public supervision (*Cp*) and the returns for reporting (*Rp*) on the strategic behavior within the evolutionary game model. The set examined values are *Cp* = 12, *Rp* = 3; *Cp* = 10, *Rp* = 5; and *Cp* = 8, *Rp* = 7. (**a**) How the probability of government regulation evolves in response to varying *Cp* and *Rp* values; (**b**) adaptation in the growers' probability of adopting green production influenced by changes in the cost–benefit structure of public reporting; (**c**) alterations in the public's engagement in supervision and reporting as a function of the adjusted *Cp* and *Rp* values; (**d**) an integrated representation of the individual simulations of x, y, and z, providing an overarching view of the system's response to modifications in public supervision costs and reporting benefits, showcasing the collective strategic adjustments.

These variations signify that the public's willingness to engage in supervisory and reporting activities is sensitive to the net balance of the associated costs and rewards. The initial rise in z when $Cp = 8$ and $Rp = 7$ underscores the intuitive expectation that lower costs and higher rewards boost public engagement. However, the eventual decline or stabilization of z suggests a complex interplay where other model dynamics, such as the effectiveness of government regulation and growers' compliance levels, might reduce the necessity or effectiveness of public oversight, as reflected in the varying convergence points of z.

3.3.6. Correlation of Simulation Outcomes with Theoretical ESS Predictions in Agricultural Sustainability

The simulation outcomes from MATLAB, showcasing the evolutionary trajectories within our model, align seamlessly with our prior analytical insights concerning the evolutionarily stable strategy (ESS) points (as is shown in Figure 9). The specific condition ($Cs - Bp - Fp - Rs < 0$) integral to our theoretical construct is echoed in the simulation results, with all evolutionary paths converging to the ESS point (1, 1, 0). This convergence delineates a scenario where governmental regulation is fully operational (x = 1), growers universally adopt green production methodologies (y = 1), and the necessity of public supervision and reporting is negated (z = 0).

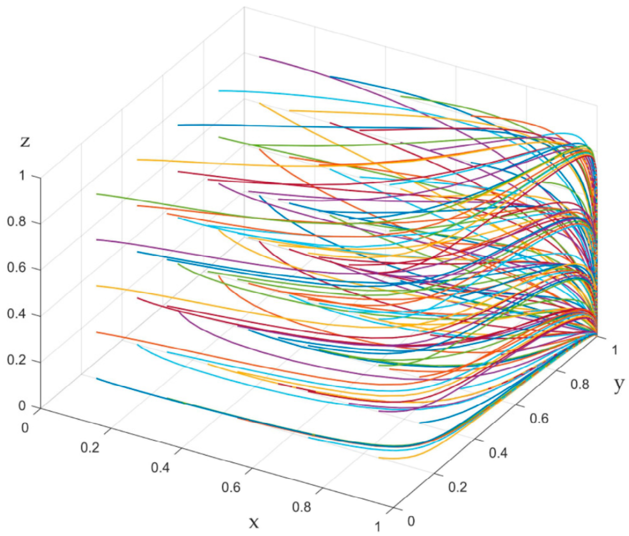

Figure 9. Convergence to evolutionarily stable strategy (ESS) in a three-dimensional simulation. This figure visualizes the dynamic evolution within a three-dimensional coordinate system, depicting numerous paths that converge at the ESS point (1, 1, 0).

This harmony between the simulation findings and the ESS analysis bolsters the model's reliability in forecasting the system's equilibrium under the defined economic and regulatory scenarios. The congruence of the simulated paths with the theoretical predictions not only validates the model's foundational premises but also affirms that the orchestrated interplay of economic incentives and regulatory mechanisms is pivotal in catalyzing the shift towards sustainable agricultural practices. The simulations provide a tangible representation of the theoretical ESS insights, offering empirical substantiation for the specific conditions that foster the targeted sustainable outcomes, thereby reinforcing the model's utility in strategic planning and policy formulation towards sustainable agricultural development.

4. Conclusions and Policy Recommendations

4.1. Conclusions

This study's exploration of the theoretical model delineates the pathway to achieving the evolutionarily stable strategy (ESS) of (1, 1, 0), which signifies a state of complete regulatory enforcement, widespread adoption of green production practices, and reduced public supervision. Central to this equilibrium is the alignment of economic incentives—encompassing rewards, costs, and market premiums—that are instrumental in promoting environmentally sustainable practices. As the government increases incentives for green production and imposes fines for non-green production, the probability of growers adopting green production also significantly increases. Strengthening the impact of reputational gains and losses is crucial for governments to fully embrace regulatory strategies and for growers to transition to sustainable production, while public oversight will become increasingly less necessary. The analysis underscores the critical interplay between economic incentives and regulatory frameworks, highlighting how this synergy is vital in directing the agricultural sector towards sustainability. It posits that a regulatory environment designed to motivate green production through strategic, incentive-driven approaches is essential.

Complementing the theoretical insights, the results of our simulation conducted using MATLAB validate the specified ESS points, especially affirming the $Cs - Bp - Fp - Rs < 0$ condition, which leads to the desired ESS of (1, 1, 0). These results confirm that a strategic enhancement of economic incentives significantly bolsters the government's regulatory commitment, aligning with the theoretical forecast of a steadfast journey towards complete regulatory adoption. The simulations also demonstrate that economic recalibrations significantly drive growers towards sustainable practices, emphasizing the foundational role of incentive structures in advancing agricultural sustainability. Support policies that help growers overcome technical barriers to green transition, provide subsidies for their transition, and increase the economic benefits of green products can greatly accelerate the transition of rice production to sustainable agriculture. Furthermore, the observed decline in public supervisory engagement aligns with the theoretical expectations, reflecting a landscape where strengthened regulatory frameworks and the intrinsic shift towards market-driven sustainability diminish the need for intensive public oversight. This shift suggests an evolving role for public participation shaped by the maturing landscape of sustainability within the sector. Consequently, this study advocates for policy frameworks that not only provide incentives for green production but also harmonize the economic interests of stakeholders with the goals of environmental sustainability, thereby facilitating a systemic transition towards the ESS (1, 1, 0) configuration.

Collectively, these findings bolster the theoretical model's applicability, providing empirical backing for the nuanced orchestration of regulatory and economic mechanisms essential for propelling the agricultural sector towards sustainable practices. The simulation insights not only corroborate the model's accuracy but also illuminate the influential role of economic and reputational factors in shaping the trajectory towards sustainable agricultural methodologies, laying a solid groundwork for informed policy development and strategic sectoral guidance.

4.2. Policy Implications

The insights garnered from the theoretical and simulation analyses of the evolutionary game model have profound policy implications for enhancing sustainability in the agricultural sector. These implications offer a roadmap for policymakers to design and implement strategies that not only promote green production practices but also ensure the long-term sustainability of agricultural ecosystems.

Policy frameworks should be designed to offer a multi-faceted incentive model that not only addresses the immediate financial concerns associated with transitioning to green practices but also builds long-term economic resilience for growers. This could involve a combination of upfront subsidies to alleviate initial transition costs, ongoing tax breaks tied to verified sustainable practices, and a dynamic pricing model that offers premium pricing or market bonuses for products verified as sustainably produced. The aim is to construct a financial landscape where the long-term economic benefits of adopting sustainable practices are transparent, substantial, and directly tied to the growers' commitment to environmental stewardship.

Regulatory policies should be adaptive and responsive and crafted to evolve in tandem with technological advancements and shifts in market dynamics. They should provide a clear framework that mandates sustainability while also being flexible enough to accommodate innovations in green agriculture. Regulations could include phased compliance milestones, allowing growers to adapt progressively, and incorporate feedback mechanisms whereby growers can contribute to the regulatory discourse. This approach ensures that regulations remain relevant, practical, and effective in promoting sustainable practices, thereby fostering an environment where growers' operational decisions are intrinsically aligned with the advancement of environmental sustainability.

While the need for public supervision and reporting diminishes as regulatory effectiveness and compliance with green practices improve, policies should still encourage public engagement through education, awareness campaigns, and platforms for community monitoring. Such engagement ensures a broad-based commitment to sustainability and fosters a culture of environmental stewardship.

We recommend the development of a framework that harnesses the incentive and restraint effects of public opinion on both the government and growers. This can be achieved by promoting transparency in reporting green practices and regulatory compliance, thereby subjecting both parties to the scrutiny and approval of the public. Initiatives could include publicizing sustainability ratings of agricultural producers, creating platforms for consumer feedback, and implementing public recognition programs for exemplary practices. Such measures can motivate both regulatory bodies and agricultural producers to uphold high standards of environmental stewardship.

We also recommend the development of a sector-specific sustainability incentive program that aligns with the practical realities of agricultural production. This program could involve a tiered incentive structure where growers achieve different levels of certification for adopting sustainable practices, akin to a sustainability label or rating system. Each level would offer distinct benefits, such as tax rebates, priority access to water rights, or enhanced market access. This system encourages continuous improvement in sustainability practices, with each tier designed around achievable, realistic goals that progressively lead to higher sustainability standards. The program should be flexible to accommodate the diversity of agricultural operations, ensuring that both small-scale farmers and large agribusinesses can participate effectively and benefit from their sustainable initiatives.

Finally, implementing sustainable practices often requires significant bureaucratic involvement, which, while necessary for regulation and enforcement, can also lead to inefficiencies or corruption. It is crucial to design administrative processes that ensure transparency and accountability, minimizing the risk of corruption while facilitating the effective adoption of eco-friendly practices.

4.3. Limitations and Further Research

While this study provides insightful contributions to the field of sustainable agricultural practices, we acknowledge certain limitations that simultaneously offer avenues for further exploration. The theoretical model's simplifications serve to make the complex dynamics of agricultural sustainability more tractable; however, this comes at the cost of nuanced specificity. Future research could enhance the model's depth and applicability by integrating empirical data, which would allow for a refinement of the model's parameters and assumptions. This integration should aim to bolster the model's robustness and extend its applicability across varied agricultural contexts, ensuring that the findings and policy recommendations are grounded in a realistic representation of the agricultural sector's multifaceted nature.

Additionally, the current model does not account for external economic and environmental factors such as market dynamics, climate change, and international tensions, which significantly influence the cost-effectiveness and viability of adopting sustainable practices. Future studies should consider these variables to provide a more detailed analysis of how such factors impact strategic decisions in agricultural policy and practice.

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