Construction and Stability Analysis of Evolutionary Game Model for Green Agricultural Production under the Leadership of Village Committees

Abstract

The promotion of agricultural green production is mired in a governance paradox of policy stagnation and farmer reluctance, rooted in the intricate strategic interplay among micro-level stakeholders. Leveraging the village committee's dual function as a policy transmission pivot and the cornerstone of rural social fabric, this paper develops an asymmetric evolutionary game model to examine interactions between village committees and agricultural producers. By specifying the strategic sets and payoff matrices for both actors, we derive the replicator dynamics of the system and conduct local stability analysis via the Jacobian matrix to pinpoint key Evolutionary Stable Strategies(ESS). Our findings indicate that the system's evolutionary trajectory does not converge to a unique equilibrium but is critically contingent on cost-benefit parameters: the optimal equilibrium $(1,1)$—where village committees champion green production and farmers adopt it—demands stringent income distribution arrangements, namely that the village committee's revenue share coefficient e must fall below a critical threshold range of $(0.3, 0.7)$, and depends on synergistic drivers such as product price P and collaborative returns R_s. In contrast, the Pareto-inefficient dilemma equilibrium $(1,0)$—where village committees promote green production but farmers refuse to participate—arises under specific cost configurations. This study is the first to document the dual-threshold effect of the income distribution coefficient, offering micro-foundations and quantitative evidence to address bottlenecks in agricultural green cooperation and inform targeted policy interventions.

Keywords: Rural Revitalization; Evolutionary Game; Village Committee; Green Production; Stability Analysis

2010 Mathematics Subject Classification: 53C25; 83C05; 57N16

1 Introduction

In 2025, the Central No. 1 Document "Opinions on Comprehensively Promoting Rural Revitalization and Accelerating Agricultural and Rural Modernization" was officially released, with "agricultural green development", "empowerment through technology", and "food security" once again emerging as core keywords. The rural revitalization strategy serves as the overarching framework for addressing issues related to agriculture, rural areas, and farmers in the new era. Ecological revitalization, as an essential component of rural revitalization, is a critical pathway to achieving sustainable agricultural and rural development (1) . With the deepening advancement of China's ecological civilization construction, green agricultural production has become the core content of promoting ecological revitalization. However, traditional agricultural production models, which rely heavily on high inputs and high consumption, have led to increasingly prominent issues such as resource wastage, environmental pollution, and ecological degradation, urgently necessitating a transition towards green, low-carbon, and circular development models. In recent years, the state has introduced a series of policies to support agricultural green development and ecological revitalization. The "Rural Revitalization Strategic Plan (2018-2022)" explicitly calls for strengthening the prevention and control of agricultural non-point source pollution and promoting agricultural green development. The "Opinions on Innovating Institutional Mechanisms to Promote Agricultural Green Development" emphasize the establishment of a green agricultural technology system and the promotion of clean production methods. These policies provide institutional safeguards and practical direction for agricultural green production. Despite ongoing policy enhancements, data from the Ministry of Agriculture and Rural Affairs in 2024 show that the adoption rate of green production technologies remains at only 38.7% (21.3% below the target), highlighting the urgency of research on micro-level decision-making mechanisms. Against this backdrop, studying the decision-making mechanisms of agricultural producers regarding green production and exploring how to achieve ecological and economic synergies through policy guidance and technological promotion hold significant theoretical and practical relevance.

The complex network evolutionary game model is well-suited to capture the influence of interactions among game agents on their decision-making. In the context of agricultural green production, interactions between village committees and groups of agricultural producers in reality are neither fully coupled nor entirely random, and their strategy choices are influenced by the system's topological structure. At its core, this represents an evolutionary game process based on complex networks, where individual strategies evolve in response to changes in the network environment and structure (2; 3). In research on multi-agent games in rural governance, Zhan Guohui and Liu Bangfan (4) argue that the public can be guided to voluntarily participate in promoting sustainable agricultural development. Weersink and Livernois (5) note that economic instruments can achieve environmental goals at lower costs while continuously incentivizing improvements in environmental performance. Compared to point-source pollution control, such policy tools demonstrate higher effectiveness in managing agricultural non-point source pollution. Gou Tianlai et al. (6) suggest that in the process of social work intervention in rural governance, the establishment of a trust mechanism is crucial for enhancing the effectiveness of rural governance, profoundly influencing collaboration methods among multiple agents and the stability of the governance system. It is also a key factor affecting the outcomes of social work interventions. The establishment of a trust mechanism can gradually develop through repeated game interactions, and the introduction of competition mechanisms can effectively accelerate cooperation with service recipients. Bayramoglu and Chakir (7) used structural econometric methods to study the relationship between higher grain crop prices and fertilizer inputs in French agricultural production, exploring the cost-benefit considerations of farmers in a market-oriented environment. Zhang Suluo et al. (8), based on the rational economic agent assumption of Western economics, employed an evolutionary game model with grassroots government organizations and local elite organizations as the two parties in the game. They argued that establishing appropriate incentive mechanisms can greatly stimulate the enthusiasm of local elite organizations to participate. Zhu, Q. H. and Dou, Y. J. (9) studied the game between the government and core enterprises in green supply chains, concluding that implementing green supply chain management, along with government subsidies and penalties, directly affects the costs and benefits of core enterprises, which are central to game outcomes. Ji Yun et al. (10), based on the development status of the "new community factory" model–a typical rural revitalization industry model in the Qinba Mountain area of Shaanxi Province–

identified key participants such as community factories, local governments, and leading enterprises. They conducted a tripartite evolutionary game and simulation study to promote the development of rural revitalization industries.

Existing literature largely overlooks the central role of village committees as network hubs in strategy diffusion and lacks exploration of quantitative thresholds for benefit distribution. Therefore, this paper, based on complex network theory and evolutionary game theory, constructs an evolutionary game model with village committees as core nodes. It quantitatively reveals the stable conditions for strategic interactions between village committees and farmers, particularly focusing on critical thresholds for benefit distribution coefficients.

2 Construction and Analysis of the Evolutionary Game Model

2.1 Analysis of Game Agents and Behavioral Logic

The process of rural ecological revitalization involves multiple stakeholders, such as the government, villagers, enterprises, and village committees. The village committee, serving as a crucial link between state power and rural society, embodies the dual roles of policy implementer and representative of villagers' interests. Its strategic choices not only influence the effectiveness of policy implementation but also shape agricultural producers' perceptions and willingness to adopt green technologies. Agricultural producers, as micro-level decision-making agents, experience the greening transformation of their production behaviors constrained by economic rationality calculations of costs and benefits, while also being deeply embedded within rural social networks predominantly led by the village committee. The game relationship between village committees and agricultural producers essentially reflects the complex landscape of state-society interaction in contemporary Chinese rural environmental governance. Modeling this pair of agents captures both the hierarchical characteristics of policy transmission-from national environmental strategies to village-level implementation and then to farmers' practices-and reveals the moderating role of informal institutions in the diffusion of green technologies. More importantly, their strategic interaction forms a governance feedback loop with positive reinforcement characteristics. Active facilitation by the village committee can increase farmers' adoption willingness, while widespread participation by farmers, in turn, strengthens the governance legitimacy of the village committee. This co-evolutionary mechanism provides a theoretical key to resolving the dual dilemma of policy ineffectiveness and farmer hesitation.

2.2 Model Assumptions and Parameter System

Let the strategic choice space for the village committee be $Sc = \{$ Facilitate Green Production, Not Facilitate$\}$, and for agricultural producers be $S_f = \{$Adopt Green Production, Not Adopt$\}$. To ensure the rigor and real-world explanatory power of the model, the following assumptions are proposed, and a parameter system is established (Table 1):

H1: Both game parties are boundedly rational economic agents, aiming to maximize their own expected payoffs.

H2: Among agricultural producers, the proportion adopting green production is x; among village committees, the proportion facilitating green production is y.

H3: Green production generates environmental synergy benefits Rs, which are realized as economic value through a product premium coefficient.

H4: Facilitation behavior by the village committee incurs promotion and training costs. Its payoff is linked to the final output of the agricultural producers.

Table 1: Game model parameters and their meanings.

Agent	Parameter	Meaning
Village Committee	c	The promotion and training cost coefficient required for the dissemination of clean production technology, $0 < c < 1$
	e	The proportion of benefits gained when promoting green production among agricultural producers and it is adopted, $0 < e < 1$
	R_S	Synergistic benefits arising from environmental improvement, $R_S > 0$
	R_L	Fixed income, $R_L > 0$
Agricultural Producer	C_f	The production cost per unit of agricultural product, $C_f > 0$
	C_p	Unit selling price of agricultural products, $C_p > 0$
	W	Quantity of waste per unit in the agricultural production process, $W > 0$
	P_W	Unit cost of waste disposal for agricultural producers who do not adopt green production strategies, $P_W > 0$
	R_W	Unit cost of waste disposal for agricultural producers who adopt green production strategies, $R_W > 0$
	b	Adoption rate of green production technology, $b > 0$
	f	Cost coefficient for agricultural producers to independently implement clean production strategies, $f > 0$
	d	Waste reduction coefficient, $0 < d < 1$
	Q	Scale of agricultural production, $Q > 0$
	S_f	Subsidies for agricultural production provided by the local government, $S_f > 0$
	a	Product premium coefficient after adopting green production technology, $a > 0$

2.3 Analysis of the Game Model

Based on the above assumptions, the mixed-strategy game matrix between agricultural producers and the village committee is obtained, as shown in Table 2.

Table 2: Game Agent Payoff Matrix.

Committee \ Producer	Adopt x	Not Adopt $1-x$
Promote y	$(1-e)\left((1+a)P-b^2C_f\right)Q-(1-d)WR_wQ+S_f$ $e\left((1+a)P-b^2C_f-cb^2C_f\right)Q+R_L+R_s$	$(P-C_f)Q-WP_WQ$ R_L-cC_fQ
Not Promote $1-y$	$e\left((1+a)P-(1+f)b^2C_f\right)Q-(1-d)WR_wQ+S_f$ R_L+R_s	$(P-C_f)Q-WP_WQ$ R_L

According to the payoff matrix and evolutionary game theory, the expected benefits and replicator dynamics equations of the two game subjects are solved. Assume that the expected benefits of agricultural producers adopting and not adopting green production are E_1 and E_2 respectively, and the average expected benefit is $\bar{E}$; the expected benefits of village committees leading and not leading green production are H_1 and H_2 respectively, and the average expected benefit is $\bar{H}$.The model construction and stability analysis of the game subjects are as follows:

2.3.1 Strategy of Agricultural Producers

The expected benefit of agricultural producers adopting green production is:

$$\begin{gathered} E_1 = y\left((1-e)\left((1+a)P - b^2 C_f\right)Q - (1-d)WR_wQ + S_f\right) \\ +(1-y)\left(e\left((1+a)P - (1+f)b^2 C_f\right)Q - (1-d)WR_wQ + S_f\right) \end{gathered} \tag{2.1}$$

The expected benefit of agricultural producers not adopting green production is:

$$E_2 = y\left((P - C_f)Q - WP_wQ\right) + (1-y)\left((P - C_f)Q - WP_wQ\right) \tag{2.2}$$

The average expected benefit is:

$$\bar{E} = xE_1 + (1-x)E_2 \tag{2.3}$$

Further, the replicator dynamics equation of agricultural producers is:

$$f(x) = x\left(E_1 - \bar{E}\right) = x(1-x)\left(A_f y + B_f\right) \tag{2.4}$$

where $A_f = Q\left(C_f b^2(-1+2e+ef) + P(1+a)(1-2e)\right), B_f = Q(P(e(1+a)-1) + C_f\left(1-e(1+f)b^2\right)) + S_f + W\left(P_W - (1-d)R_w\right)Q$.

Taking the first derivative of the replicator dynamics equation of agricultural producers:

$$df(x)/dx = (1-2x)\left(A_f y + B_f\right) = (1-2x)G(y) \tag{2.5}$$

According to the stability theorem of differential equations, the probability of agricultural producers' choice being in a stable state must satisfy: $f(x) = 0,\ df(x)/dx < 0.\ \partial G(y)/\partial y = A_f$, when $y = -B_f/A_f, G(y) = 0$, and the stable state cannot be determined at this time, let $y* = -B_f/A_f (0 < y* < 1)$,

Case 1: If $A_f > 0, B_f < 0$, then $G(y)$ is an increasing function. Wheny $< y*$, $G(y) < 0$, and $df(x)/\left.dx\right|_{x=0} < 0$, non-adoption by agricultural producers is a stable strategy; when $y > y*, G(y) > 0$, ang $df(x)/\left.dx\right|_{x=1} < 0$, adoption by agricultural producers is a stable strategy.

Case 2: if $A_f < 0, B_f > 0$, then $G(y)$ is a decreasing function. When $y < y*$, $G(y) > 0$, and $df(x)/\left.dx\right|_{x=1} < 0$, adoption by agricultural producers is a stable strategy; when $y > y*, G(y) < 0$, and $df(x)/\left.dx\right|_{x=0} < 0$, non-adoption by agricultural producers is a stable strategy.

2.3.2 Strategy of Village Committees

The expected benefit of village committees leading agricultural producers in green production is:

$$\begin{gathered} H_1 = x\left(e\left((1+a)P - b^2 C_f - cb^2 C_f\right)Q + R_L + R_s\right) \\ +(1-x)\left(R_L - cC_f Q\right) \end{gathered} \tag{2.6}$$

The expected benefit of village committees not leading agricultural producers in green production is:

$$H_2 = x\left(R_L + R_s\right) + (1-x)\left(R_L + R_s\right) \tag{2.7}$$

The replicator dynamics equation of village committees is:

$$f(y) = y\left(H_1 - \bar{H}\right) = y(1-y)\left(A_v x + B_v\right) \tag{2.8}$$

where $A_v = Q\left(e(1+a)P - e(1+c)b^2C_f + cC_f\right), B_v = -cC_fQ$.

Taking the first derivative of the replicator dynamics equation of village committees:

$$f(y)/dy = (2y-1)\left(A_vx + B_v\right) = (2y-1)J(x) \tag{2.9}$$

According to the stability theorem of differential equations, the probability of village committees choosing to lead being in a stable state must satisfy: $f(y) = 0$, $df(y)/dy < 0$. $\partial J(x)/\partial x = A_v$, when $x = -B_v/A_v, J(x) = 0$, and the stable state cannot be determined at this time. Let $x* = -B_v/A_v(0 < x* < 1)$.

Case 3: Since $-B_v > 0$, he condition can only be satisfied when $A_v > 0$, and $J(x)$ is an increasing function at this time. When $x < x*, J(x) < 0$, and $f(y)/\left.dy\right|_{y=0} < 0$, non-leadership by village committees is a stable strategy; when $x > x*, J(x) > 0$, and $f(y)/\left.dy\right|_{y=1} < 0$, leadership by village committees is a stable strategy.

2.3.3 Stability Analysis

Setting the replicator dynamics equations of both game parties to 0, i.e., $f(x) = 0$ and $f(y) = 0$, four stable equilibrium points are obtained: $(0,0), (0,1), (1,0)$, $(0,0)$, By solving the Jacobian matrix, the eigenvalues of each point are obtained as shown in Table 3.

Table 3: Eigenvalues of Each Equilibrium Point.

Equilibrium Point	Eigenvalue λ_1	Eigenvalue λ_2
$(0,0)$	B_f	B_v
$(0,1)$	$A_f + B_f$	$-B_v$
$(1,0)$	$-B_f$	$A_v + B_v$
$(1,1)$	$-\left(A_f + B_f\right)$	$-\left(A_v + B_v\right)$

According to Friedman's equilibrium stability criterion:(0,1) cannot become an evolutionarily stable strategy (ESS) under the parameter condition $-B_v > 0$, and the mixed strategy $(x*, y*)$ is a saddle point, which is unstable.

(1) Stability of $(0,0)$: If point $(0,0)$ is a stable equilibrium point, i.e., $B_f < 0$, the green production benefits of farmers are insufficient and lower than the benefits of traditional production.

(2) Stability of $(1,0)$: If point $(1,0)$ is a stable equilibrium point, i.e., $B_f > 0$ and $A_v + B_v < 0$, farmers are willing to engage in green production, but the net benefit of village committees' leadership is negative (costs exceed income).

$B_f > 0$ means that even without the leadership of village committees, farmers can still benefit from adopting green production. The driving factors may include a high government subsidy Sf, a significant savings in waste disposal costs $P_W \gg (1-d)R_w$, a sufficiently high green product premium a, and a high technical efficiency b that makes costs more controllable.

$A_v + B_v < 0$ means that the net benefit of village committees' leadership is negative. The reasons may include that the total income of green products $(1+a)P$ is insufficient to cover the costs $(1+c)C_fb^2$, the cost coefficient c of village committees' leadership is too high, and although the profit-sharing ratio e is positive, the overall benefit is still negative, and the technical efficiency b is not high enough to achieve a sufficient cost reduction.

(3)Ideal equilibrium of $(1,1)$: Achieving the ideal state of cooperative evolution between both parties requires more stringent conditions: $A_f + B_f > 0$ and $A_v + B_v > 0$.

Condition 1 (Incentive for village committees): Under the leadership of village committees, the net benefit of farmers adopting green production is positive. To ensure that the incremental net income of agricultural producers from green production under the leadership of village committees is positive, the product premium and benefit distribution must satisfy $(1+a)(1-e) > 1$; to ensure that the cost savings are positive, it is necessary to satisfy $(1-e)b^2 < 1$.

Condition 2 (Incentive for agricultural producers): The total income of green products is greater than the total cost, making the leadership of village committees profitable, i.e., $(1+a)P > (1+c)C_f b^2$, which requires a sufficiently high economic efficiency of green production.

These two conditions jointly point to the "double-threshold effect" of the benefit distribution coefficient e:If the value of e is too small, the benefits of village committees are insufficient, i.e., $A_v + B_v$ is small; if the value of e is too large, the benefits of farmers are insufficient, i.e., $A_f + B_f$ is small. Therefore, there is a reasonable interval that satisfies both parties.

This double-threshold effect clearly defines the "Pareto optimal" interval for benefit distribution, providing an accurate theoretical basis and operable regulatory scope for balancing "incentive compatibility" and "fair distribution" in policy design.

3 Numerical Simulation Analysis

To verify the correctness of the above analysis and directly present the results of the evolutionary game, this paper uses MATLAB to simulate the strategy choices of the two stakeholder groups, exploring the impact of key parameters through numerical simulations.

Case 1: ESS point $(1,0)$, with parameters satisfying $B_f > 0$ and $A_v + B_v < 0$.

Let: $a = 0.3,\ b = 0.6, C_f = 15, P = 5,\ W = 1, P_w = 2, R_w = 1,\ d = 0.3,\ S_f = 8, e = 0.15, c = 0.4, R_L = 30, f = 0.2, R_s = 80, Q = 100$. At this time, the leadership cost of village committees exceeds the income.

Case 2: ESS points $(0,0)$ and $(1,1)$, with parameter assignments satisfying $A_f + B_f > 0, A_v + B_v > 0$, and $B_f < 0$. Let : $a = 0.3,\ b = 0.7, C_f = 5, P = 10,\ W = 1, P_w = 2, R_w = 1,\ d = 0.3,\ S_f = 1, e = 0.3, c = 0.3, R_L = 30, f = 0.3, R_s = 80, Q = 100$.

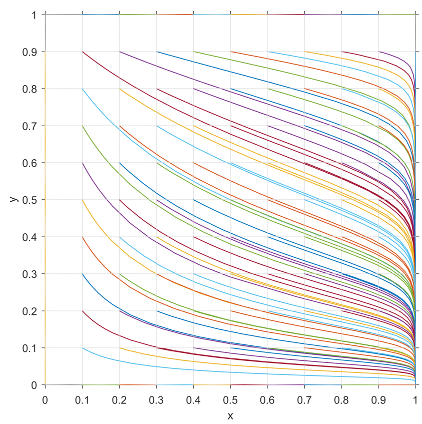

Figure 1: $(1,0)$ is the stable equilibrium point

For regions trapped in the $(1,0)$ dilemma, it is necessary to evolve to $(1,1)$ by increasing the benefits of village committees, which can be achieved by increasing income and income coefficients and reducing costs and cost coefficients. On the basis of Case 1, the cost C_f is reduced, the price P is increased, the leadership cost coefficient c of village committees is reduced, and the benefit coefficient e and technical efficiency b of village committees are increased. Figure 3 shows the simulation results.

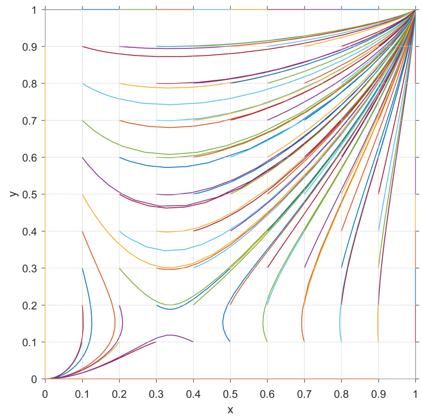

Figure 2: $(0,0)(1,1)$ is the stable equilibrium point

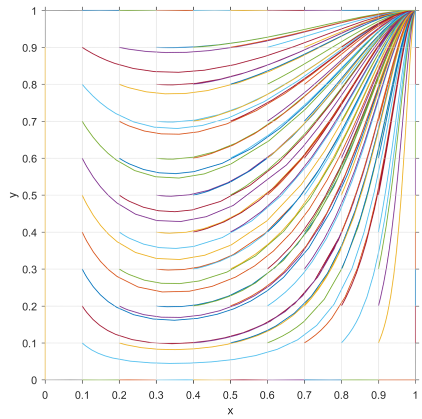

Figure 3: Simulation results of increasing revenue and reducing costs

According to the simulation results, the evolutionary trends of strategy choices in the three cases are consistent with the theoretical research results. Taking the simulation results of Case 2 as the control group, the impact of the game between the two participating subjects is analyzed by changing the values of income and cost-related parameters. The benefit distribution coefficient e is a key factor affecting the income and distribution of both game parties. The impact of e on the game results is explored by changing its value. As shown in Figure 4, when the benefit distribution coefficient is moderate, the two game parties are most likely to reach a cooperative consensus. When $e \in (0.3, 0.7)$, the evolutionary stable point is $(1,1)$; when $e < 0.3$, a result of non-cooperation between both parties may occur; when $e > 0.7$, the evolutionary stability of the two game parties breaks down.

In addition to the income and costs brought by village committees and agricultural producers themselves, there are additional benefits, such as government subsidies for agricultural producers'

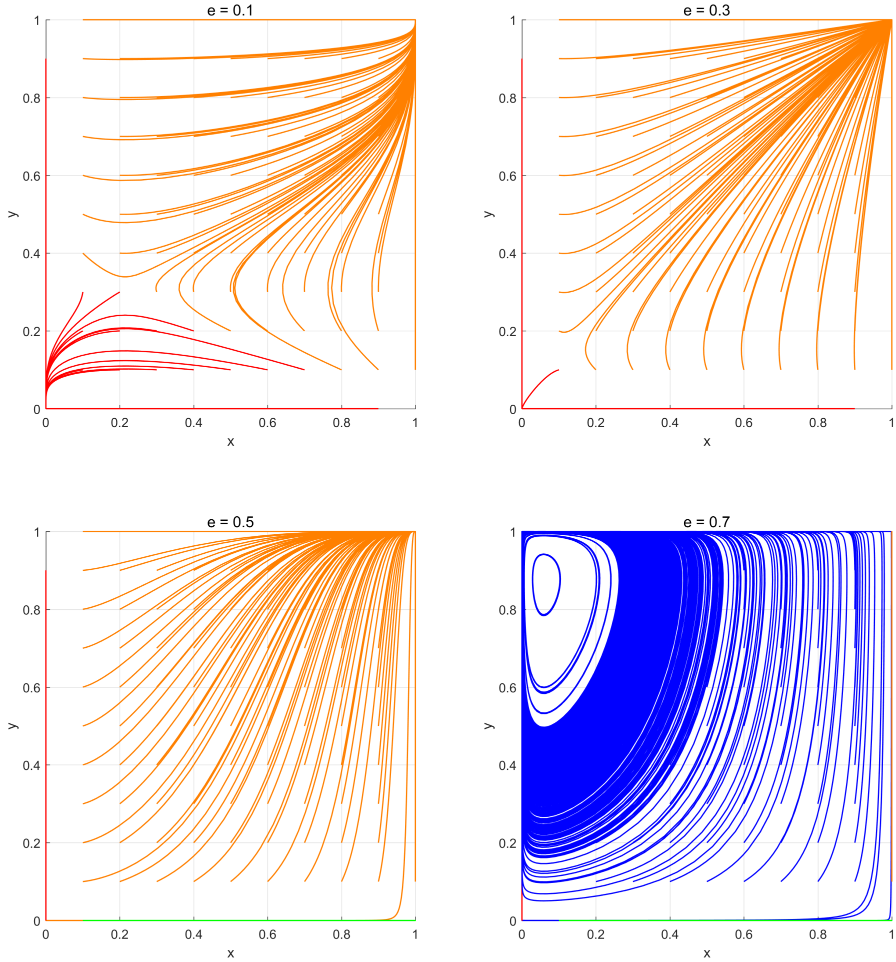

Figure 4: Simulation results of changing benefit distribution

green production and environmental benefits brought to village committees after green production. Agricultural producers are more likely to reach a cooperative consensus with village committees under appropriate subsidies. The simulation results are shown in Figure 5.

4 Conclusion

By constructing and analyzing an evolutionary game model between village committees and agricultural producers, this paper reveals the causes and solutions of the green agricultural production cooperation dilemma from the perspective of micro-motivations. The research shows that the evolutionary stable state of the system is highly dependent on cost-benefit parameters, and simple administrative orders or universal subsidies are difficult to ensure policy effectiveness.

The policy implications of this model are as follows:

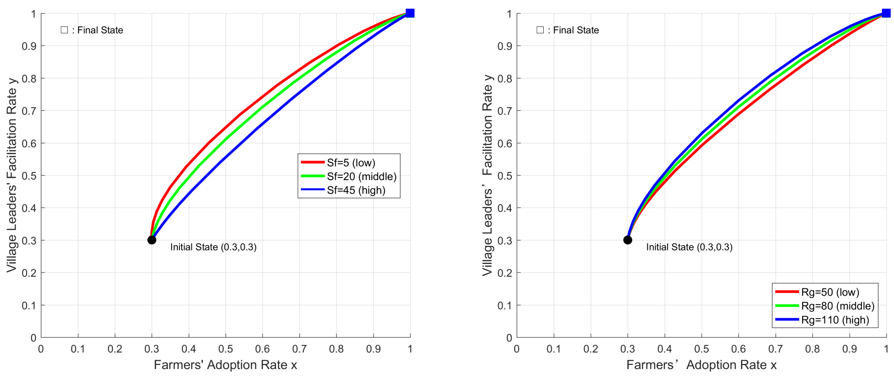

Figure 5: Simulation results for different subsidies and environmental benefits

(1) Precise policies and classified interventions: For regions close to the $(1, 1)$ equilibrium, policies should focus on consolidating benefits, such as building green brands to increase the premium a; for regions trapped in the $(1, 0)$ dilemma, it is necessary to adjust the coefficients of costs and income to make it easier for both parties to reach a cooperative strategy.

(2) Optimize distribution and activate hubs: It is necessary to carefully design an incentive-compatible mechanism for village committees. The double-threshold effect of the benefit distribution coefficient revealed in this study provides a precise lever for policy design. It is recommended that local governments guide village committees to determine a reasonable distribution ratio between e_{min} and e_{max} to achieve incentive compatibility.

(3) Beyond the economy and cultivate capital: The model confirms the significant role of government subsidies (S_f) and environmental synergistic benefits (R_s). It is necessary to provide a reasonable amount of green subsidies to agricultural producers–not the more subsidies, the more green production is promoted–and the greater the environmental synergistic benefits, the more it can drive cooperatio between village committees and agricultural producers. Therefore, in addition to economic levers, policies should also focus on cultivating a sense of identity and honor for green production in rural acquaintance networks, and use social norms to promote behavioral changes.

Future research can embed this model into a "small-world" network to simulate the impact of the distance of social relations on the speed of technology diffusion, making the research conclusions more practically guiding.

Disclaimer (Artificial Intelligence)

This manuscript utilized artificial intelligence (AI) tools during the editorial process for the purpose of language polishing and grammatical revision. The AI was employed to enhance academic expression, improve logical coherence, and correct grammatical errors within the content, which focuses on financial network research. Details of AI usage are as follows:

1. AI Tool: ChatGPT (Version 4o), developed by OpenAI (https://openai.com/).

2. Purpose of Use: The tool was used exclusively for refining academic language and revising grammatical structures in the manuscript. No AI-generated content was directly incorporated into the research findings, data analysis, or original conclusions.

3. Human Oversight: All AI-edited content was thoroughly reviewed, validated, and approved by the authors. The authors assume full responsibility for the accuracy, integrity, and originality of the final published content.

Competing Interests

Authors have declared that no competing interests exist.

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