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Tripartite Game Analysis of Straw Burning Management Considering the Dispersed Locations of Farms

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Abstract

Against the backdrop of the dual carbon strategy and rural revitalization, straw burning poses environmental and carbon emission pressures, while high collection and transportation costs coupled with insufficient policy incentives hinder its effective recycling. By constructing a tripartite evolutionary game model involving farmers, straw collection/storage/utilization enterprises, and local governments—incorporating farmer dispersion factors—this study conducts sensitivity analyses on fixed costs, storage/transportation costs, penalty levels, purchase prices, and subsidy intensity. It evaluates the marginal effects of policy tools on straw recovery efficiency and system stability. Results indicate that both fixed costs and storage/transportation costs influence system evolution, though through distinct mechanisms. Moderate penalties, reasonable prices, and subsidies promote farmer-enterprise coordination, maximizing both straw resource utilization and environmental benefits. Farmer dispersion primarily affects convergence speed without altering the final equilibrium. Overall, the stable equilibrium of the straw collection and transportation system relies more on institutional design and market incentives than on objective spatial factors. Moderate penalties, prices, and subsidy policies can effectively promote tripartite coordination, achieving maximized straw resource utilization and environmental benefits. This provides a theoretical basis for optimizing rural straw management policies and offers guidance for achieving green transformation and sustainable agricultural development.

Keywords: Straw Recycling; Evolutionary Games; Accounting for Farmer Dispersion; Dual Carbon Goals; Rural Green Transition

1. Introduction

Driven by both the dual carbon strategy and rural revitalization, the resource utilization of agricultural waste has become a crucial component in advancing the green transformation of rural areas. Among these, straw—a byproduct of agriculture with massive production and widespread distribution — represents both a potential renewable resource and an environmental burden constraining sustainable agricultural development . For a long time, some farmers have preferred to burn straw on-site due to the lack of efficient collection and storage channels and reasonable economic compensation. While this practice offers short-term convenience, it leads to air pollution, soil degradation, and increased carbon emissions (Liu and Ma, 2023). Taking the water source areas of the South-to-North Water Diversion Project as an example, the highly dispersed locations of farmers' residences and farmland significantly increase the costs of straw collection and transportation. Against this backdrop, the traditional " point-to-area " recycling model faces efficiency challenges. Balancing farmer income, corporate profitability, and government governance objectives has become an urgent practical challenge requiring resolution(Shi et al., 2018).

In recent years, academia and policy makers have conducted multidimensional explorations into the comprehensive utilization of crop residues. Some studies have focused on conversion technologies and energy utilization pathways for straw resources, emphasizing the potential of industrial chain extension and circular economy models in improving rural ecosystems. For instance, Chen (2022) proposed utilization methods including fertilization, fuel production, feed conversion, substrate preparation, and raw material processing; Kang Suoqian et al. (2019) analyzed straw recycling from a circular economy perspective, arguing that systematic recovery of rural straw could propel China's transition from linear resource utilization to circular cascading use ; Li and Song (2018) proposed diversified processing models including biological straw return to fields, straw papermaking, integrated "gas-heat-electricity-fertilizer" production, straw-based edible fungus humus preparation technology, and SRM. While these studies provide crucial theoretical and practical foundations for technological and industrial pathways, their limitations lie in predominantly focusing on process feasibility and industrial prospects, with insufficient consideration of multi-stakeholder behavioral interactions in straw governance.

To address the shortcomings of technology-oriented research, some scholars have turned to game theory and evolutionary game analysis frameworks to reveal how strategic interactions among farmers, enterprises, and governments shape straw management performance. For instance, He et al.(2023) used an evolutionary game model to demonstrate that a dual mechanism of subsidies and penalties can effectively curb farmers' burning tendencies, though its policy effectiveness is highly dependent on collection and storage costs and market price fluctuations. Bai (2024) further discovered that the dispersed locations of farmers significantly amplify cost pressures in the collection and storage process, making enterprises more likely to exit the straw market when lacking long-term policy incentives. These studies highlight the sensitivity of policy outcomes to game-theoretic dynamics, yet often simplify subject relationships into linear games, lacking systematic analysis of the interactions between policy instruments, market conditions, and geographical factors. Concurrently, policy implementation reveals coordination deficiencies: government regulations face fiscal constraints and enforcement delays, corporate collection models lack economies of scale, and individual farmer behaviors exhibit insufficient endogenous alignment with environmental objectives (Yang et al., 2024) .

Overall, while existing literature offers valuable analyses within policy and game-theoretic frameworks, it exhibits three shortcomings: First, research predominantly focuses on the behavioral decisions of individual actors or the evaluation of specific policy effects, lacking systematic modeling of the interactions among farmers, enterprises, and government. Second, existing game studies often assume homogeneity among farmers, failing to reveal how the dispersion of farmer locations affects straw collection costs, governance efficiency, and overall system stability. Third, most models remain theoretical, lacking empirical exploration through numerical simulations to test dynamic evolution and the marginal effects of policies.

To address these shortcomings, this study introduces innovations in three key areas: First, it constructs a tripartite evolutionary game model encompassing farmers, enterprises, and local governments, transcending previous bilateral or single-agent frameworks to comprehensively depict multi-agent interactions under diverse policy and market conditions. Second, it introduces the factor of farmer location dispersion into the straw management game analysis framework for the first time, revealing how this dispersion alters the game equilibrium by increasing collection costs, thereby affecting recycling efficiency and environmental benefits. Third, it employs numerical simulations to test the model's dynamic evolution, quantitatively evaluating the marginal effects of policy instruments—such as subsidies, penalties, and regulations—under different scenarios. This provides a more intuitive demonstration of the effectiveness boundaries and optimization pathways for policy tools. Compared to existing research, this study not only expands the theoretical application boundaries of game theory but also offers more operationally feasible analytical tools at the methodological level, providing more targeted and practical references for policy design.

2. Model Development

2.1. Scenario Description

This study focuses on the governance of straw burning within China's agricultural context, examining the interactive relationships among farmers, straw collection/storage/utilization enterprises, and local governments during the straw recovery process. The dispersed locations of farmers increase the difficulty and cost of straw collection. Enterprises' collection, storage, and utilization activities are influenced by market and policy environments. Meanwhile, governments regulate straw governance outcomes through regulatory and subsidy policies. The interplay of decisions among these three parties determines the efficiency of straw recovery and its environmental benefits. This study aims to reveal the dynamics of straw management within this tripartite interaction, providing insights for developing scientifically sound and effective policies. The strategic relationship among stakeholders is illustrated in Figure 1.

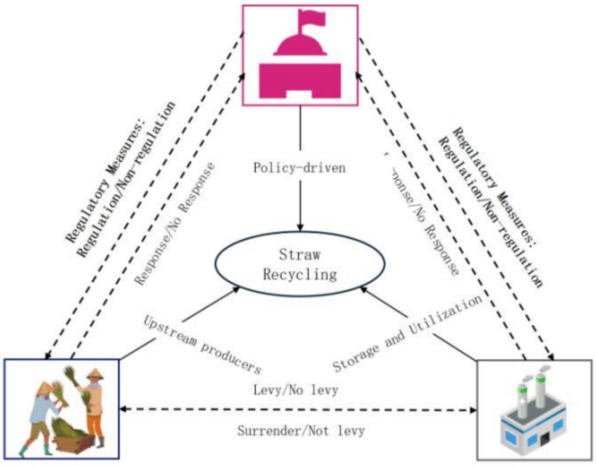

Figure 1. Game relations among stakeholders

2.2. Basic Assumptions

Assumption 1: Farmers' strategy choices are (sell, burn), where the probability of selling is $x \in [0,1]$. Thus, the probability of choosing to burn is $1-x$. The enterprise's strategy choices are (taxation, no taxation), with the probability of choosing taxation set as $y \in [0,1]$. The probability of choosing no taxation is $1-y$. The local government's strategy choices are (regulation, no regulation), with the probability of choosing regulation set as $z \in [0,1]$. The probability of choosing no regulation is $1-z$.

Assumption 2: Farmers possess a certain quantity of disposable straw Q annually. Collection incurs a unit collection cost C_f, which increases due to the farmer's location dispersion factor θ. When farmers choose to burn straw, they receive a direct benefit R per unit of burned straw. However, if the government imposes regulatory measures, they face a penalty amount F. If farmers choose to sell straw to enterprises, they receive a unit purchase price P_u and government subsidy S_1, but must deduct collection costs and location dispersion costs. Thus, farmers' decision benefits primarily depend on balancing collection costs, burning benefits, selling prices, and government subsidies, while constrained by the intensity of government regulation.

Assumption 3: Enterprises' decisions on straw collection and storage are driven by the following dedicated parameters: unit purchase price paid to farmers P_u, transportation cost C_t, storage cost C_S, fixed investment cost C_n for participation, alternative business revenue L if not participating, long-term policy opportunity cost E lost by non-participation, and government subsidy per unit S_2. Considering the impact of supply dispersion: Transportation cost C_t increases monotonically with the farmer location dispersion factor θ. Furthermore, storage cost C_S also rises when purchase-sales scale or collection frequency decreases due to dispersion. To control these dispersion-related costs, enterprises may adopt strategies such as lowering purchase prices, raising acquisition thresholds, or reducing collection frequency. They tend to prioritize stable cooperation with village collectives or farmer organizations that exhibit "regional concentration and strong cooperative willingness" to minimize transportation costs.

During processing, enterprises convert raw straw into products at a conversion rate η and sell them at market price P_s.

Assumption 4: Local governments incur implementation costs C_g related to governance and oversight when enforcing regulations, while gaining reputational benefits M from regulatory actions. Under regulation, governments must provide subsidies S_1 and S_2 to farmers and enterprises respectively, while enhancing policy enforcement through penalties F for farmers engaging in burning. If the government refrains from regulation, it may incur environmental benefit losses K due to ineffective straw collection and storage, and face fiscal penalties N from higher-level governments. Thus, in choosing between regulation and non-regulation, local governments weigh regulatory costs and subsidy expenditures against reputational gains, environmental protection, and fiscal constraints.

Based on the assumptions outlined above, the payoff matrix for the three-party game can be derived as shown in Table 1.

Table 1. Payoff Matrix for the Three-Party Game

Strategy	Farmers	Enterprises	Local Governments
x, y, z	$P_u+S_1-C_f\theta$	$P_s\eta Q-P_uQ-C_t\theta-C_s-C_n+S_2$	$M-C_g-S_1-S_2$
$x, y, 1-z$	$P_u-C_f\theta$	$P_s\eta Q-P_uQ-C_t\theta-C_s-C_n$	$-K-N$
$x, 1-y, z$	$-C_f\theta$	$-E+L$	$M-C_g-S_1-S_2$
$x, 1-y, 1-z$	$-C_f\theta$	L	$-K-N$
$1-x, y, z$	$R-F$	$-C_n+S_2$	$M-C_g-S_1-S_2+F$
$1-x, y, 1-z$	R	$-C_n$	$-K-N$
$1-x, 1-y, z$	$R-F$	$-E+L$	$M-C_g-S_1-S_2+F$
$1-x, 1-y, 1-z$	R	L	$-K-N$

2.3. Model Solving and Analysis

2.3.1. Analysis of Farmers' Evolutionarily Stable Strategies

Expected payoff V_{11} for selling, expected payoff V_{12} for not selling, average expected payoff V_1, replicating dynamic equation F(x).

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$$\begin{cases} V_{11} = y(C_f Q + P_u Q)(z-1) - yz(C_f Q - QS_1 + P_u Q) - z(QS_1 - C_f Q)(y-1) - C_f Q(y-1)(z-1) \\ V_{12} = yz(R-F) - Ry(z-1) + R(y-1)(z-1) - z(R-F)(y-1) \\ V_1 = \mathrm{x}V_{11} + (1-x)V_{12} \end{cases}$$

$$F(x) = -x(x-1)\left(-R - C_f Q + yP_u Q + zQS_1 + zF\right)$$
$$F'(x) = (2x-1)\left(R + C_f Q - P_u Q y - QS_1 z - Fz\right)$$

Proposition 1: There exists a threshold y* such that when y > y*, farmers' stable strategy is to sell straw; when y < y*, farmers' stable strategy is to burn straw; when y = y*, their stable strategy cannot be determined.

Proof: Let $G(x) = R + C_f Q - P_u Q y - QS_1 z - Fz$, $\partial G(x)/\partial y < 0$. Thus, G(x) is a decreasing function of y. When y > y*, G(x) < 0. Since F(x) | $_{x=1}$ = 0 and F'(x) | $_{x=1}$ < 0, x = 1 is stable. When y < y*, G(x) > 0, F(x)| $_{x=0}$=0, and F'(x) | $_{x=0}$ < 0, thus x = 0 is stable; when y = y*, F(x) = 0 and F'(x) = 0, making the stable strategy undeterminable. Q.E.D.

Proposition 1 indicates that in the three-party game involving farmers, enterprises, and the government, whether enterprises collect straw directly determines farmers' stable strategy. When enterprises prefer not to collect straw (y < y*), farmers find it difficult to gain benefits even if they choose to sell straw, while incurring transportation and opportunity costs. Thus, they are more inclined to choose straw burning as their stable strategy. Conversely, when enterprises prefer to collect straw (y>y*), farmers gain direct economic benefits from selling straw and may receive government subsidies or avoid environmental penalties. In this scenario, selling straw becomes the evolutionary stable strategy. When enterprises are at the critical point (y=y*), the stable strategy becomes uncertain, with outcomes heavily influenced by the strength of government intent z. If the government intensifies regulation against straw burning or increases subsidies for straw delivery, farmers are more likely to shift from burning to delivery. The phase diagram illustrating farmers' strategy choices is shown in Figure 2.

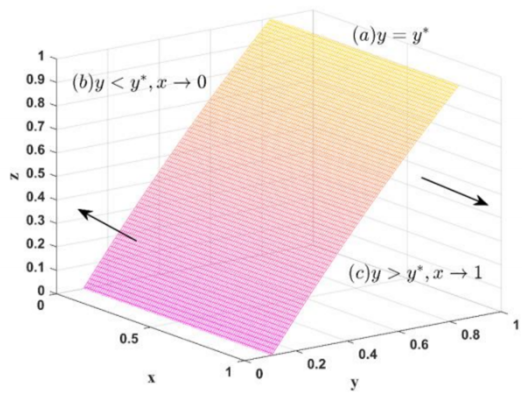

Figure 2. Dynamic Evolution Phase Diagram of Farmer Strategy Selection

2.3.2. Analysis of Evolutionary Stable Strategies for Enterprises

Expected payoff of choosing to pay taxes V_{21}, expected payoff of choosing not to pay taxes V_{22}, average expected payoff V_2, replicating dynamic equation F(y).

$$\begin{cases} V_{21} = (C_n + QS_2)(x-1)(z-1) - z(C_n + QS_2)(x-1) - \\ \quad x(z-1)(C_n - C_s - C_t\theta + P_sQ\eta + P_uQ) \\ \quad + xz(C_n - C_s + QS_2 - C_t\theta + P_sQ\eta + P_uQ), \\ V_{22} = x(E-L)(z-1) + z(E-L)(x-1) - (E-L)(x-1)(z-1) - xz(E-L), \\ V_2 = yV_{21} + (1-y)V_{22} \end{cases}$$

$$F(y) = -y(y-1)\left(C_n + E - L + QS_2 - C_s x - P_u Q x - QS_2 x - C_t \theta x + P_s Q \eta x + QS_2 xz\right)$$

$$F'(y) = -(2y-1)\left(C_n + E - L + QS_2 - C_s x - P_u Q x - QS_2 x - C_t \theta x + P_s Q \eta x + QS_2 xz\right)$$

Proposition 2: There exists a threshold z*. When z > z*, the stable strategy for firms is to collect straw; when z < z*, the stable strategy is to refrain from collecting straw; when z = z*, the stable strategy cannot be determined.

Proof: Let $G(y) = C_n + E - L + QS_2 - C_s x - P_u Q x - QS_2 x - C_t \theta x + P_s Q \eta x + QS_2 xz$, $\partial G(y)/\partial z > 0$.Thus, G(y) is an increasing function of z. When z > z*, G(y) > 0. Since $F(y)\,|_{y=1} = 0$ and $F'(y)\,|_{y=1} < 0$, y = 1 is stable. When z < z*, G(y) < 0, $F(y)\,|_{y=0} = 0$ and $F'(y)\,|_{y=0} < 0$, thus y = 0 is stable; when z = z*, F(y) = 0 and F′(y) = 0, making the stable strategy indeterminate. Q.E.D.

Proposition 2 indicates that the government's regulatory intensity decisively influences the decision-making of straw collection and storage enterprises. When the government adopts a lower regulatory intensity (z < z*), enterprises face difficulties in obtaining additional subsidies or advantages through government policies even if they engage in straw collection, while simultaneously bearing the operational costs of collection, transportation, and processing. Under such circumstances, enterprises are more inclined to refrain from collecting straw to avoid additional economic burdens. Conversely, when government regulation is stringent (z>z*), it signifies increased penalties for burning and proactive subsidy policies. Enterprises refusing to collect straw may face policy risks and social pressure, whereas collecting straw not only secures government subsidies but also fosters stable transactional relationships with farmers. Thus, straw collection becomes the enterprises' evolutionarily stable strategy. When government regulation is at the critical threshold (z=z*), the stable strategy becomes indeterminate, with outcomes influenced by external factors such as farmers' willingness to sell and market purchase prices. The phase diagram illustrating the firm's strategy selection is shown in Figure 3.

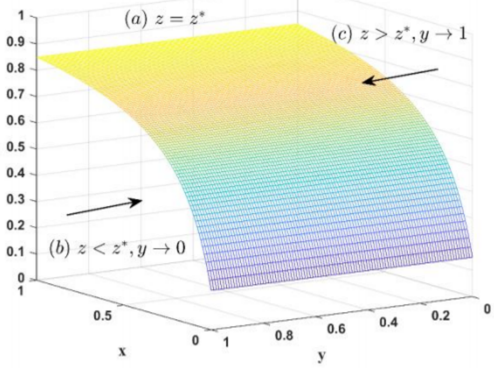

Figure 3: Dynamic Evolution Phase Diagram of Corporate Strategy Selection

2.3.3. Analysis of Evolutionary Stable Strategies for Local Governments

Expected payoff of choosing regulation V_{31}, expected payoff of choosing non-regulation V_{32}, average expected payoff V_3, replicating dynamic equation F(z).

$$\begin{cases} V_{31} = x(y-1)(C_g - M + QS_1) + y(x-1)(C_g - M + QS_2 - F\alpha) - xy(C_g - M + QS_1 + QS_2) \\ \qquad -(x-1)(y-1)(C_g + K - M - F\alpha) \\ V_{32} = Nx(y-1) - Nxy - (x-1)(y-1)(K+N) + Ny(x-1) \\ V_3 = zV_{31} + (1-z)V_{32} \end{cases}$$

$$F(z) = z(z-1)\left(C_g - M - N - F + QS_1x + QS_2y + Fx\right)$$

$$F'(z) = (2z-1)\left(C_g - M - N - F + QS_1x + QS_2y + Fx\right)$$

Proposition 3: There exists a threshold x* such that when x > x*, the government's stable strategy is to choose non-regulation; when x < x*, the government's stable strategy is to choose regulation; when x = x*, its stable strategy cannot be determined.

Proof: Let $G(z) = C_g - M - N - F + QS_1x + QS_2y + Fx$, $\partial G(z)/\partial x < 0$. Thus, G(z) is a decreasing function of x. When x > x*, G(z) < 0. Since $F(z)|_{z=0} = 0$ and $F'(z)|_{z=0} < 0$, z = 0 is stable. When x < x*, G(z) > 0, $F(z)|_{z=1} = 0$, and $F'(z)|_{z=1} < 0$, thus z = 1 is stable; When x = x*, F(z) = 0 and F′(z) = 0, making the stability strategy indeterminate. Q.E.D.

Proposition 3 indicates that farmers' behavioral preferences directly influence the government's regulatory choices. When farmers exhibit high motivation (x > x*), most farmers tend to sell straw, enabling straw resource utilization to be largely achieved through market mechanisms. Even without strict government regulation, satisfactory environmental governance outcomes can be maintained. In this scenario, to avoid additional regulatory costs and administrative resource consumption, the government is more inclined to choose non-regulation as a stable strategy. Conversely, when farmer willingness is low (x < x*), farmers are more likely to adopt straw burning strategies, causing environmental pollution and resource waste. Government inaction would not only degrade environmental quality but also risk triggering public pressure and governance accountability failures. Thus, regulation becomes the preferred evolutionary stable strategy. When farmer willingness is at the critical threshold (x=x*), the stable strategy becomes indeterminate. The final choice may be influenced by external factors such as corporate enthusiasm for straw collection and storage, policy implementation costs, and public concern for environmental protection. The phase diagram illustrating government strategy selection is shown in Figure 4.

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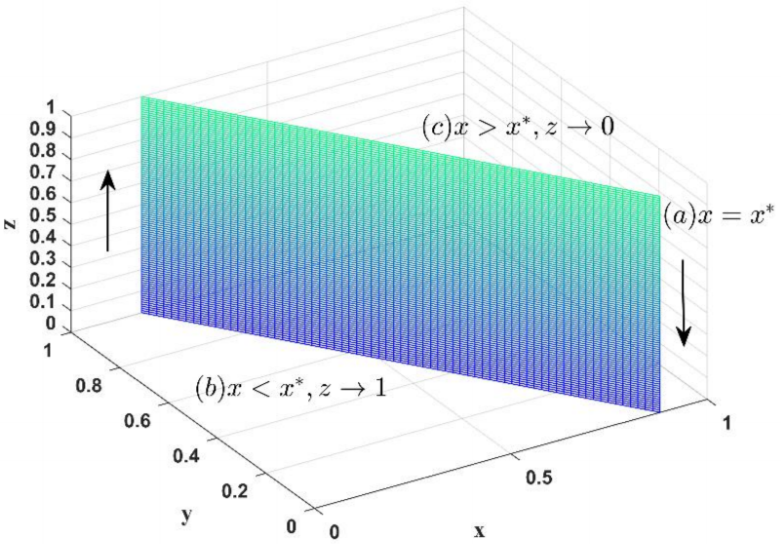

Figure 4. Dynamic Evolution Phase Diagram of Local Government Strategy Selection

2.3.4. Analysis of Evolutionary Stable Strategies in Three-Party Game Systems

The replicator equation describes the evolutionary dynamics of strategies within a population, and its single equilibrium solution does not necessarily correspond to the evolutionarily stable state of the entire system. According to (Friedman,1991) , the stability of equilibrium points in multi-party games must be assessed in conjunction with the overall system's dynamic characteristics. Therefore, in a three-party interaction scenario, constructing a joint replicator dynamics system and conducting local stability analysis of each equilibrium point via the Jacobian matrix is necessary for accurately analyzing the system's evolutionary trends. The Jacobian matrix for this system is as follows:

$$J_{(x,y,z)} = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix}$$

According to Lyapunov's First Law (Weinstein,1986), stable equilibria in multi-agent evolutionary games typically correspond to strict Nash equilibria, and strict Nash equilibria must be pure strategy solutions. In this system, calculations identified a total of 8 pure strategy equilibrium points, with their corresponding eigenvalues shown in Table 2. Only when the real parts of all eigenvalues at an equilibrium point are negative does that point possess local asymptotic stability, thereby qualifying as an evolutionary stable strategy (ESS) for the system.

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Table 2. Evolutionary Game Equilibrium Points and Eigenvalues

Equilibrium Point	Eigenvalue 1	Eigenvalue 2	Eigenvalue 3
(0 , 0 , 0)	$R-C_fQ$	$C_n+E-L+QS_2$	$F-C_g+M+N$
(0 , 1 , 0)	P_uQ-R-C_fQ	$L-E-C_n-QS_2$	$F-C_g+M+N-QS_2$
(0 , 0 , 1)	$F-R+QS_1-C_fQ$	$C_n+E-L+QS_2$	$C_g-F-M-N$
(0 , 1 , 1)	$F-R+P_uQ+QS_1-C_fQ$	$L-E-C_n-QS_2$	$C_g-F-M-N+QS_2$
(1 , 0 , 0)	$R+C_fQ$	$C_n-C_s+E-L-P_uQ-C_t\theta+P_sQ\eta$	$M-C_g+N-QS_1$
(1 , 1 , 0)	$R-P_uQ+C_fQ$	$C_s-C_n-E+L+P_uQ+C_t\theta-P_sQ\eta$	$M-C_g+N-QS_1-QS_2$
(1 , 0 , 1)	$R-F-QS_1+C_fQ$	$C_n-C_s+E-L-P_uQ+QS_2-C_t\theta+P_sQ\eta$	$C_g-M-N+QS_1$
(1 , 1 , 1)	$R-F-P_uQ-QS_1+C_fQ$	$C_s-C_n-E+L+P_uQ-QS_2+C_t\theta-P_sQ\eta$	$C_g-M-N+QS_1+QS_2$

3. Numerical Simulation Analysis

Based on the practical significance of the cost-benefit trade-offs among farmers, enterprises, and local governments in their tripartite interactions, numerical simulations were conducted using MATLAB R2021a software. Under the assumption of stability, parameter values were assigned as shown in Table 3 below, incorporating practical considerations and relevant literature(Qin et al., 2023).

Table 3. Assignment of parameters

Parameter	Assignment	Parameter	Assignment	Parameter	Assignment	Parameter	Assignment	Parameter	Assignment	Parameter	Assignment
C_t	10	C_f	0.3	θ	0.5	R	1	P_u	0.15	K	6
C_S	8	η	0.5	P_s	6	C_n	6	L	4.5	E	4
S_1	0.2	S_2	0.8	F	0.8	M	5	N	6	C_g	0.5

3.1. Initial Path

To test the stability and effectiveness of the system evolution, the array from Table 3 was substituted into the model for simulation. Under the combination strategy of the initial intentions of the three entities, simulation results were obtained after 50 evolutionary iterations of the three participating entities. The results are shown in Figure 5. As shown in the figure, at this point, the system exhibits only one evolutionarily stable equilibrium combination (sale, collection, regulation). The simulation results align with the conclusions drawn from the scenario analysis. This consistency demonstrates that the simulation findings and the stability analysis of the three-party evolutionary strategies share consistent conclusions and possess practical validity.

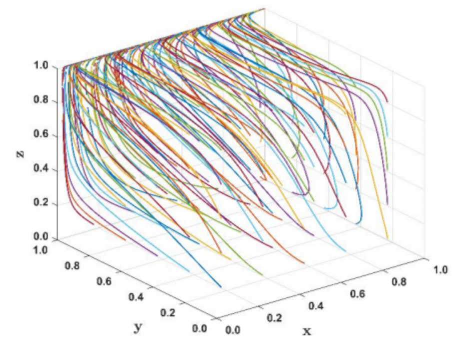

Figure 5. The influence of the initial intention of each subject on the evolution path

3.2. Sensitivity Analysis

3.2.1. Impact of Fixed Costs and Storage Costs on the Evolutionary Game System

Figure 6 illustrates the strategy evolution characteristics of the straw collection and transportation system under fixed input costs C_n and storage costs C_S. Results indicate that when fixed costs remain low, enterprises incur lower marginal collection costs. Collection firms can establish scaled "collection-transportation-storage-utilization" chains with minimal investment, leading the system to converge toward a stable equilibrium: farmers selling, enterprises collecting, and government regulating. As fixed costs rise to medium-high levels, convergence slows significantly but the system still achieves stability.

In contrast, storage cost C_S exhibits a distinct mechanism in shaping system evolution. Fixed cost C_n represents a non-recoverable, upfront entry cost borne by farmers during sales. Storage cost C_S, however, manifests as a variable cost continuously incurred by enterprises during collection and storage. When C_S is low, the tripartite game smoothly achieves a cooperative equilibrium, leading the system toward stability. However, once C_S exceeds a certain threshold, even if farmers retain their willingness to sell, enterprises gradually reduce their procurement scale due to sustained cost pressures. The system then undergoes a dynamic evolution from full coordination to partial coordination and eventually withdrawal.

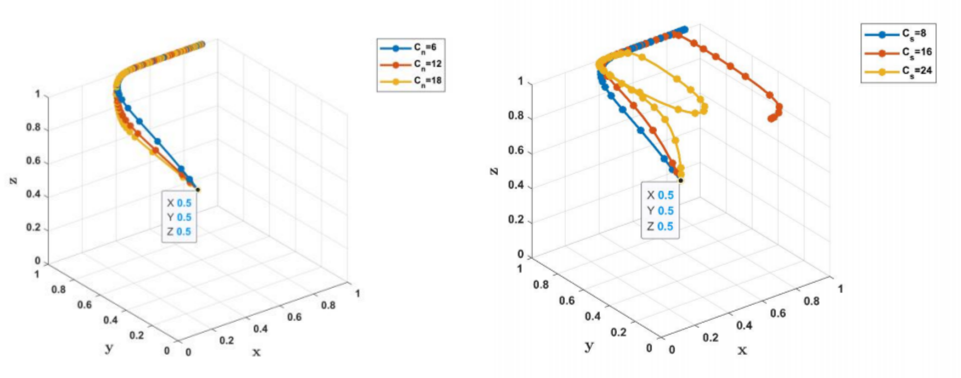

Figure 6. Impact of Different Costs on Evolutionary Game Systems

3.2.2. Impact of Penalty Levels on Evolutionary Game Systems

Figure 7 illustrates the strategic evolution outcomes of the straw collection and transportation system under varying penalty levels. When no penalties are imposed, the system ultimately stabilizes at (0, 1, 1), where farmers refuse to sell straw and opt for burning instead. In this scenario, the absence of external constraints and punishment mechanisms diminishes farmers' willingness to sell. As penalty levels increase, the system's equilibrium gradually shifts toward the state (1, 1, 1), indicating that moderate penalties significantly enhance farmers' motivation to sell. With strengthened farmer willingness, enterprises also become more inclined to participate in collection and storage under government regulatory pressure and cost constraints, achieving coordination. Further increases in penalty levels accelerate the evolutionary system's convergence toward a stable state.

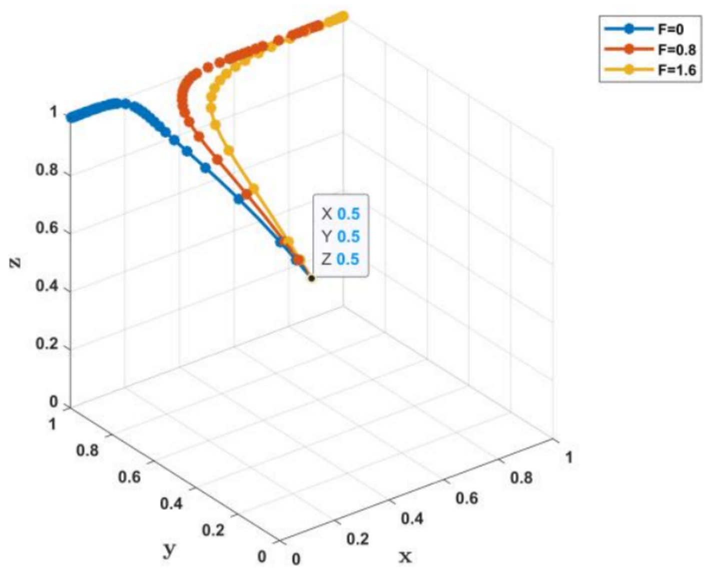

Figure 7. Impact of Different Penalty Levels on the Evolutionary Game System

3.2.3. The Impact of Unit Purchase Price on Evolutionary Game Systems

Figure 8 illustrates the strategic evolution outcomes of the straw collection and transportation system under varying unit purchase price levels. When the purchase price is low, the game system ultimately converges to a stable state (1, 1, 1) where farmers are unwilling to sell and enterprises refrain from collecting — a non-cooperative equilibrium indicating that price signals fail to sufficiently incentivize collaboration between farmers and enterprises. As the purchase price rises to a moderate level, the system's equilibrium shifts to a state (1, 0, 1) where farmers sell, government regulations are enforced, but enterprises remain cautiously engaged. At this point, due to relatively high collection and transportation costs, price incentives are still insufficient to fully drive enterprises to undertake large-scale collection. When purchase prices further rise to high levels, the system fails to converge to a stable equilibrium, manifesting as prolonged, fluctuating adjustments in the strategies of all actors. This outcome demonstrates that while excessively high prices boost farmers' willingness to sell, enterprises struggle to maintain stable profits due to prohibitively high acquisition costs, ultimately destabilizing the system.

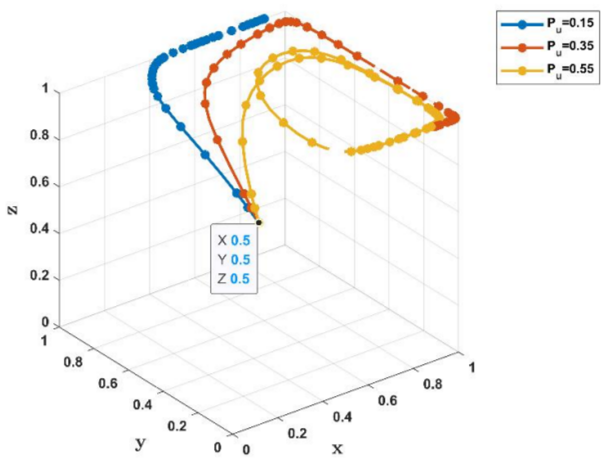

Figure 8. Impact of Different Unit Purchase Prices on the Evolutionary Game System

3.2.4. Impact of Subsidy Levels on Evolutionary Game Systems

Figure 9 illustrates the strategic evolution of the straw collection and transportation system under varying subsidy levels, where S_1 and S_2 represent subsidies provided by local governments to farmers and enterprises, respectively. For farmers, without subsidies, the lack of external incentives leads them to prefer burning, causing the system to ultimately evolve toward (0, 1, 1) . As subsidy levels gradually increase, farmers' willingness to sell straw grows, shifting the system's equilibrium toward (1, 1, 1) . However, when subsidies reach their maximum level, the system cannot stabilize because local governments cannot sustain such high payments.

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For enterprises, without government subsidies, they cannot profit from straw collection and thus refrain from collection efforts. Farmers, lacking sales channels, also choose burning, preventing the system from stabilizing. As subsidies reached a moderate level, collection and transportation cost pressures eased, and the system began to stabilize at (1, 1, 1). When subsidies to enterprises reached their maximum, farmers, guided by fairness theory, reduced their willingness to sell. Local governments, unable to sustain excessively large subsidies, began to opt for deregulation, shifting the system's equilibrium point to (0, 1, 0).

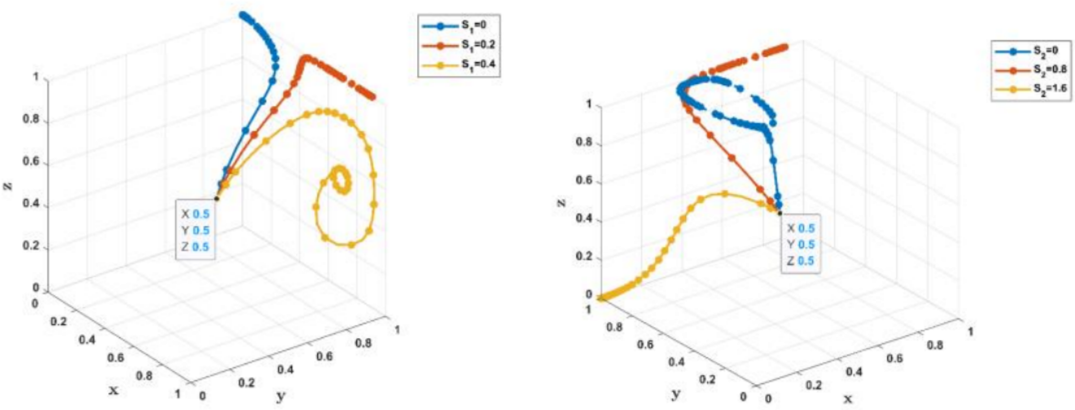

Figure 9. Impact of Different Subsidy Levels on the Evolutionary Game System

3.2.5. Impact of Farm Location Dispersion Factor on Evolutionary Game Systems

Figure 10 illustrates the strategic evolution of the straw collection and transportation system as a function of the dispersion factor of farm locations. When the dispersion factor is low — indicating concentrated farm locations — the three stakeholders can reach consensus relatively quickly, and the system rapidly converges to a stable state (1, 1, 1). As the dispersion factor gradually increases — reflecting less concentrated or highly dispersed farmer locations — the system evolution time lengthens. However, it ultimately converges to the same stable state, with the equilibrium point remaining unchanged. This counterintuitive phenomenon can be explained through economic mechanisms. While dispersed farm locations increase transportation radii and collection costs, these additional expenses can often be partially internalized through government subsidies and policy regulations within the three-party game. This mitigates their impact on the system equilibrium. Consequently, the key to policy design lies in how to offset geographical disadvantages through subsidies, regulations, and price signals, enabling stable coordination across different regions under institutional arrangements.

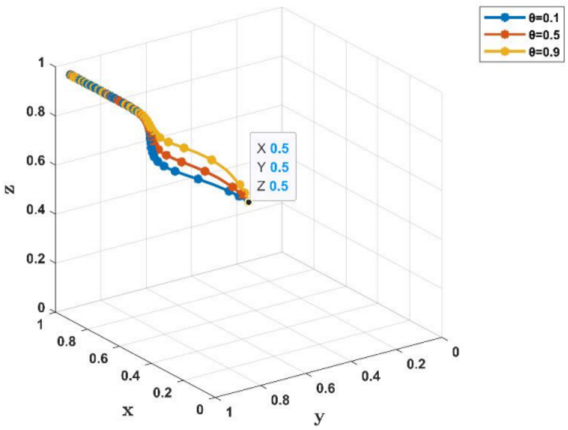

Figure 10. Impact of Different Farm Location Dispersion Factors on the Evolutionary Game System

4. Conclusions

4.1. Discussion

This study not only enriches the theoretical framework for game analysis in straw management but also provides more targeted evidence for policy formulation, emphasizing the pivotal role of policy instruments in achieving multi-stakeholder coordination and rural green transformation. Findings indicate that policy instruments such as subsidies, penalties, and regulations exhibit significantly differentiated marginal effects across different market and geographic contexts. This not only reveals the complexity of straw management but also offers insights for exploring more adaptive governance models.

From a broader sustainable development perspective, the study's findings align closely with the "dual carbon" strategy, green agricultural development, and circular economy initiatives. Straw management transcends mere agricultural waste disposal; it constitutes a systemic endeavor encompassing energy substitution, carbon reduction, and rural ecological revitalization. By unraveling the interactive mechanisms among farmers, enterprises, and governments, this research provides theoretical support for achieving policy-behavior synergy under conditions of local fiscal constraints, farmer dispersion, and market uncertainty. This perspective resonates with international academic discourse and policy practices. For instance, the European Union's Common Agricultural Policy (CAP) introduced "green direct payments" to incentivize eco-friendly farming practices and residue management. In India, Punjab and Haryana states enacted straw burning bans and subsidized harvesting equipment to curb straw burning, yet limited policy effectiveness persists due to absent long-term incentives. The United Nations Sustainable Development Goals (SDGs) explicitly address issues like "Responsible Consumption and Production" and "Climate Action," emphasizing the contribution of agricultural waste resource utilization to global sustainable development. Thus, this research not only serves domestic policy needs but also offers insights for international sustainable development governance frameworks.

Future research may expand in the following directions:

First, introduce dynamic and phased policy tools to explore institutional adaptive adjustments across different time scales and their long-term impacts on system evolution. Dynamic policy design not only flexibly responds to market fluctuations and farmer behavior changes but also provides theoretical support for policy sustainability and resilience.

Second, calibrate and validate model parameters using regional empirical data to enhance the practical interpretability and operational applicability of research conclusions. This not only tests the model's extrapolation validity but also provides local governments with more targeted policy design references.

Third, incorporate external institutional factors such as emerging mechanisms like carbon trading, green finance, and rural energy substitution to examine their long-term incentive effects and cross-sectoral synergies in straw management. This expansion will facilitate examining straw management within the broader framework of green development and energy transition.

Fourth, conduct cross-regional comparative studies to reveal differentiated mechanisms of straw management across plains, hills, and mountainous areas. This addresses the “tailored to local conditions” requirement in sustainable development policies, providing theoretical and practical foundations for regionally differentiated policy design.

Overall, this study not only expands the application boundaries of game theory in agricultural environmental governance but also offers new perspectives for policy design within the context of sustainable development. By emphasizing the dynamic analysis of the interaction between farmer dispersion, cost constraints, and policy instruments, this research provides theoretical contributions and practical insights into achieving a balance among policy effectiveness, social equity, and ecological sustainability during the agricultural green transition.

4.2. Summary and Recommendations

To address the comprehensive utilization and management of agricultural straw collection and transportation in rural areas, this study constructs a tripartite evolutionary game model involving farmers, straw collection/storage/utilization enterprises, and local governments. For the first time, it incorporates the spatial dispersion of farmers into the analytical framework. Through numerical simulation, the model analyzes how policy instruments, market conditions, and spatial factors influence system evolution. The findings reveal:

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First, while both fixed costs and storage/transportation costs increase system burdens, their mechanisms differ significantly. Fixed costs, acting as one-time entry barriers, primarily influence evolutionary speed, whereas storage/transportation costs, as ongoing burdens, may lead to gradual degradation of tripartite coordination. Second, penalty levels within an appropriate range effectively incentivize farmers to sell straw and encourage enterprises to participate in straw collection. However, penalties that are too low or too high may weaken the policy's binding effect. Third, purchase prices exhibit a pronounced threshold effect: low levels fail to generate incentives, moderate levels promote system coordination, while high levels destabilize the system due to cost-benefit imbalances. Fourth, subsidy policies provide positive incentives for both farmers and enterprises. However, excessive subsidies not only intensify fiscal pressures but may also trigger farmers' perceptions of unfairness, thereby disrupting system equilibrium. Finally, the dispersion factor of farmers' locations primarily affects the convergence speed of the system without altering the final equilibrium state. This indicates that while geographical distribution increases collection and transportation difficulties, it is not a decisive constraint under reasonable policy regulation. Overall, the equilibrium of the straw collection and transportation system relies more on policy tools and market conditions than on objective geographical factors, highlighting the critical role of institutional design in achieving green recycling and multi-party coordination.

Based on these findings, this study proposes the following policy recommendations: First, reduce fixed and storage/transportation costs through scaled operations and technological innovation to enhance system efficiency. Scaling and digital management minimize redundant transport and collection losses, alleviating cost pressures from farmer dispersion. Second, establish a reasonable penalty mechanism that curbs opportunistic behavior while avoiding counterproductive over-punishment, thereby ensuring active participation from both farmers and enterprises. Third, scientifically define the price range for straw acquisition to strike a balance between insufficient incentives at low levels and instability at high levels, ensuring price signals effectively guide market participants' behavior. Fourth, implement differentiated subsidy policies that balance the incentive effects for farmers and enterprises with fiscal sustainability, avoiding excessive benefits for either party that could raise fairness concerns. Fifth, optimize straw collection and transportation systems based on local conditions. In areas with dispersed farmer populations, mitigate geographical disadvantages through improved infrastructure, information management, and policy compensation to ensure the universality and fairness of institutional arrangements. Through these measures, synergistic optimization of straw recovery and utilization can be achieved while balancing environmental benefits, economic efficiency, and policy feasibility.

Author Contributions:

Conceptualization,M.C. and H.Z.; methodology, M.C. and H.Z.; software,H.Z.; validation, M. Z.; project administration,M.C.; funding acquisition, M.C. All authors have read and agreed to the published version of the manuscript. Please turn to the credit taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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Conflict of Interest:

The authors declare no conflict of interest.

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