

Article

Exploring Sustainable Agricultural Supply Chain Financing: Risk Sharing in Three-Party Game Theory

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Abstract

Agricultural supply chain finance plays a vital role in alleviating the financing constraints faced by agricultural business entities in developing countries and promoting inclusive and sustainable agricultural development. However, issues such as high operational risks, weak credit foundations, and insufficient risk safeguards among stakeholders in the agricultural supply chain have hindered its long-term stability. From the perspective of cooperative sustainability, this study develops a tripartite evolutionary game model involving agricultural enterprises, financial institutions, and farmers to explore the behavioral dynamics and evolutionary stability of their strategies. Using the Fuping mushroom supply chain as a case, Matlab-based simulation analysis reveals that the three-party strategy combinations failed to converge to an evolutionarily stable strategy (ESS) but instead exhibited dynamic changes characterized by non-periodic oscillations. Sensitivity analysis further demonstrates that farmers' credit behavior is a key determinant of the sustainable operation of the supply chain financing system, while enhancing enterprises' guarantee willingness can effectively mitigate farmers' default risk. Moreover, stronger cooperative relationships between enterprises and farmers improve the overall resilience and stability of the system. The findings provide practical insights for building sustainable and resilient agricultural financial ecosystems, emphasizing the need to introduce third-party guarantee institutions, strengthen credit constraint systems, and design incentive mechanisms that promote long-term cooperation among stakeholders.



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1. Introduction

As a fundamental sector of the national economy, agriculture plays an irreplaceable role in ensuring food security, maintaining social stability, and enhancing ecological resilience. Especially in some underdeveloped countries, agriculture contributes over 25% to the Gross Domestic Product (GDP) [Source: <https://www.worldbank.org/en/topic/agriculture/overview#1> (accessed on 1 November 2025)]. However, despite the important role of agriculture in the economic system, many agricultural operators worldwide face severe financing constraints due to long planting cycles, high production risks, and limited collateral [1,2]. For example, by 2024, the unmet financing needs of small farmers in sub-Saharan Africa, South Asia, Southeast Asia, and Latin America reached USD 170 billion [Source: <https://www.ifad.org/en//initiatives/agri-business-capital-fund> (accessed on 1 November 2025)]. This funding difficulty not only weakens the stability and

risk resistance of the agricultural production system but also poses a huge obstacle to the transformation of agricultural modernization and the achievement of sustainable development goals. Therefore, alleviating agricultural financing constraints and improving the agricultural financial support system have become key issues in promoting high-quality agricultural development.

Agricultural industry chain financing, as an innovative financial model based on supply chain transaction relationships, is widely regarded as an important way to overcome agricultural financing exclusion and promote inclusive growth [3]. By embedding financial services into the agricultural industry chain, agricultural supply chain financing promotes efficient allocation of agricultural resources and factor synergy [4]. According to data from the People's Bank of China, as of the end of February 2025, the balance of agricultural loans was CNY 51.88 trillion, a year-on-year increase of 8.9% [Source: https://www.gov.cn/lianbo/bumen/202504/content_7019984.htm (accessed on 1 November 2025)]. Rural financial service institutions in various regions actively carry out various agricultural industry chain financing innovations. For example, the Agricultural Bank of China has launched the “Beef Cattle Special Industry Loan” and “Potato Loan”, while the China Construction Bank has initiated financing products such as the “Jiyang Cloud Loan” and “Gannan Navel Orange Loan”, covering multiple fields such as grain, fruits and vegetables, animal husbandry, aquaculture, and tobacco and tea, effectively promoting the coordinated development of the upstream and downstream of the agricultural industry chain. However, despite the continuous deepening of financial innovation, the financing costs of agricultural operators are still generally 2 to 3 percentage points higher than those in the industrial sector, and the penetration rate of supply chain finance is less than 30% [5]. Agricultural business entities generally face high operational risks, weak credit foundations, and insufficient risk protection [6], resulting in fragile financing cooperation relationships in the industrial chain and difficulty in the long-term stable operation of financing mechanisms. This not only restricts the stable development of the agricultural financial system but also weakens the institutional support for sustainable agricultural development.

China officially proposed and promoted “agricultural industry chain financing” during the 11th Five Year Plan period (2006–2010), referring to agricultural industry chain finance as the systematic financial services provided by banking and financial institutions to various operating entities in the agricultural industry chain through various forms such as inventory financing, prepayments, and accounts receivable [7,8], providing financing support to upstream and downstream entities in the industry chain based on transaction contracts [9]. The main participants in agricultural industry chain financing are financial institutions such as banks, agricultural enterprises, and farmers. Through dynamic cooperation, each participant mutually benefits and maximizes their own interests [8]. The prospects of applying agricultural industry chain financing in developing countries and regions are broad [10], which can effectively solve the problem of farmers’ financing difficulties [11]. However, due to the complex transaction relationships between the entities in the industrial chain, the financing model of the industrial chain is not complete [12]. To reduce the impact of financing risks on supply chain stability, it is necessary to emphasize the credit transmission role of core enterprises in supply chain financing [13], as well as the dominant position of financial institutions in risk control [14]. Agricultural supply chain financing relies on the logistic, commercial, and information flows formed by real transactions [15], creating a collateral substitution mechanism for farmers and alleviating the information asymmetry problem faced by both borrowers and lenders in the financing process [9]. It is proposed to reduce credit risk through contract design [16], guarantee mechanisms, and policy support [17]. In recent years, due to multiple factors such as climate change [18], market volatility [19], and environmental uncertainty [20], the external environment of

agricultural supply chains has become increasingly complex. Scholars have paid more attention to the impact of risk on the stability of agricultural supply chain financing and explored optimization paths for its sustainability mechanism design.

Although research has investigated agricultural supply chain financing issues from the perspectives of financial product innovation, risk governance, and policy support, the game logic between micro-actors has not been fully elucidated. In practice, factors such as the insufficient guarantee willingness of agricultural enterprises, high default risk of farmers, and risk aversion of financial institutions have led to a lack of stability in the tripartite cooperation relationship, thereby weakening the sustainable development potential of agricultural supply chain financing. In depth analysis of this issue not only helps to improve the operational efficiency and cooperation stability of agricultural supply chain financing but also provides theoretical and empirical references for improving the risk-sharing system and formulating precise financial support policies. Given the above research motivation, this article aims to answer the following three core questions: (1) Can agricultural enterprises, financial institutions, and farmers achieve a stable cooperative state in supply chain financing? (2) How do different risk-sharing mechanisms (such as guarantee willingness, default penalties, and cooperative benefits) affect the stability of tripartite cooperation and the dynamic evolution of the system? (3) How to enhance the long-term resilience and sustainability of agricultural supply chain financing by optimizing risk-sharing mechanisms?

To address the aforementioned issues, this study incorporates agricultural enterprises, financial institutions, and farmers into an evolutionary game model. Assuming that farmers grow characteristic agricultural products based on the sales needs of agricultural enterprises, in order to alleviate financial pressure, small farmers can directly obtain financing from banks or through guarantees from agricultural enterprises. This study analyzes the equilibrium state of the system from the perspective of the behavioral decisions of the three parties and their cost–benefit analysis. Research has found that relying solely on the decision-making of financing participants makes it difficult to form an evolutionarily stable strategy (ESS). The credit behavior of farmers is the key factor affecting the sustainable development of industrial chain financing. Improving the willingness of agricultural enterprises to provide guarantees can effectively reduce the default risk of farmers, while the cooperative benefits between agricultural enterprises and farmers can significantly enhance the stability of the system. Although the model was validated using the mushroom industry in Hebei Province as an example, its production organization structure, financing model, and risk characteristics are highly representative and can reflect the game logic between farmers, enterprises, and financial institutions in different agricultural supply chain financing systems. This study aims to provide a new design method and decision-making basis for sustainable development-oriented agricultural supply chain financing, combining theoretical depth with practical value to provide valuable decision support for policy makers and financial institutions in designing risk-sharing schemes and promote the sustainable development of agricultural supply chain financing.

The remaining sections of this article are arranged as follows: Section 2 reviews the literature related to the topic. Section 3 elaborates on the basic issues and model assumptions and constructs a three-party evolutionary game payoff matrix to analyze the stability of different equilibrium points. Section 4 introduces the case background and explores the risk-sharing mechanism and optimization path among banks, agricultural enterprises, and farmers through numerical simulation and sensitivity analysis. Section 5 summarizes the main research findings, proposes policy implications, and points out future research directions. The survey questionnaire can be found in the Appendix A.

2. Literature Review

Agricultural supply chain financing is proposed on the basis of value chain financing and supply chain financing. It refers to the flow of financial products and services through the agricultural supply chain to various entities [7], enabling financial services to closely align with industrial development needs and effectively alleviate capital shortages faced by participants [21]. This financing mechanism, which uses the production, processing, and sale of agricultural products as a medium to address financing constraints along the production chain, first emerged in Japan in the late 19th century and in the United States in the early 20th century. It was later widely applied in the vegetable and seed industries in Europe and the United States [22], enhancing the operational efficiency and effectiveness of the entire supply chain through the collaboration of various links [23]. Entities within the agricultural supply chain can be regarded as forming a “credit community”, wherein the strong creditworthiness of core enterprises is transmitted to upstream and downstream firms, thereby reducing overall financial risk and improving access to finance for vulnerable actors [2,8]. By lowering interest rates, extending payment terms, and mobilizing multi-party capital to alleviate operational pressures, participants across the production chain can collectively benefit [24]. Compared with traditional agricultural loans, the integration of capital flow and logistics information within the agricultural supply chain enables external financial institutions to monitor capital risk conditions more accurately, reduce post-loan management costs, and improve risk management efficiency [23,25]. In the study of agricultural supply chain financing, scholars have explored diverse approaches such as innovating guarantee mechanisms, integrating supply chain resources, and applying digital technologies to lower the guarantee threshold for financing entities, improve cash flow efficiency, strengthen risk control, and enhance overall profitability [2,26].

The combination of endogenous risks within the supply chain and external environmental uncertainties contributes to the accumulation of financing risks in the agricultural supply chain. The risk associated with supply chain financing, also referred to as “fragility”, is primarily manifested in the inability to repay or redeem financing products on time [27]. Internal fragility mainly arises from the decision-making biases and conflicts of interest among participants within the supply chain, such as weak credit foundations of borrowing farmers [28], deteriorating operating conditions of agricultural enterprises [29], poor liquidity within the supply chain, and inadequate management capacity of financial institutions, which may result in fund mismatches [30]. Due to the interconnectivity among entities in the supply chain, operational difficulties encountered by a single entity can trigger rapid risk transmission across the financial system, resulting in a chain reaction [31]. External vulnerability mainly comes from market, macroeconomic, or climate risks [32]. Price fluctuations lead to unstable capital flows among all parties in the supply chain, and demand uncertainty increases the risk of inventory management and production decisions [33]. For agricultural supply chains, extreme weather events and sudden natural disasters caused by climate change have become important uncertainties in agricultural production [34]. Climate change not only directly affects crop yields and supply chain efficiency [35] but also damages the ecological environment, increases production costs, weakens farmers’ income stability, and thus affects the long-term sustainable development of the industrial chain [36]. Systemic risk is influenced by the interaction of scale, business complexity, and economic cycles [37]. The higher the complexity of the network, the greater the possibility of instability in the financial system [38].

The risk control of agricultural industry chain financing should attach importance to the role of core organizations [39]. By using mortgage guarantees, monopolistic forces in the industrial chain, and supervision from upstream and downstream entities, a trustworthy commitment mechanism can be constructed [40,41]. Linking big data technologies that

process information on capital flows, information flows, and logistics generated by internal transactions within the industrial chain with financing risk monitoring and prevention can ensure the effective fulfillment of credit contracts among participants in the agricultural supply chain [42]. Further, the introduction of digital platforms can achieve information sharing and integration in the supply chain [43], enhance trust between borrowers and lenders, alleviate information asymmetry, and effectively reduce credit risk [44]. Digital technologies can also enable the assetization of agricultural production factors, expand collateral-based financing channels, and optimize capital allocation [45], thereby further mitigating financing risks within the agricultural supply chain. In addition, scholars have developed different risk-sharing mechanisms tailored to various agricultural supply chain financing models. Boufounou et al. [22] highlighted that in transaction contract-based financing models, the enterprise-led approach enhances the creditworthiness and risk-bearing capacity of individual farmers, serving as an effective tool to reduce default risk and promote the transformation and upgrading of the primary sector. Under the tripartite cooperation mechanism involving government, financial institutions, and enterprises, the government's role in providing risk subsidies to financial institutions can effectively alleviate the financing constraints faced by enterprises [46]. However, the moral hazard of principal cooperation [47], anchoring bias of financing targets [48], and insufficient risk identification before lending [49] all affect the operational quality of the cooperation mechanism among all parties involved in industrial chain financing.

Although scholars have examined agricultural supply chain finance from multiple perspectives, existing studies have mainly focused on development models, risk types, and financial instrument innovations, with relatively few studies on risk sharing mechanisms. Based on this, the main contributions of this paper are as follows: (1) Unlike previous research that emphasized risk identification or external environmental factors, this paper adopts an internal system perspective to reveal the mechanism by which behavioral interactions among agricultural enterprises, financial institutions, and farmers affect the sustainability of agricultural supply chain financing, expanding the theoretical research perspective in this field. (2) This paper employs a combination of evolutionary game theory and numerical simulation to dynamically depict the strategic adjustments and system stability of the three parties, revealing the optimal strategy evolution paths under different risk-sharing and incentive constraints. This methodologically enriches the research framework for analyzing the stability of cooperation mechanisms in the agricultural finance field. (3) This paper systematically analyzes the impact of internal management models such as willingness to guarantee, default penalties, and income distribution mechanisms on system evolution outcomes, clarifying the adjustment directions and optimization paths for key parameters and providing policy references for improving agricultural supply chain financial governance.

3. Problem Description and Model Framework

3.1. Problem Description

The supply chain led by agricultural enterprises brings together diversified agricultural management entities, such as farmers and cooperatives, forming a closely connected community of interests [50]. The agricultural supply chain financing model of “agricultural enterprises + farmers + financial institutions” centers on dominant agricultural sectors, with agricultural enterprises serving as the core. This model leverages the collaborative relationships between upstream and downstream entities within the supply chain, treats the entire agricultural supply chain as the credit subject, and relies on product purchase agreements signed between agricultural enterprises and farmers [4]. It provides standardized financial services to both upstream and downstream entities in the supply chain and addresses

the financing constraints and high borrowing costs faced by vulnerable participants [51]. The strategic choices made by agricultural enterprises, farmers, and financial institutions directly affect farmers' financing access and the overall benefits of each participating entity. To simplify the game scenario, it is assumed that agricultural enterprises face no financing constraints. In the interest of enhancing coordination efficiency within the supply chain, once a cooperation agreement is signed between agricultural enterprises and farmers, the enterprises provide guarantees for farmers with financing difficulties in the supply chain, thereby increasing the likelihood of loan approval from financial institutions.

From the perspective of farmers, they can rely on contractual relationships to obtain guarantees from agricultural enterprises, thereby effectively enhancing their financial accessibility by leveraging the high-quality credit of these enterprises [52], and they can sell their agricultural products to them. After signing contracts with agricultural enterprises, farmers may also receive technical guidance or production inputs [7]. This not only reduces production risks such as unstable yields but also promotes production standardization and improves product quality stability among small farmers [53]. Banks, in turn, may become more willing to provide loans to farmers, given the reduced production risks and increased stability in expected income [54]. Under such arrangements, the contractual relationship can be regarded as a form of “virtual collateral” [25]. Agricultural enterprises constrain farmers' opportunistic behavior through punitive mechanisms such as suspending technical support, terminating contracts, or enforcing penalty clauses. From the perspective of banks, the agricultural supply chain financing model reduces the frequency of one-on-one negotiations with individual farmers and lowers transaction costs. Meanwhile, easing farmers' financial burdens also brings indirect benefits to agricultural enterprises. Enterprise-led organization of the supply chain can enhance farmers' access to external financing, strengthen cooperation among various entities, coordinate the allocation of resources and production factors, and reduce information asymmetry [51,55]. Based on these interactions, as shown in Figure 1, this study constructs a tripartite evolutionary game model involving agricultural enterprises, farmers, and banks. By simulating the strategic evolution of stakeholders within the supply chain in areas such as credit guarantees, contract performance, and credit issuance, this study systematically investigates the formation and transmission mechanisms of credit and default risks in agricultural supply chain financing. It further explores strategies to optimize risk sharing among multiple stakeholders. By enhancing risk governance mechanisms, this paper aims to alleviate the financing difficulties faced by farmers due to limited credit and collateral, thereby promoting the stability and sustainable development of the agricultural supply chain financial system.

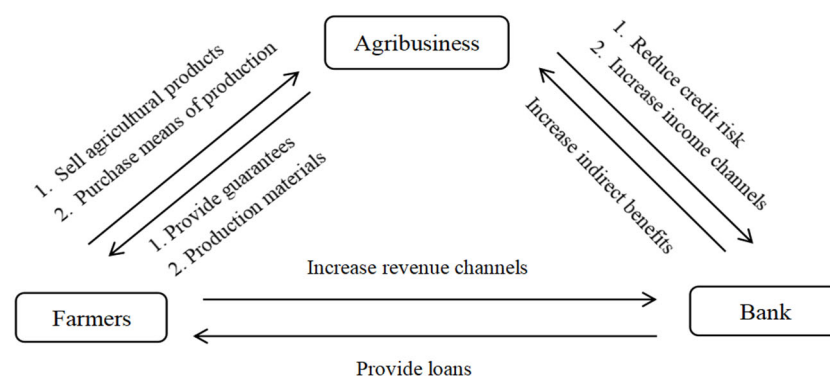


Figure 1. Interactive relationship between participants in supply chain financing.

3.2. Model Assumptions and Parameter Definitions

Without considering the influence of other external factors on farmers' financing behavior, an evolutionary game model involving agricultural enterprises, farmers, and banks is constructed to analyze the impact of each participant's strategic choices on the stability of agricultural supply chain financing. Based on this, the following assumptions are proposed, and the main variables in the evolutionary game model are summarized in Table 1:

Table 1. Main variables and definitions in the tripartite evolutionary game model.

Variables	Meaning
T_1	Cooperative benefits earned by agricultural enterprises when providing loan guarantees
T_{11}	Net operating income of agricultural enterprises when banks issue loan
T_{12}	Net operating income of agricultural enterprises when banks do not issue loans
T_{21}	Net operating income of farmers when banks issue loans
T_{22}	Net operating income of farmers when banks do not issue loans
T_3	Interest income of banks from lending to other low-risk projects
C_1	Search cost incurred by agricultural enterprises when not providing guarantees
C_2	Cost incurred by farmers to obtain loans without guarantees from agricultural enterprises
C_{21}	Operational costs incurred by farmers due to default under guaranteed loan contracts
C_3	Screening costs incurred by banks when enterprises do not provide guarantees and banks issue loans
P	Penalty income received by agricultural enterprises when providing guarantees, banks issue loans, and farmers breach
I_0	Initial funds owned by farmers
I	Loan demand of farmers
r	Interest rate on agricultural supply chain loan products

Assumption 1 (Participants and Behavioral Assumptions). *Agricultural industrialization enterprises participating in agricultural supply chain financing, farmers with loan demand but facing financing constraints, and banks providing loan services are selected as the three participants in the evolutionary game. It is assumed that all three parties are boundedly rational, aim to maximize their own interests, and possess incomplete and asymmetric information. Throughout the game process, as time progresses and outcomes evolve, the three participants dynamically adjust their strategies and ultimately converge toward a stable optimal strategy.*

Assumption 2 (Strategy Set Definitions). *In the financing process of the agricultural supply chain, the strategy set of agricultural enterprises is denoted by $A_1 = \{\text{guarantee, non-guarantee}\}$, where the probability of choosing the "guarantee" strategy is x , and the probability of choosing the "non-guarantee" strategy is $1 - x$; the strategy set of farmers is denoted by $A_2 = \{\text{compliance, breach}\}$, where the probability of choosing the "compliance" strategy is y , and the probability of choosing the "breach" strategy is $1 - y$; and the strategy set of the bank is denoted by $A_3 = \{\text{loan issuance, non-loan issuance}\}$, where the probability of choosing the "loan issuance" strategy is z , and the probability of choosing the*

“non-loan issuance” strategy is $1 - z$. Among them, $0 \leq x \leq 1, 0 \leq y \leq 1, 0 \leq z \leq 1$, and x, y, z are all functions of time t .

Assumption 3 (Payoff Structure for Agricultural Enterprises). When agricultural enterprises adopt the “guarantee” strategy, they can, due to their strong financial capacity and good credit standing, share the loan risk borne by banks and help improve loan efficiency. This assists farmers in overcoming financing constraints while allowing agricultural enterprises to gain cooperation benefits T_1 . If banks simultaneously adopt the “loan issuance” strategy, the net operating income earned by agricultural enterprises is denoted as T_{11} . However, if the cooperation between agricultural enterprises and farmers fails due to contract breach by the farmer, the enterprise imposes penalties on the farmer and gains corresponding penalty income P . If banks choose the “non-loan issuance” strategy, the procurement cost of primary agricultural products for agricultural enterprises increases, and their net operational income declines to T_{12} , implying that $T_{12} < T_{11}$. When agricultural enterprises choose the “non-guarantee” strategy, their cooperation benefits T_1 become zero. When the banks adopt the “loan issuance” strategy, agricultural enterprises will obtain net operating income T_{11} . When the banks adopt the “non-loan issuance” strategy, agricultural enterprises will obtain net operating income T_{12} . However, in order to obtain sufficient high-quality agricultural products, they incur a search cost denoted by C_1 .

Assumption 4 (Financing Constraints and Payoffs for Farmers). The loan demand of farmers is I . Due to a lack of collateral or insufficient credit, farmers face loan constraints. When agricultural enterprises do not provide guarantees and banks choose the “loan issuance” strategy, farmers invest both their initial capital I_0 and loan funds I into production and receive a net operational income of T_{21} . If agricultural enterprises provide guarantees, the probability of successful loan access increases substantially, and after securing the loan and investing in production, farmers can obtain a net operating income of T_{21} . If banks choose the “non-loan issuance” strategy, regardless of whether agricultural enterprises provide guarantees, farmers can only invest their initial capital and obtain an operating income of T_{22} , with $T_{22} < T_{21}$. In addition, if farmers choose the “breach” strategy after investing funds in production and agricultural enterprises have provided guarantees, farmers incur a penalty cost P and must pay an additional cost C_{21} to seek a new enterprise that can provide guarantees for restarting agricultural production in the future. In the absence of agricultural enterprises, farmers incur a cost C_2 to obtain an equivalent loan.

Assumption 5 (Lending Payoffs and Risk Exposure of Banks). The loan interest rate charged by banks for agricultural supply chain financing products is denoted by r . When banks choose the “loan issuance” strategy and agricultural enterprises provide guarantees, if farmers comply with the contract, banks earn interest income I_r . If farmers breach the contract, agricultural enterprises do not bear liability for loan repayment, and banks incur a loss of $I + I_r$. When agricultural enterprises choose the “non-guarantee” strategy, if farmers comply, banks can earn interest income I_r ; however, if farmers breach, the bank suffers the full loss of the loan principal and interest $I + I_r$. In cases where agricultural enterprises do not provide loan guarantees, banks must assess farmers’ assets, creditworthiness, and other information before issuing loans, incurring a screening cost of C_3 . Additionally, due to the lack of a risk-sharing entity, banks may choose the “non-loan issuance” strategy and instead lend the funds to lower-risk projects, thereby earning interest income of T_3 , with $T_3 < I_r$.

3.3. Model Analysis

3.3.1. Payoff Matrix

Based on the basic assumptions and variable definitions outlined above, the tripartite evolutionary game payoff matrix involving agricultural enterprises, farmers, and banks is constructed, as shown in Table 2.

Table 2. Payoff matrix of the evolutionary game among agricultural enterprises, farmers, and banks.

Agricultural Enterprises	Farmer		Bank
	Compliance y	Breach $1-y$	
Guarantee x	$T_{11} + T_1$	$T_{11} + T_1 + P$	Loan issuance z
	$T_{21} - Ir$	$T_{21} + I - C_{21} - P$	
	Ir	$-I(1+r)$	
	$T_{21} + T_1$	$T_{12} + T_1$	Non-loan issuance $1-z$
	T_{22}	$T_{22} - C_{21}$	
	T_3	T_3	
Non-guarantee $1-x$	$T_{11} - C_1$	$T_{11} - C_1$	Loan issuance z
	$T_{21} - Ir - C_2$	$T_{21} + I - C_2$	
	$Ir - C_3$	$-I(1+r) - C_3$	
	$T_{12} - C_1$	$T_{12} - C_1$	Non-loan issuance $1-z$
	T_{22}	T_{22}	
	T_3	T_3	

3.3.2. Replicator Dynamic Equations

Due to the information asymmetry among agricultural enterprises, farmers, and banks involved in the agricultural supply chain financing process, the three parties dynamically adjust their strategic choices over time by changing the proportions of x , y , and z . The average expected payoffs of agricultural enterprises, farmers, and banks under this financing model are denoted by $\bar{E}_1$, $\bar{E}_2$, and $\bar{E}_3$, respectively.

The expected payoff of agricultural enterprises adopting the “guarantee” strategy is given by

$$E_{11} = yz(T_{11} + T_1) + (1-y)z(T_{11} + T_1 + P) + y(1-z)(T_{12} + T_1) + (1-y)(1-z)(T_{12} + T_1) \quad (1)$$

The expected payoff of agricultural enterprises adopting the “non-guarantee” strategy is given by

$$E_{12} = yz(T_{11} - C_1) + (1-y)z(T_{11} - C_1) + y(1-z)(T_{12} - C_1) + (1-y)(1-z)(T_{12} - C_1) \quad (2)$$

The average expected payoff of agricultural enterprises is given by

$$\bar{E}_1 = xE_{11} + (1-x)E_{12} \quad (3)$$

The replicator dynamic equation of agricultural enterprises is given by

$$F(x) = d(x)/d(t) = x(E_{11} - \bar{E}_1) = x(1-x)(E_{11} - E_{12}) = x(1-x)(zP - yzP + T_1 + C_1) \quad (4)$$

Following the same derivation procedure, the replicator dynamic equation for farmers is obtained as

$$F(y) = d(y)/d(t) = y(E_{21} - \bar{E}_2) = y(1-y)(E_{21} - E_{22}) = y(1-y)(-zIr + xC_{21} + xzP - zI) \quad (5)$$

Similarly, the replicator dynamic equation for banks is given by

$$F(z) = d(z)/d(t) = z(E_{31} - \bar{E}_3) = z(1-z)(E_{31} - E_{32}) = z(1-z)[yIr + yI(1+r) + xC_3 - I - Ir - C_3 - T_3] \quad (6)$$

3.4. Steady-State Equilibrium Analysis

The replicator dynamic equations of agricultural enterprises, farmers, and banks describe the strategy adjustment processes of boundedly rational participants through learning and imitation over time. By solving the system under conditions where $F(x) = 0$, $F(y) = 0$, and $F(z) = 0$, eight equilibrium points can be obtained: $D_1(0,0,0)$, $D_2(0,1,0)$, $D_3(0,0,1)$, $D_4(1,0,0)$, $D_5(1,1,0)$, $D_6(1,0,1)$, $D_7(0,1,1)$, and $D_8(1,1,1)$.

According to the evolutionary game equilibrium strategy criterion proposed by Friedman [37], the Jacobian matrix of the tripartite game system is denoted as J , as shown in Equation (7). Based on the first method of Lyapunov, if all the real parts of the eigenvalues of the Jacobian matrix at a given equilibrium point are less than zero, the point is considered an evolutionarily stable strategy (ESS). If at least one eigenvalue has a positive real part, the equilibrium point is unstable. When some eigenvalues have real parts equal to zero while the others are negative, the stability of the equilibrium point cannot be determined solely by the sign of the eigenvalues [38]. By calculating the Jacobian matrix J , the corresponding eigenvalues and stability conclusions for each pure strategy equilibrium point are derived and presented in Table 3.

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix} \quad (7)$$

Table 3. Stability analysis of equilibrium points based on eigenvalues.

Equilibrium Point	λ_1	Eigenvalue λ_2	λ_3	Signs of Real Parts	Stability Conclusion
$D_1(0,0,0)$	$T_1 + C_1$	0	$-I - Ir - C_3 - T_3$	(+, 0, −)	Instability
$D_2(0,1,0)$	$T_1 + C_1$	0	$Ir - C_3 - T_3$	(+, 0, ×)	Instability
$D_3(0,0,1)$	$P + T_1 + C_1$	$-Ir - I$	$I + Ir + C_3 + T_3$	(+, −, +)	Instability
$D_4(1,0,0)$	$-(T_1 + C_1)$	C_{21}	$-I - Ir - T_3$	(−, +, −)	Instability
$D_5(1,1,0)$	$-(T_1 + C_1)$	$-C_{21}$	$Ir - T_3$	(−, −, +)	Instability
$D_6(1,0,1)$	$-P - T_1 - C_1$	$C_{21} + P - Ir - I$	$I + Ir + T_3$	(−, ×, +)	Instability
$D_7(0,1,1)$	$T_1 + C_1$	$Ir + I$	$-(Ir - T_3 - C_3)$	(+, +, ×)	Instability
$D_8(1,1,1)$	$-(T_1 + C_1)$	$-(C_{21} + P - Ir - I)$	$-(Ir - T_3)$	(−, ×, −)	Undetermined

Note: “×” indicates that the sign of the real part is indeterminate—it may be either positive or negative depending on parameter values.

As shown in Table 3, (i) the eigenvalues λ_1 of $D_1(0,0,0)$ and $D_2(0,1,0)$ are both greater than zero; the eigenvalues λ_1 and λ_3 of $D_3(0,0,1)$ are greater than zero; the eigenvalues λ_2 of $D_4(1,0,0)$ are greater than zero; the eigenvalues λ_3 of $D_6(1,0,1)$ are greater than zero; and the eigenvalues λ_1 and λ_2 of $D_7(0,1,1)$ are both greater than zero. Therefore, equilibrium points $D_1(0,0,0)$, $D_2(0,1,0)$, $D_3(0,0,1)$, $D_4(1,0,0)$, $D_6(1,0,1)$, and $D_7(0,1,1)$ are all evolutionarily unstable and cannot be considered ESSs. (ii) According to Assumption 5, $Ir > T_3$, the eigenvalues λ_3 of $D_5(1,1,0)$ become positive, further confirming its instability. Thus, $D_5(1,1,0)$ cannot be an ESS under these conditions. (iii) For equilibrium point $D_8(1,1,1)$, the eigenvalues λ_1 and λ_3 are both negative, while the sign of λ_2 is indeterminate. Therefore, to further verify the stability of the equilibrium point $D_8(1,1,1)$, this study first makes judgments by analyzing the signs of eigenvalues and draws the following inferences:

Inference 1. For equilibrium point $D_8(1,1,1)$, if “ $C_{21} + P - Ir - I < 0$ ”, its eigenvalue λ_2 is greater than zero, and thus $D_8(1,1,1)$ is unstable and cannot be an ESS.

Inference 2. For equilibrium point $D_8(1, 1, 1)$, if “ $C_{21} + P - Ir - I > 0$ ”, its eigenvalue λ_2 is less than zero, and thus $D_8(1, 1, 1)$ is locally asymptotically stable and may be an ESS. This suggests that when the cost C_{21} incurred by farmers for re-engaging in agricultural operations, together with the penalty P paid to agricultural enterprises, exceeds the principal and interest of the loan $Ir + I$, farmers are more likely to comply with the contract, making this cooperative mechanism evolutionarily stable.

4. Simulation Analysis

To verify the evolutionary stability of the model and more intuitively illustrate the impact of various factors on the strategic cooperation among participants, this study uses the mushroom supply chain led by Hebei Guoxu Biotechnology Co., Ltd. (Baoding, China) and the “Mushroom Loan” agricultural supply chain financing product launched by the China Construction Bank as case examples. Based on actual conditions, model parameters are assigned accordingly, and Matlab R2024b is used to conduct numerical simulations of the evolutionary game dynamics.

4.1. Simulation Parameter Settings

The mushroom industry in Fuping County, Baoding City, Hebei Province, has become a pillar industry for farmers to eradicate poverty and achieve prosperity, as well as for the government to transform its industries. By 2024, Fuping County had established 102 mushroom industrial parks, with an annual output of over 80 million mushroom spawn sticks, driving an average annual income increase of CNY 9400 per capita for 8620 impoverished households. It has been listed as a typical case of poverty alleviation through green industries nationwide [Source: https://baike.baidu.com/reference/55992285/533aYdO6cr3_z3kATKeCya2jMymXP9qstrPXU7FzzqIPmGapB5nyTcYw5NEq7v5pE0XMv44sY9hamO29SVRE7f8YdfNtBuh- (accessed on 2 November 2025)]. As a key industry for poverty alleviation, the China Construction Bank and Hebei Rural Credit Union have offered the “Mushroom Loan” product since 2021, targeting farmers cooperating with four leading enterprises including Hebei Guoxu Biotechnology Co., Ltd. (hereinafter referred to as “Guoxu”). Through the deep integration of poverty alleviation industries and bank supply chain financial products, the availability of financing and production efficiency for farmers have been improved, promoting the sustainable development of the Fuping mushroom industry. However, mushroom cultivation is vulnerable to natural disasters such as rainstorms and floods, which can damage facilities and reduce production. Frequent fluctuations in the market price of mushrooms also weaken the stability of farmers’ income and affect their ability to repay loans on time. For example, on 30–31 July 2025, continuous rainstorms in Fuping County caused floods to local mushroom spawn stick factories and cultivation parks, damaging more than 40 greenhouses in the Nanyu Village mushroom industrial park, with over 60% of the greenhouses affected. To this end, through standardized production and year-round supply to stabilize market prices, the cooperation among banks, enterprises, and farmers reduces financing risks and demonstrates strong industry representativeness and replicability.

The key parameters in this study are derived from field research and interviews conducted with the China Construction Bank Fuping Branch, Guoxu, and its cooperative farmers from 2023 to 2024. As a leading enterprise in the industry, Guoxu integrates planting, production, harvesting, screening, storage and transportation, processing, and sales, with annual sales of approximately CNY 280 million. It currently has over 2000 mushroom greenhouses and promotes farmer participation in mushroom production through the leasing of planting greenhouses [Source: <http://www.hebeiguoxu.com/> (accessed on 2 November 2025)]. To improve the accuracy of the parameters, we conducted interviews with 2 bank customer managers, 4 corporate managers, and 40 mushroom growers from

8 townships. Combining corporate financial information and production data, we calculated the mean values of each variable as key parameters in the model, which have strong practical rationality. These parameter values have been further verified by multiple parties to test the rationality of the data and the representativeness of the case. In this study, we conducted a perturbation test on the key parameters within a range of $\pm 20\%$, and the results showed that the evolutionary direction and stability of the system remained unchanged. The specific data are as follows.

The annual rent for each mushroom greenhouse is CNY 3000. After signing a leasing agreement, Guoxu Company provides standardized mushroom sticks and free technical guidance to farmers. Each mushroom stick is sold at CNY 3 per unit, with a production cost of CNY 2.7. Since each greenhouse requires 16,000 mushroom sticks, the cooperative income T_1 for the enterprise is CNY 4800 per greenhouse. In the event of a contract breach by farmers, the enterprise retains the greenhouse rental as a penalty income P and prohibits the defaulting farmers from leasing again. If farmers choose to re-cooperate with another agricultural enterprise offering loan guarantees in the future, an additional operating cost C_{21} of CNY 15,000 is incurred. Meanwhile, if agricultural enterprises choose the “non-guarantee” strategy, they will bear a search cost C_1 of CNY 1500 yuan to secure sufficient high-quality agricultural products. The loan demand I for each farmer (per greenhouse) is CNY 50,000, mainly to cover the cost of mushroom sticks and greenhouse rental. To meet these financing needs, the China Construction Bank has introduced the innovative “Mushroom Loan” product, offering a loan interest rate r of 3.55%. When lending the same amount to lower-risk projects, the bank earns an average interest income T_3 of CNY 1400. In the absence of enterprise guarantees, the bank incurs an average per-loan evaluation cost C_3 of CNY 10 per farmer. Based on the actual conditions described above, parameter values are assigned accordingly, as shown in Table 4.

Table 4. Simulation parameter values (Data source: Based on field research data from the China Construction Bank Fuping Branch, Hebei Guoxu Biotechnology Co., Ltd., and the Mushroom planting base. Monetary variables $I, P, C_1, C_{21}, C_3, T_1$, and T_3 are measured in units of CNY 10,000; the interest rate variable r is measured as a percentage (%)).

Variable	I	r	P	C_1	C_{21}	C_3	T_1	T_3
Value	5	3.55	0.3	0.15	1.5	0.001	0.48	0.14

4.2. Initial Evolution Dynamics Analysis

Substituting the above parameters into Matlab, the evolution directions of the tripartite game system under different initial strategy probabilities are simulated. As shown in Figure 2, the evolution trajectories exhibit complex dynamic characteristics: the system does not converge to a unique fixed point but forms a cyclic structure in the three-dimensional strategy space. This suggests that under the “Mushroom Loan” financing model, the strategic combinations among agricultural enterprises, farmers, and banks do not reach a fixed equilibrium but remain in a state of dynamic adjustment. As can be further seen from Figure 3, with the initial strategy probabilities of all three players set to 0.5, the strategies of agricultural enterprises (x) and farmers (y) quickly evolve toward 1, stabilizing at high levels with minor fluctuations. In contrast, the strategy trajectory of the Construction Bank (z) exhibits significant non-periodic fluctuations and fails to converge stably to 1. This indicates that in the practice of the “Mushroom Loan” financing, agricultural enterprises and farmers can generally gradually form stable cooperative expectations, but the strategy of the China Construction Bank is affected by various factors and exhibits strong dynamic volatility, failing to eventually evolve to a state of disbursing loans. This verifies the conclusion in Inference 1 that $D_8(1, 1, 1)$ is an unstable point.

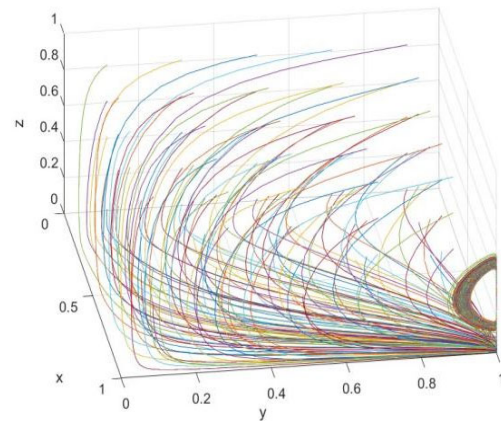


Figure 2. Three-dimensional trajectories of initial evolutionary dynamics (1).

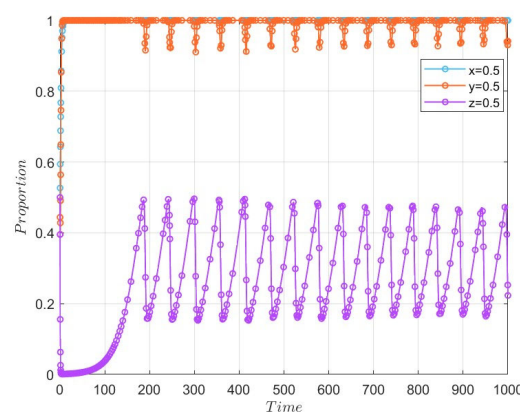


Figure 3. Three-dimensional trajectories of initial evolutionary dynamics (2).

Simulation results indicate that due to factors such as unstable farmer incomes, market price fluctuations, and the potential credit risks of farmers, banks maintain caution in lending decisions, leading to low-level fluctuations in their strategies and thereby weakening the stability of the overall financing chain. This result reveals that relying solely on spontaneous adjustments among banks, agricultural enterprises, and farmers to achieve stable cooperation in agricultural industry chain financing is difficult. Therefore, external intervention mechanisms, especially government participation, play a crucial role in promoting tripartite cooperation [56]. For example, the government can provide guarantees for farmers by establishing wholly owned agricultural guarantee companies [57] or reduce farmers' planting risks through policy-based agricultural insurance [58]. Government policy intervention plays a significant role in enhancing financing efficiency and system stability.

4.3. Sensitivity Analysis

Based on the evolutionary trajectory presented in Figure 3, it is evident that even after 1000 iterations, the system fails to converge to a stable equilibrium point. This outcome reflects the bank's inability to form a consistent loan issuance strategy in the long-term evolutionary game. Meanwhile, the strategic interactions between agricultural enterprises and farmers may influence the bank's decision-making process. To further explore the underlying causes of this persistent instability, this section presents detailed analyses based on the first 10 iterations of the evolutionary process. By examining these early-stage trajectories, we investigate how initial strategy settings and parameter changes affect the dynamic outcomes. This section analyzes why banks hold a cautious attitude toward lending, how the strategic choices of agricultural enterprises and farmers interact, and how

credit risks are transmitted and accumulated within the tripartite dynamic, in order to provide a basis for optimizing the agricultural supply chain financing model.

4.3.1. Impact of Initial Strategy Preferences on the Evolutionary Dynamics of the System

Figures 4 and 5 illustrate the impact of changes in the initial strategic intentions of agricultural enterprises, farmers, and the Construction Bank on their evolutionary trajectories, while holding other parameter conditions constant.

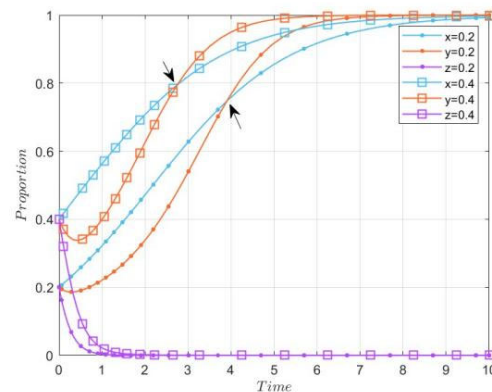


Figure 4. Impact of simultaneous changes in initial strategy intentions x , y , and z (under low-willingness conditions).

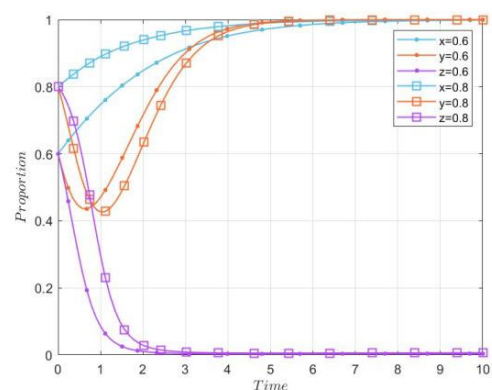


Figure 5. Impact of simultaneous changes in initial strategy intentions x , y , and z (under high-willingness conditions).

As shown in Figure 4, when the initial strategy values of all three parties are within the range of $[0.1, 0.5]$, the Construction Bank (z)'s strategy probability declines toward 0 at a faster rate than the strategies of the agricultural enterprises (x) and farmers (y) converge toward 1. At a certain point, the evolutionary speed of the farmers (y) surpasses that of the agricultural enterprises (x). This indicates that under conditions of low initial willingness, agricultural enterprises gradually reach cooperation as farmers' contract compliance awareness improves. However, the bank's willingness to issue loans declines rapidly. As the bank's expectations regarding credit risk deteriorate, it ultimately chooses to withdraw from the financing process.

As shown in Figure 5, when the initial strategy values of all three parties are within the range of $[0.6, 0.9]$, the Construction Bank (z)'s rate of decline toward 0 slows, while the agricultural enterprises' (x) convergence toward 1 accelerates. Farmers (y) initially evolve toward the "breach" strategy, followed by a shift toward "compliance". The higher the initial willingness, the greater the degree of reverse evolution and the slower the convergence to equilibrium. This suggests that when initial willingness is high, farmers will adopt incomplete contract fulfillment strategies at the beginning of the game, that is, by

defaulting in the short term to test whether banks and agricultural enterprises will continue to provide loan support and then adjusting their future choices. Due to the high early-stage default rate, banks' confidence in agricultural lending weakens, leading to a gradual reduction in credit issuance. Once banks choose the "non-loan issuance" strategy, farmers begin to comply gradually. This path dependency is not conducive to the sustainable development of the supply chain financing model.

The simulation results suggest that farmers' adoption of the "compliance" strategy not only enhances the guarantee willingness of agricultural enterprises but that the synergy of these two strategies can also improve the bank's willingness to issue credit. Therefore, the key to optimizing the agricultural supply chain financing model lies in strengthening the credit constraint mechanism for farmers and reducing their default motivation. This may be achieved by establishing a more comprehensive credit rating system or introducing government-backed credit enhancement mechanisms to stabilize cooperation expectations among banks, enterprises, and farmers.

Figures 6–8 illustrate the impact of changing the initial strategy intentions of agricultural enterprises, farmers, and the Construction Bank on the evolutionary trajectories of the three parties, while holding other parameter conditions constant. These figures reveal the dynamic game characteristics and transmission mechanisms within the financing model of the agricultural supply chain.

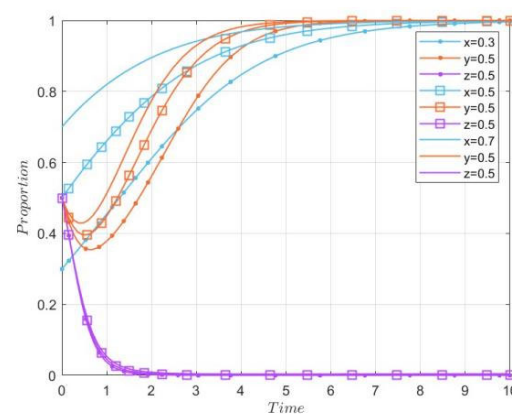


Figure 6. Impact of changes in initial strategy intention of agricultural enterprises x .

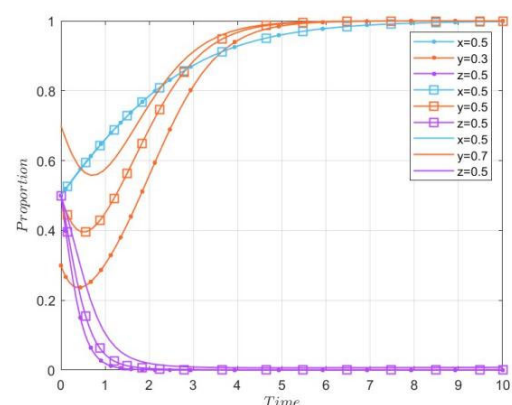


Figure 7. Impact of changes in initial strategy intention of farmers y .

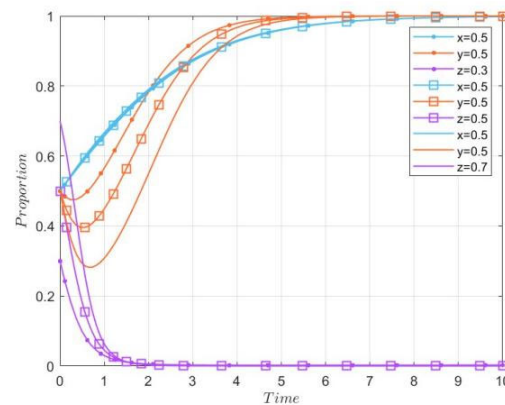


Figure 8. Impact of changes in initial strategy intention of bank z.

As shown in Figure 6, an increase in the initial guarantee willingness of agricultural enterprises helps reduce the default risk of farmers. In other words, when enterprises are more inclined to provide guarantees, farmers are more likely to fulfill their contractual obligations. However, changes in the enterprises' guarantee willingness have a limited impact on whether banks issue loans. This phenomenon indicates that the guarantee behavior of agricultural enterprises primarily affects the financing chain indirectly by influencing the strategic choices of farmers, while its direct impact on banks is relatively limited. In the credit decision-making process, banks rely more on their assessment of farmers' creditworthiness rather than on the strength of corporate guarantees.

As shown in Figure 7, the initial willingness of farmers to comply has a significant impact on the bank's loan decisions. When farmers' credit awareness is enhanced and their initial willingness to fulfill obligations is high, banks are more inclined to continue issuing loans. This suggests that the credit behavior of farmers plays a crucial role in the financing chain, significantly increasing banks' confidence and reducing their credit risk expectations. Therefore, improving farmers' creditworthiness can not only optimize their own financing environment but also promote the stable development of the agricultural supply chain by enhancing the credit supply capacity of banks.

As shown in Figure 8, the initial lending willingness of banks is inversely proportional to the speed at which farmers evolve toward compliance strategies. That is, when banks' initial willingness to lend is high, the rate at which farmers shift to compliance strategies decreases, indicating a certain degree of moral hazard. This may result from the lack of performance pressure faced by farmers in an accommodative credit environment, leading to a stronger tendency toward short-term strategic default and a slower improvement in their credit behavior. In addition, changes in the initial lending willingness of banks have little impact on the guarantee strategies of agricultural enterprises. This suggests that enterprises' strategic choices within the financing chain rely more on their own market expectations and risk assessments rather than being directly influenced by bank credit policies.

The simulation results indicate that the core transmission mechanism of agricultural supply chain financing lies in the enhanced guarantee willingness of enterprises, which helps reduce farmers' default risk. Meanwhile, the improvement of farmers' creditworthiness serves as the key driving force for bank credit allocation. Furthermore, in designing credit policies, banks must remain vigilant about the potential moral hazard associated with high initial lending willingness. Excessively accommodative credit conditions may weaken farmers' awareness of contractual compliance, thereby undermining the long-term stability of agricultural financing.

4.3.2. Impact of Parameter Changes on the Evolutionary Dynamics of the System

Figures 9–11 illustrate the impact of changes in the parameters of farmers' production and operation costs (C_{21}), agricultural enterprises' cooperative benefits (T_1), and penalty income (P) on the evolution trajectory of the agricultural supply chain financing model, while keeping other parameter conditions constant (The sensitivity analysis in this section does not include all model parameters. Parameters such as I (loan demand of farmers), r (loan interest rate), C_1 (search cost for agricultural enterprises), T_3 (return from banks issuing equal loans to lower-risk projects), and C_3 (per-loan evaluation cost of banks) are derived from actual operating practices and considered relatively stable in the short term. As such, they are excluded from the current sensitivity analysis.).

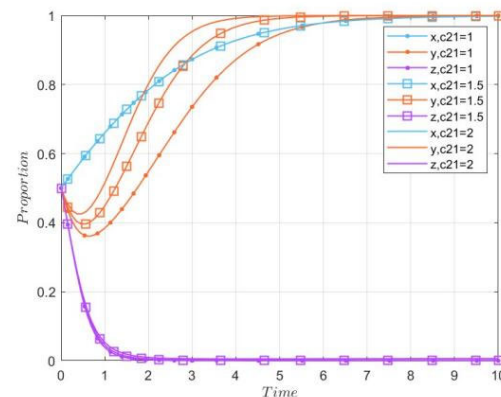


Figure 9. Impact of changes in operational cost C_{21} .

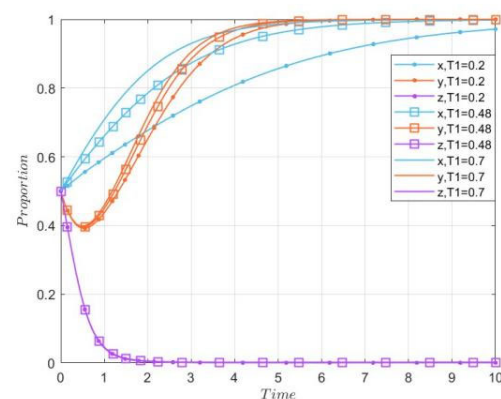


Figure 10. Impact of changes in cooperative benefit T_1 .

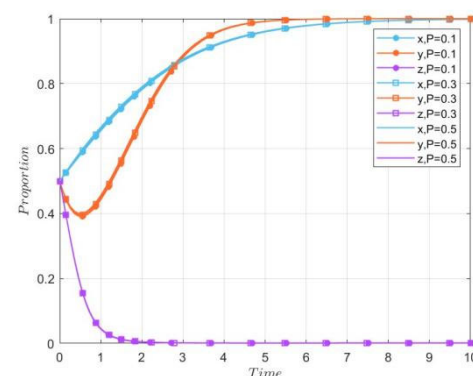


Figure 11. Impact of changes in penalty income P .

As shown in Figure 9, when agricultural enterprises choose the “guarantee” strategy and farmers choose the “breach” strategy, the increase in farmers' operational costs C_{21}

significantly accelerates their evolution toward the “compliance” strategy. This indicates that higher operational costs strengthen farmers’ credit constraints, making them more inclined to fulfill contractual obligations. At the same time, the result suggests that the collaborative relationship between agricultural enterprises and farmers not only contributes to improving the overall creditworthiness within the financing chain but also helps share credit risks with banks to some extent. This finding offers a new perspective on enhancing farmers’ compliance awareness, suggesting that an appropriate increase in post-default operational costs may encourage farmers to place greater emphasis on credit discipline.

As shown in Figure 10, an increase in the cooperative benefits T_1 obtained by agricultural enterprises providing guarantees not only enhances enterprises’ own willingness to provide guarantees but also promotes farmers’ compliance with contractual obligations. This indicates that the incentive mechanism for agricultural enterprises, as guarantee entities within the financing system, plays a significant role in improving farmers’ credit behavior. Higher cooperative benefits increase enterprises’ willingness to participate in guarantee activities, thereby lowering the financing threshold for farmers and further enhancing their credit awareness and repayment capacity. A well-designed incentive mechanism can generate a positive feedback loop of “enterprise guarantee–farmer compliance” within the agricultural financing system, thereby reducing credit risk in the financing process and contributing to the system’s overall stability.

As shown in Figure 11, under the scenario where agricultural enterprises provide guarantees, banks issue loans, and farmers breach contracts, the impact of changes in the penalty income P imposed by enterprises on the evolution of the overall system is relatively limited. This suggests that relying solely on punitive mechanisms is insufficient to effectively improve farmers’ credit behavior or enhance banks’ willingness to issue loans. A possible explanation is that punitive measures exert only a short-term deterrent effect on default behavior and fail to fundamentally strengthen farmers’ credit awareness or promote long-term cooperative incentives among the three parties.

The simulation results indicate that, firstly, increasing the operational costs for farmers after default can enhance their willingness to fulfill contracts. Secondly, compared to the one-time punishment mechanism, the cooperative benefits between agricultural enterprises and farmers are more conducive to improving the overall stability of the system. As can be seen from Figures 10 and 11, adjusting the cooperative benefit T_1 significantly increases the willingness of agricultural enterprises to provide guarantees and enhances the willingness of farmers to fulfill contracts. However, under the same scenario, adjusting the penalty income P has no significant impact on system evolution, indicating that the punishment mechanism has limited effectiveness and cannot fundamentally improve farmers’ credit behavior or effectively enhance banks’ motivation to issue loans. Therefore, when optimizing agricultural financing models, emphasis should be placed on building a credit mechanism centered on incentives, such as increasing collaborative benefits between farmers and enterprises and strengthening credit incentives, rather than relying on punishment mechanisms to constrain farmers’ behavior.

5. Conclusions

This study constructs a tripartite evolutionary game model involving agricultural enterprises, farmers, and banks to explore risk-sharing mechanisms and sustainable development in agricultural supply chain financing. The key findings reveal the crucial role of different stakeholders in maintaining supply chain stability: (1) Market mechanisms themselves have limitations: Relying solely on participating entities cannot achieve a stable equilibrium in agricultural supply chain financing, indicating the necessity of government coordination and intervention. (2) Farmers’ credit behavior is pivotal: Farmers’ credit

qualifications and repayment behavior are central to the stable functioning of supply chain financing, emphasizing the importance of effective monitoring and credit mechanisms. (3) Enterprises' guarantee willingness mitigates risk: Increasing the willingness of agricultural enterprises to provide credit guarantees can substantially reduce farmers' default risk and enhance overall system stability. (4) Cooperative incentives outperform punitive measures: Structuring mutual benefits between enterprises and farmers is more effective than one-time punitive actions in sustaining long-term collaboration and mitigating systemic risk.

Based on the results of this study, several policy implications can be drawn to enhance the stability and sustainability of agricultural supply chain financing. First, establishing multi-party risk-sharing platforms, including policy-based guarantee institutions, agricultural insurance companies, and government financial support, can reduce banks' credit risk exposure and strengthen trust among stakeholders. Second, improving farmers' creditworthiness is crucial for reducing default risk and promoting the efficient allocation of financial resources. Developing comprehensive credit rating systems and creating individual credit profiles can alleviate information asymmetry between financial institutions and borrowers, enabling more accurate risk assessments and facilitating farmers' access to financing. Integrating these systems with digital financial tools can further strengthen supervision and enforcement, thereby promoting a more sustainable credit environment. Third, incentivizing agricultural enterprises to provide credit guarantees through measures such as fiscal subsidies and tax incentives can enhance their willingness to participate in supply chain financing. By emphasizing cooperative benefits over punitive measures, these strategies encourage long-term collaboration between enterprises and farmers, thereby enhancing systemic resilience and promoting the sustainable development of agricultural supply chains. In summary, effective risk governance requires a combination of policy guidance, institutional support, and market incentives.

This study provides a structured framework for understanding strategic interactions and risk sharing in agricultural supply chains, but it also has certain limitations. The analysis primarily focuses on endogenous factors within the financing chain, while external shocks such as policy changes, climate risks, or market volatility are not fully considered. Future research could expand the model to include additional stakeholders, such as government agencies, creating a four-party framework, and incorporate cross-regional empirical validation to further test and refine the model's applicability.

Overall, this research highlights the importance of multi-stakeholder cooperation and internal risk governance mechanisms in promoting the stability of agricultural supply chain financing. It provides practical insights for policy makers and financial institutions to alleviate farmers' financing constraints and enhance the sustainable development of agricultural industry chain financing.

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Abbreviations

The following abbreviations are used in this manuscript:

ESS Evolutionarily Stable Strategy

Appendix A

Survey Questionnaire on Agricultural Industry Chain Financing

Dear Participant, this questionnaire is for academic research purposes. It aims to explore the risk management issues in the process of farmers' participation in agricultural industry chain financing. All responses will be kept strictly confidential. Your answers will not cause any adverse effects on you personally. Thank you for your cooperation!

I. Farmers' Financing Needs

1. What is your main crop? _____
2. Planting scale: Total _____ mu (Note: 1 mu $\approx$ 0.0667 hectares) (_____ greenhouses, _____ mu/greenhouse, _____ sticks/greenhouse)
3. Your cost and revenue information:

Year	Scale/mu	Yield/jin (Note: 1 jin = 0.5 Kg)	Price (Yuan/jin)	Cost (Yuan/mu)
2022				
2023				

4. Did you experience a shortage of funds during the planting period? ()
A. Yes B. No
5. If yes, how did you solve it? ()
A. Borrowed from relatives/friends B. Bank loan C. Personal savings D. Other
6. If you chose bank loan, the main reasons were (choose up to 2):
A. Low interest rate B. Large loan amount C. Simple procedure D. High efficiency
7. Your loan method from the bank: ()
A. Mortgage loan, collateral: _____ B. Guaranteed loan, guarantor: _____ C. Credit loan
8. If you did not apply for a bank loan, what were the main reasons? (choose up to 2)
A. Did not meet bank standards B. Loan amount too small C. Lack of collateral D. Complicated procedure, long approval time E. Other
9. Purpose of the loan: (choose up to 2)
A. Expand production (build greenhouses, rent land, etc.) B. Purchase seedlings
C. Buy fertilizer/pesticides D. Purchase machinery E. Introduce new planting techniques
F. Infrastructure (storage, water, electricity) G. Other _____
10. Do you think it's easy to get funding from banks? ()
A. Very difficult B. Difficult C. Average D. Relatively easy E. Easy
11. From the perspective of future farm operations, do you anticipate a need for loans? ()
A. Yes B. No C. Uncertain

II. Participation in Agricultural Industry Chain Financing

1. Are you aware of the "Mushroom Loan" agricultural industry chain financing product offered by banks? ()
A. Completely unaware B. Heard of it but not used C. Currently using

2. How did you learn about the “Mushroom Loan”? (choose up to 3)
A. Never learned about it B. Through relatives/friends C. TV, newspapers, internet
D. Government promotion E. Bank staff F. Enterprise promotion
3. If you participated in the “Mushroom Loan”, what were your reasons? (choose up to 3)
A. Enterprise provides guarantee, no collateral required
B. High loan efficiency and quick disbursement
C. Simple loan process D. Low interest rate
E. Meets different loan needs (large/small amounts)
4. How did you participate in the “Mushroom Loan”? ()
A. Guarantee from leading enterprise B. Credit loan C. Mortgage loan D. Other
5. If guaranteed by a leading enterprise, what other support did the enterprise provide? (select all that apply)
A. None B. Cash C. Agricultural inputs (seedlings, fertilizers, etc.)
D. Technical training E. Other
6. Your loan application details:

Year	Own Funds (Yuan)	Loan Applied (Yuan)	Bank Approved (Yuan)	Repayment Period (Years)	Interest Rate (%)
2022					
2023					

7. What is your repayment source when participating in chain financing? ()
A. Income used directly for repayment B. Borrowing C. Other
8. Have you ever failed to repay on time and in full? ()
A. Yes B. No
9. If yes, what were the reasons? (select all that apply)
A. Natural disasters reduced production B. Pests/diseases reduced production
C. Improper operations reduced production D. Significant price drops
E. Poor sales F. Enterprise default caused poor sales
10. If unable to repay on time/in full, what measures did you take? ()
A. Defaulted B. Applied for extension
C. Partial repayment with collateral for remainder D. Other
11. Does the bank monitor the usage of your loan funds? ()
A. Yes B. No
12. Are you satisfied with this loan product? ()
A. Satisfied B. Quite satisfied C. Neutral D. Somewhat dissatisfied E. Dissatisfied
13. Has your planting scale expanded due to the loan? ()
A. Yes B. No
14. Has the loan helped increase your income? ()
A. Yes B. No
15. If you have not participated in industry chain financing, what are the reasons? (select all that apply)
A. Unfamiliar with it B. No need C. Process too complex
D. Obtained funding from other sources E. High financing costs
F. Ineligible for industry chain financing

III. Risks in Agricultural Industry Chain Financing

1. Please rank the following sources of loan risk from highest to lowest:
A. Leading enterprises default and buy from other farmers

- B. Natural disasters reducing output
 C. Technical problems leading to lower yields and inability to repay
 D. Market price fluctuations reducing income
 E. Losses due to poor storage/transport technology
 F. Unstable policies or lack of protection of rights

2. Impact of different risk types on financing (check the appropriate box):

Risk Type	Very High	High	Medium	Low	No Impact
Moral Risk					
Natural Risk					
Technical Risk					
Price Risk					
Storage Risk					
Legal/Policy Risk					

3. At what level of loss would you be unable to bear it? (check the appropriate box):

Risk Type	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Moral Risk										
Natural Risk										
Technical Risk										
Price Risk										
Storage Risk										
Legal/Policy Risk										

IV. Data Collection for Evolutionary Game Simulation

Note: For yes/no questions, mark “√” for Yes and “×” for No.

- Company Name: _____
- Main Business: _____, Types of Crops: _____
- Number of cooperating farmers: _____ households; Does the enterprise purchase agricultural products from these farmers? (); Is a purchase order signed? (); Does the order include a guaranteed minimum price? ()
- How is the purchase price in the order determined? ()
 A. Slightly above market price B. Average market price C. Slightly below market price
- Total planting area by all farmers: _____ mu; Yield per mu: _____ jin; Purchase price: _____ Yuan/jin; Cost per mu: _____ Yuan; Net profit per mu: _____ Yuan
- Do farmers need to have some initial capital? (); If yes, how much? _____ Yuan; Typical loan amount: _____ Yuan; Loan interest rate: _____; This loan amount can cover _____ mu of planting.
- Processing, storage, and transportation costs per jin: _____ Yuan; Selling price per jin: _____ Yuan; Net profit per jin: _____ Yuan
- Does the enterprise require farmers to deposit funds in advance as a condition for providing a loan guarantee? (); If yes, amount: _____ Yuan; Is this amount deducted in case of default? (); Cooperative benefit: _____ Yuan/mu (includes seedlings, fertilizer, technology support, etc.)
- Cost incurred by farmers to find another guarantor after default: _____ Yuan; Cost to find a new bank: _____ Yuan (due to stricter terms)

10. Bank assessment and review cost: _____ Yuan; If the bank lends to a lower-risk project, what is the interest rate? _____
11. Does the enterprise provide rewards or additional penalties for farmer compliance or default? (); If yes, please describe:

12. Does the enterprise charge a guarantee fee? (); If yes, please specify:

13. Do farmers have counter-guarantee mechanisms? (); If yes, please specify:

14. Default situation of farmers: _____; Reason for default: _____; Consequences of default: _____ (to banks and enterprises)
15. Does the government provide rewards or penalties to banks for participating in industry chain financing? (); If yes, please describe:

16. Compared with the situation before using industry chain financing products, has the number of cooperating farmers increased significantly? ()
17. Has the implementation of the industry chain loan product increased the number of borrowing farmers? (); If yes, please describe:

Has it encouraged the bank to develop other industry chain loan products? (); If yes, what products?

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