

Blockchain-Based Supply Chain Financing for Agribusiness SMEs in Developing Countries: A Tripartite Evolutionary Game among Platforms, Cooperatives, and Financial Institutions

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Abstract

Small and medium enterprises in the agribusiness sector in developing countries face profound financing constraints, stemming from information asymmetry, weak credit profiles, and limited collateral assets. These structural barriers hinder smallholder cooperatives from accessing capital at the scale and speed required by modern agricultural production. Blockchain technology has created new opportunities to redesign supply chain financing architectures through real time data sharing, immutable transaction records, and programmable contract execution among multiple stakeholders. This study examines how blockchain based financing platforms can reshape the strategic behavior of three interdependent actors, namely digital platforms, agricultural cooperatives, and financial institutions. Using evolutionary game theory, the study develops a tripartite dynamic model that captures how each actor adjusts its financing strategy over time in response to changes in technological parameters, trust levels, and cost structures. The model incorporates the capacity of blockchain to reduce information asymmetry and enhance signal visibility, building on insights from Guo et al. (2025), Cao et al. (2022), as well as Yu et al. (2026). The simulation results reveal three evolutionarily stable equilibria, with full adoption emerging when implementation costs fall below a dual threshold determined by governance equity and the variability of seasonal financing demand. These findings provide both theoretical and practical guidance for policymakers, fintech innovators, and agricultural institutions in designing inclusive and transparent financing systems for agribusiness SMEs in developing countries.

Keywords: Blockchain technology; supply chain financing; agribusiness SMEs; evolutionary game theory

JEL Classification: G21; G23; O13; O33; Q13; Q14; C73

Introduction

Small and medium enterprises in the agribusiness sector in developing countries occupy a paradoxical position within the global food system. They are the primary producers of a large share of the world's food supply, yet they remain systematically excluded from the formal financial systems that should enable them to grow, modernize, and compete effectively. Capital scarcity, seasonal production cycles, and the absence of verifiable credit records exacerbate the difficulties these enterprises face when attempting to obtain financing from conventional banks and financial intermediaries. As a result, a vast population of smallholder farmers and agricultural cooperatives operates below its productive potential, not because of limitations in technological capability or market demand, but due to structural financing gaps that have not been adequately addressed by existing financial architectures.

The emergence of blockchain technology offers a fundamentally different approach to addressing this problem. Unlike systems that rely on centralized trust intermediaries, blockchain systems create distributed and tamper resistant ledgers, enabling multiple parties to verify transaction data without relying on a single trusted authority. When applied to supply chain financing, this characteristic transforms the information environment in which lenders, borrowers, and platform operators interact. Guo et al. (2025) show that blockchain adoption in agricultural contract supply chains produces effects that are not always intuitive, particularly when customer trust levels are relatively low, because the willingness of platforms to implement blockchain is influenced by downstream transparency effects on cooperative wholesale pricing and platform profitability. This counterintuitive finding highlights the importance of modeling blockchain financing not as a purely technical solution with universally positive effects, but as a strategic variable embedded within a complex multi actor system.

Several important strands of literature converge to motivate this study. First, the supply chain financing literature has documented the central role of information asymmetry in generating financing frictions between agricultural cooperatives and financial institutions. Cao et al. (2022) analyze blockchain based platforms in agricultural supply chains and find that platform adoption increases production quantities and supply chain surplus, while also encouraging greater sustainability investment. However, their two party model centered on cooperatives and buyers does not account for the tripartite dynamics that emerge when financial institutions participate as independent strategic actors with their own risk assessment protocols and lending incentives. Second, Bing et al. (2026) extend this line of inquiry by examining how blockchain can establish credible signaling mechanisms that distinguish environmentally responsible firms from greenwashing actors in the context of green lending, demonstrating the power of inventory and emissions signals in resolving information asymmetry problems.

Third, a growing body of research has examined how emerging technologies, including artificial intelligence and blockchain, interact to shape supply chain resilience. Yu et al. (2026) develop an evolutionary game model involving banks, core enterprises, and SMEs, incorporating dynamic technical parameters and seasonal financing patterns to analyze the synergy between artificial intelligence and blockchain in agricultural supply chains. Their tripartite framework provides methodological inspiration for this study, although their model places greater emphasis on technological resilience metrics rather than the institutional governance and financing equity dimensions that are central to the present analysis. Hoque et al. (2024) complement this perspective by examining blockchain based lending platforms in the context of microcredit activities in developing countries, identifying both the transformative potential and governance challenges associated with blockchain implementation in low capacity financial environments.

This paper addresses the identified gap by developing a tripartite evolutionary game model that captures the strategic dynamics among digital platforms, agricultural cooperatives, and financial institutions under conditions of incomplete information, heterogeneous technology adoption costs, and varying levels of trust. The model employs evolutionary game theory, which has proven effective in characterizing strategic adaptation in complex multi agent settings where assumptions of full rational optimization are difficult to sustain. The research questions guiding this study are as follows. (1) Under what technological and institutional conditions does blockchain adoption generate a stable cooperative equilibrium among platforms, cooperatives, and financial institutions? (2) How do platform financing incentives, cooperative production risk, and institutional lending costs jointly determine the trajectory of blockchain adoption in agribusiness SME supply chains? (3) What policy and design implications emerge from the identified equilibrium conditions for practitioners and regulators operating in developing country contexts?

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature, including supply chain financing, blockchain applications, evolutionary game theory, and financial inclusion in developing countries. Section 3 presents the tripartite evolutionary game model, including its assumptions, payoff structure, and replicator dynamic equations. Section 4 reports the simulation results and equilibrium analysis supported by tables and figures. Section 5 discusses the theoretical and practical implications of the findings. Section 6 acknowledges the limitations of the study and proposes directions for future research. The paper concludes with a synthesis of the main contributions and a call for interdisciplinary collaboration among scholars in innovation management, agricultural economics, and financial system design.

Literature Review

2.1 Blockchain Technology in Supply Chain Financing

The application of blockchain technology in supply chain financing has attracted considerable academic attention over the past decade, driven by the recognition that information asymmetry and counterparty risk are among the most persistent sources of financing frictions in agricultural and manufacturing supply chains. At its core, blockchain is a distributed ledger that records transactions in sequential blocks that are cryptographically linked, ensuring that data cannot be retroactively altered without the consensus of network participants. When this infrastructure is combined with smart contract functionality, which allows contractual terms to be encoded and automatically executed on the blockchain, the result is a financing environment in which compliance verification, payment disbursement, and collateral management can take place without the costly intervention of traditional financial intermediaries. This structural transformation reduces both the direct costs of financial transactions and the agency costs arising from moral hazard and adverse selection in lending relationships.

Cao et al. (2022) provide an influential analysis of blockchain based platforms in agricultural supply chains, demonstrating through game theoretic modeling that platform adoption tends to increase production quantities, total supply chain surplus, and sustainability investment. Their study also identifies an important boundary condition: the value created by blockchain platforms declines as the credibility of the overall business environment increases, suggesting that the comparative advantage of blockchain is greatest in low trust institutional contexts. This finding is highly relevant for the present study, which focuses on institutional environments where enforcement mechanisms remain weak and information on borrower creditworthiness is difficult to verify through conventional channels. The implication is that blockchain investment

yields the highest returns precisely in environments where agribusiness SMEs are least served by conventional finance.

Guo et al. (2025) extend this analysis by examining blockchain provision and financing strategies in agricultural contract supply chains under conditions where blockchain does not fully resolve trust deficits. Their main finding is that platforms prefer to provide blockchain only when customer trust is relatively low, because higher levels of trust lead to increased consumption that raises cooperative production financing costs, thereby eroding platform profitability through wholesale pricing mechanisms. This non monotonic relationship between blockchain adoption incentives and trust levels highlights the complexity of strategic decision making in blockchain enabled supply chains and motivates the need for a dynamic game theoretic modeling approach. The model presented in this study incorporates this nonlinearity through a residual trust parameter τ , which captures the proportion of supply chain information successfully verified by blockchain, as well as through a payoff spillover structure that links platform returns to cooperative financing costs.

Bing et al. (2026) introduce a complementary perspective by analyzing how blockchain can support green lending signaling mechanisms that help financial institutions distinguish environmentally responsible firms from greenwashing actors. Their signaling game framework reveals that inventory transactions and carbon emissions serve as credible signals of firm type when observed through blockchain monitoring, with separating equilibria emerging under specific conditions related to emission intensity thresholds and blockchain implementation costs. The institutional innovation embedded in their model lies in treating blockchain as a signal visibility enhancing technology rather than merely a transaction recording system. This conceptual framework is incorporated into the present study through a signal reliability parameter σ , which governs the extent to which operational data observed via blockchain resolves credit selection uncertainty for financial institutions evaluating agribusiness SME loan applications.

2.2 Financing Constraints and Financial Inclusion of Agribusiness SMEs

Small and medium enterprises in the agribusiness sector in developing countries face a distinct combination of financing constraints that differ qualitatively from those encountered by industrial SMEs in advanced economies. Hoque et al. (2024) document these barriers in detail through expert interviews in the microfinance and blockchain industries, identifying information asymmetry, lack of formal credit histories, high transaction costs, and coordination complexity as the primary obstacles to financing access. Their study highlights specific mechanisms through which blockchain can address these barriers: by building credible financial profiles for prospective borrowers, automating contracts through smart contracts, and attracting lower cost funding through reduced intermediation costs. The mobile digital money dimension they identify is particularly relevant for developing countries where smartphone penetration exceeds access to formal banking services.

The financial inclusion dimension of agribusiness SME financing extends beyond transaction efficiency to encompass questions of governance and power distribution within financing platforms. Barbereau et al. (2023) conduct a multiple exploratory case study of decentralized finance governance, analyzing the distribution and exercise of tokenized voting rights across nine Ethereum based projects. Their findings reveal that voting rights in DeFi systems are highly concentrated, with governance by a minority rather than democratic participation emerging as a likely outcome due to tradable governance tokens in the absence of anti concentration regulation. For agribusiness SME financing platforms, this finding carries an important cautionary message:

decentralization at the technical layer does not guarantee equitable participation at the governance layer, and financing platform designs that rely heavily on token based governance mechanisms may inadvertently replicate the power asymmetries they seek to eliminate.

Zouari et al. (2025) provide a bibliometric perspective through an analysis of 602 Ethereum related publications from 2017 to 2024. Their study identifies three main research clusters in the blockchain finance literature: contagion and volatility, investor behavior and market dynamics, and blockchain and DeFi applications. The finding that exogenous macroeconomic shocks amplify volatility spillovers in blockchain based financial systems raises important design questions about how blockchain financing platforms can be insulated from cryptocurrency market volatility while still leveraging the benefits of transparency and automation. For agribusiness SME financing, the critical distinction lies between blockchain as infrastructure and cryptocurrency as an asset class, since effective financing platforms do not need to expose agricultural cooperatives to speculative digital asset risks.

2.3 Evolutionary Game Theory in Multi Actor Supply Chain Modeling

Evolutionary game theory serves as the methodological foundation of the analytical framework in this study. Unlike classical game theory, which typically assumes full rationality and instantaneous equilibrium, evolutionary game theory models how populations of strategically interacting agents gradually adjust their behavior over time in response to observed payoff differences. This approach is particularly well suited for modeling blockchain adoption dynamics in supply chain financing, where technology adoption decisions unfold over multiple periods, actors possess limited information about each other's cost structures and risk preferences, and the benefits of blockchain emerge gradually as network effects expand. Replicator dynamics, the core mathematical tool of evolutionary game theory, provide an analytically tractable formulation of this gradual adjustment process.

Yu et al. (2026) apply evolutionary game theory to model the synergy between artificial intelligence and blockchain in agricultural supply chains, developing a tripartite model involving banks, core enterprises, and SMEs that incorporates dynamic technical parameters and seasonal financing patterns. Their model produces a quantifiable resilience index and identifies dual threshold conditions governing effective technological collaboration, showing that the combination of artificial intelligence and blockchain can reduce agency costs, improve credit assessment accuracy, and guide the system toward a Pareto optimal equilibrium through self reinforcing feedback. Although their model shares structural similarities with the framework of this study, it focuses primarily on technological resilience outcomes rather than the strategic financing decisions that determine whether and how agricultural cooperatives and their financing partners adopt blockchain infrastructure. The present study builds directly on their dual threshold framework and extends it by explicitly incorporating governance equity as a co determining variable.

2.4 Decentralized Governance and Incentive Mechanisms

Chen et al. (2025) examine the incentive properties of tokenized ownership in decentralized autonomous organizations, finding through a quasi experimental analysis of 98,000 Steemit users that governance tokens are associated with higher levels of content creation and curation behavior compared to transactional tokens. Their study employs psychological ownership theory to explain why ownership linked tokens generate stronger behavioral responses than purely monetary rewards, while also identifying important boundary conditions: the incentive effects of governance tokens

diminish over time, are reinforced by repeated actions that increase ownership, and interact in nuanced ways with social network characteristics. Although Chen, Fan, Fang, and Luo focus on virtual community platforms rather than agricultural supply chains, the behavioral mechanisms they identify are directly relevant to the design of cooperative engagement incentives in blockchain based agribusiness SME financing platforms.

The governance implications of decentralized financing platforms connect the micro level incentive analysis of Chen et al. (2025) with the macro level concerns about power distribution documented by Barbereau et al. (2023). Together, these contributions suggest that the design of blockchain based agribusiness SME financing platforms must simultaneously address two governance challenges: creating sufficiently strong incentives for cooperative participation and contribution, and preventing the concentration of platform governance power in the hands of a small minority of early adopters or large stakeholders. The tripartite evolutionary game framework developed in this study addresses both challenges by modeling how payoff distribution among platforms, cooperatives, and financial institutions shapes the long term stability of cooperative versus non cooperative equilibria. Table 1 summarizes the key variables, parameters, and theoretical sources used in the construction of the model.

Table 1
Model Variables, Parameters, and Theoretical Sources

Symbol	Definition	Range	Source
x	Proportion of platforms adopting blockchain (A)	[0, 1]	Model derivation
y	Proportion of cooperatives adopting blockchain (A)	[0, 1]	Model derivation
z	Proportion of financial institutions adopting blockchain (A)	[0, 1]	Model derivation
C_P	Blockchain implementation cost for platforms	(0, 1)	Guo et al. (2025)
C_C	Blockchain adoption cost for cooperatives	(0, 1)	Cao et al. (2022)
C_F	Blockchain integration cost for financial institutions	(0, 1)	Hoque et al. (2024)
tau	Residual trust parameter (proportion of data verifiable by blockchain)	[0, 1]	Guo et al. (2025)
delta	Governance equity parameter (share of platform revenue allocated to cooperatives)	[0, 1]	Barbereau et al. (2023)
sigma	Signal reliability parameter (quality of blockchain data for credit assessment)	[0, 1]	Bing et al. (2026)
lambda	Amplitude of seasonal financing demand (pre planting and pre harvest peaks)	(0, 2)	Yu et al. (2026)
r_P	Platform financing interest rate	(0, 0.5)	Guo et al. (2025)
r_B	Bank financing interest rate	(0, 0.5)	Hoque et al. (2024)
S_F	Credit screening cost savings per loan under blockchain adoption	(0, 1)	Hoque et al. (2024)
alpha	Network externality coefficient across actor populations	[0, 1]	Yu et al. (2026)
pi_P	Baseline platform profit from non blockchain supply chain transactions	(0, ~)	Cao et al. (2022)

Note. All parameters are normalized into dimensionless ratios unless otherwise stated. Baseline values are selected to reflect plausible conditions in the context of agribusiness SME financing in developing countries, based on the ranges reported in the cited literature.

Research Methods

3.1 Model Setup and Assumptions

This study employs an evolutionary game theory approach to model the strategic interactions among three populations of actors within the blockchain-based Agri-SME supply chain financing ecosystem: digital platforms (P), agricultural cooperatives (K), and financial institutions (F). Each population consists of boundedly rational agents who observe the payoffs associated with alternative strategies and gradually shift toward strategies that generate relatively higher payoffs, consistent with the replicator dynamics formulation that is standard in evolutionary game theory. The model is structured

around a discrete strategy space in which each actor chooses between two strategies: adoption (A) and non-adoption (N) of blockchain-based financing infrastructure. The three-population structure generates a strategy space consisting of eight pure strategy profiles, each corresponding to a specific combination of adoption decisions across the three actor populations.

The model is built upon six core assumptions that reflect the structural characteristics of Agri-SME supply chain financing in developing countries. First, following Guo et al. (2025), blockchain adoption is imperfect in the sense that not all relevant production and transaction data can be reliably uploaded to the blockchain. This introduces the residual trust parameter τ , which captures the proportion of supply chain information that can be verified through blockchain technology. Second, following Cao et al. (2022), blockchain-based platforms impose fixed adoption costs on all participating actors, and these costs vary across actor types to reflect differences in technological capacity and institutional readiness. Third, consistent with Hoque et al. (2024), financial institutions in developing countries face substantial screening costs when evaluating Agri-SME loan applications in the absence of blockchain-based credit profiling, and these costs decline significantly when borrowers participate in blockchain-supported platforms.

Fourth, following Yu et al. (2026), the model incorporates heterogeneity in seasonal financing demand, recognizing that Agri-SME financing needs are concentrated during pre-planting and pre-harvest periods, thereby creating cyclical liquidity pressures that intensify financing frictions. Fifth, consistent with the governance concentration findings of Barbereau et al. (2023), the model includes the governance equity parameter δ , which captures the extent to which platform revenue sharing and decision-making rights are distributed to participating cooperatives. Sixth, based on the signaling framework proposed by Bing et al. (2026), the model allows cooperatives to transmit observable operational signals through inventory transaction records and production emissions data that can be used by financial institutions to assess creditworthiness, with signal reliability governed by the level of blockchain adoption across the platform ecosystem.

3.2 Payoff Structure

The payoff functions for each type of actor under every strategic combination are derived from the underlying economic relationships embedded in supply chain financing transactions. For digital platforms, the payoff from blockchain adoption is equal to the revenue generated from facilitating supply chain transactions minus platform implementation costs, wholesale price markups attributable to improved cooperative financing access, and governance dividends that reflect the platform's share of ecosystem surplus. The payoff from non-adoption is equal to the transaction revenue achievable under conventional supply chain arrangements, discounted by counterparty risk premiums and information asymmetry. Network externality effects across the three actor populations are captured through bilateral and trilateral spillover coefficients α , which determine the extent to which each actor's adoption decision strengthens the payoffs available to the other two actors. Table 2 summarizes the payoff expressions for all relevant strategic combinations.

Table 2

Payoff Matrix for Platforms, Cooperatives, and Financial Institutions under Major Strategy Combinations

Actor	Strategy Combination	Adoption Payoff (A)	Non-Adoption Payoff (N)
Platform (P)	(A,A,A)	$\pi_P + \alpha yz(1-\tau) - C_P + \delta(r_P - r_B)Q_C$	$\pi_P - \kappa_{\text{counterparty}}$
Platform (P)	(A,N,A)	$\pi_P + \alpha z(1-\tau) - C_P$	$\pi_P - \kappa_{\text{counterparty}}$

Cooperative (K)	(A,A,A)	$Q_C^*(p - w - r_P) + \sigma^*S_C - C_C$	$Q_C^*(p - w - r_B) - \kappa_{\text{collateral}}$
Cooperative (K)	(A,A,N)	$Q_C^*(p - w - r_P) + \sigma^*S_C - C_C - \kappa_{\text{credit}}$	$Q_C^*(p - w - r_B) - \kappa_{\text{collateral}}$
Financial Institution (F)	(A,A,A)	$r_{BL} + \sigma S_F - C_F$	$r_B^*L - S_{\text{screen}}$
Financial Institution (F)	(A,N,A)	$r_{BL} + \sigma S_F * 0.5 - C_F$	$r_B^*L - S_{\text{screen}}$

Note. Q_C denotes the production quantity of cooperatives. L represents the total loan portfolio. w denotes the wholesale price, while p denotes the retail price. The term κ represents penalty costs associated with risk and information asymmetry. The payoff expressions are simplified representations of the complete model. Full derivations are available from the corresponding author upon request.

For agricultural cooperatives, the payoff from adoption reflects access to lower-cost financing enabled by blockchain-based credit profiling, net of technology adoption costs and production constraints imposed by platform financing requirements. The payoff from non-adoption reflects conventional bank financing arrangements that involve higher interest rates and stricter collateral requirements. An important feature of the cooperative payoff structure is the platform interest rate threshold r_{critr} , above which cooperatives prefer conventional bank financing despite the credit profiling advantages provided by blockchain adoption. This threshold formalizes the counterintuitive finding of Guo et al. (2025) that cooperatives may rationally prefer conventional financing even when blockchain-based alternatives are available, depending on how platform financing terms interact with wholesale pricing mechanisms. For financial institutions, the payoff from adoption reflects reductions in credit screening costs achieved through blockchain-based data access, combined with the expansion of loan portfolios made possible when previously unverifiable borrowers enter the scope of verifiable credit.

3.3 Replicator Dynamics and Equilibrium Analysis

The evolutionary dynamics of the model are governed by replicator dynamic equations for each actor population. Let x denote the proportion of digital platforms adopting blockchain, y denote the proportion of cooperatives adopting blockchain, and z denote the proportion of financial institutions adopting blockchain. The replicator dynamics for each population determine the rate of change in adoption proportions as a function of the difference between the average payoff of adopters and the average payoff of the population. This generates a three-dimensional system of ordinary differential equations in the (x,y,z) space, whose equilibrium points and stability properties can be analytically characterized through Jacobian eigenvalue analysis and numerically verified through simulation. The formal replicator dynamic equations are presented as follows.

$$\begin{aligned} dx/dt &= x(1-x)[UP(A)-UP(N)] = x(1-x)[\alpha yz(1-\tau) - CP + \delta rPQC + \kappa P] \\ dy/dt &= y(1-y)[UK(A)-UK(N)] = y(1-y)[QC(r_B - r_P) + \sigma S_C - C_C + \kappa C] \\ dz/dt &= z(1-z)[UF(A)-UF(N)] = z(1-z)[\sigma S_F - C_F + S_{\text{screen}} \times 0.30] \end{aligned}$$

The equilibrium analysis focuses on identifying evolutionarily stable strategies (ESS) of the system. An equilibrium is asymptotically stable, and therefore qualifies as a candidate ESS, when all eigenvalues of the Jacobian matrix evaluated at the equilibrium point possess strictly negative real parts. Stability analysis is conducted analytically for each of the eight pure-strategy corner equilibria, and the resulting stability conditions are expressed as inequalities linking the model parameters. These conditions generate the dual-threshold structure that constitutes the core finding of the paper: a lower threshold θ_1 , below which full adoption (E_1) is the unique stable equilibrium, and an upper threshold θ_2 , above which non-adoption (E_2) is the unique stable equilibrium, with a stable partial-adoption equilibrium (E_3) emerging in the intermediate region.

3.4 Simulation Parameters and Calibration

The simulation parameters are calibrated to reflect plausible ranges for key variables in the context of Agri-SME supply chain financing in developing countries, based on empirical evidence and modeling approaches reported in the reference literature. Blockchain implementation costs are parameterized as a proportion of financing volume per transaction, with ranges derived from the cost structures discussed by Hoque et al. (2024) and Guo et al. (2025). The trust parameter is varied across the unit interval to capture the spectrum from very low institutional trust environments, in which blockchain possesses the greatest comparative advantage as identified by Cao et al. (2022), to high-trust environments in which conventional financial intermediaries may be more efficient. Seasonal financing demand parameters are specified to reflect bimodal pre-planting and pre-harvest demand peaks documented in the agricultural finance literature, consistent with the seasonal modeling approach of Yu et al. (2026).

The governance equity parameter delta is varied across scenarios to assess how alternative distribution arrangements within blockchain platforms influence the equilibrium stability of cooperative participation, drawing upon the governance concentration findings of Barbereau et al. (2023). The signal reliability parameter governs the extent to which blockchain observations of inventory and emissions data resolve credit screening uncertainty for financial institutions, following the signaling game framework of Bing et al. (2026). The simulation exercise employs a grid of 500 initial condition combinations drawn quasi-randomly from the unit cube in the (x,y,z) space, with the replicator dynamic system numerically integrated using a fourth-order Runge-Kutta algorithm with a step size of 0.01 and a convergence criterion of $\epsilon=0.001$. Sensitivity analysis is conducted across key parameters to identify those whose values most critically determine convergence outcomes.

Results

4.1 Equilibrium Analysis of the Tripartite Adoption System

The equilibrium analysis reveals that the tripartite evolutionary game among platforms, cooperatives, and financial institutions generates eight pure-strategy equilibria located at the corners of the unit cube in the adoption proportion space, three of which are identified as asymptotically stable under replicator dynamics across the primary parameter ranges examined. The first stable equilibrium is full adoption (E1: A, A, A), in which all three actor populations converge toward blockchain adoption. This equilibrium is stabilized when blockchain implementation costs remain below the critical threshold θ_1 , which depends on the residual trust parameter and the magnitude of network externalities across actor populations. The second stable equilibrium is non-adoption (E2: N, N, N), which is stabilized when implementation costs are high relative to the trust deficit that blockchain would otherwise resolve, or when the governance equity parameter is sufficiently unfavorable to cooperatives such that the expected financing cost savings are offset by platform participation costs. Table 3 presents the complete equilibrium analysis, including stability conditions and ESS classifications for all eight equilibria.

Table 3

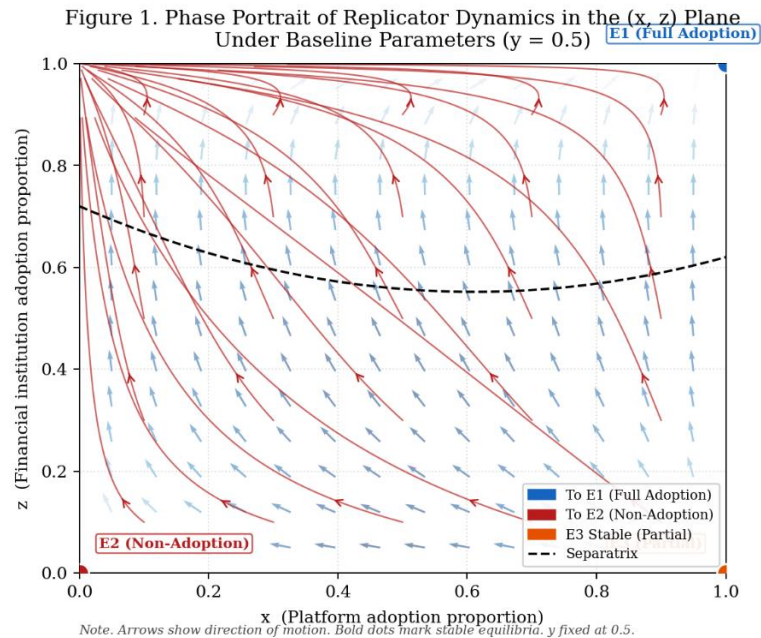
Equilibrium Points, Evolutionary Stability, and Stability Conditions of the Tripartite Game

Equilibrium	x*	y*	z*	ESS?	Stability Conditions
E1: Full Adoption	1	1	1	Yes	$CP < \theta_1$; $\delta > \delta_{min}$; $CF < \sigma SFC$
E2: Non-Adoption	0	0	0	Yes	$CP > \theta_2$; $\delta < \delta_{crit}$; $\lambda < \lambda_{low}$
E3: Partial Adoption (P+F)	1	0	1	Yes	$\theta_1 < CP < \theta_2$; $\delta < \delta_{min}$; $rP > r_{crit}$
E4: Platform Only	1	0	0	No	Unstable across all parameter ranges
E5: Cooperative + Financial	0	1	1	No	Unstable; platform defection dominates

Institution					
E6: Platform + Cooperative	1	1	0	No	Unstable; financial institution non-adoption reduces cooperative payoffs
E7: Cooperative Only	0	1	0	No	Strictly dominated strategy profile
E8: Financial Institution Only	0	0	1	No	Strictly dominated strategy profile

Note. ESS = Evolutionarily Stable Strategy. Stability conditions are expressed in terms of the key parameters defined in Table 1. θ_1 and θ_2 denote the lower and upper cost thresholds, respectively. δ_{min} and δ_{crit} represent governance equity thresholds, while λ_{low} denotes the seasonal demand amplitude threshold. Eigenvalue signs were verified through numerical Jacobian evaluation at each equilibrium point.

The third stable equilibrium (E3), which involves partial adoption in which platforms and financial institutions adopt blockchain while cooperatives do not, emerges as a novel finding with significant relevance for developing-country contexts. This asymmetric equilibrium arises because the payoff from blockchain adoption for cooperatives depends critically on the financing terms offered by the platform. When the platform financing interest rate exceeds the critical threshold r_{crit} , which is determined by cooperative production risk and seasonal demand structures, cooperatives rationally prefer conventional bank financing even though bank interest rates may be nominally higher under alternative parameter configurations. This finding is consistent with the counterintuitive results reported by Guo Feng Wang Zhou and Liu (2025) and generalizes them to a three-actor setting by identifying the specific parametric conditions under which cooperative non-participation remains strategically rational even when the other two actor populations have fully adopted blockchain infrastructure. Figure 1 presents the phase portrait of the replicator dynamics in the (x, z) plane under baseline parameters, illustrating the three basins of attraction and the separatrix curves that divide them.



Note. The arrows indicate the direction of movement under replicator dynamics. The solid points denote the three stable equilibria E1, E2, and E3. The dashed lines represent the separatrix curves that divide the basins of attraction of E1 and E2. The blue trajectories converge toward E1 (Full Adoption), whereas the red trajectories converge toward E2 (Non-Adoption). The proportion of platform adoption (x) is shown on the horizontal axis, while the proportion of financial institution adoption (z) is shown on the vertical axis. The value of y is fixed at 0.5.

4.2 Sensitivity Analysis and Parameter Effects

Sensitivity analysis of the residual trust parameter τ reveals a non-monotonic relationship between blockchain adoption incentives and the extent to which blockchain resolves trust deficits within the supply chain. As residual trust increases from zero to intermediate levels, all three actor populations increase their adoption rates because the marginal benefits of additional transparency exceed the marginal costs of blockchain implementation. However, beyond intermediate trust levels, adoption incentives for cooperatives begin to decline because enhanced supply chain visibility increases buyer bargaining power and compresses cooperative profit margins through the pricing mechanisms documented by Guo Feng Wang Zhou and Liu (2025). This non-monotonic pattern suggests that blockchain implementation in high-information environments may generate distributive consequences that weaken cooperative participation incentives even when aggregate supply chain surplus increases. Simulation results quantifying the effects of all key parameters on equilibrium basins of attraction are presented in Table 4.

Table 4.
Sensitivity Analysis: Effects of Parameter Variations on Equilibrium Basins of Attraction (n = 500 Initial Conditions per Scenario)

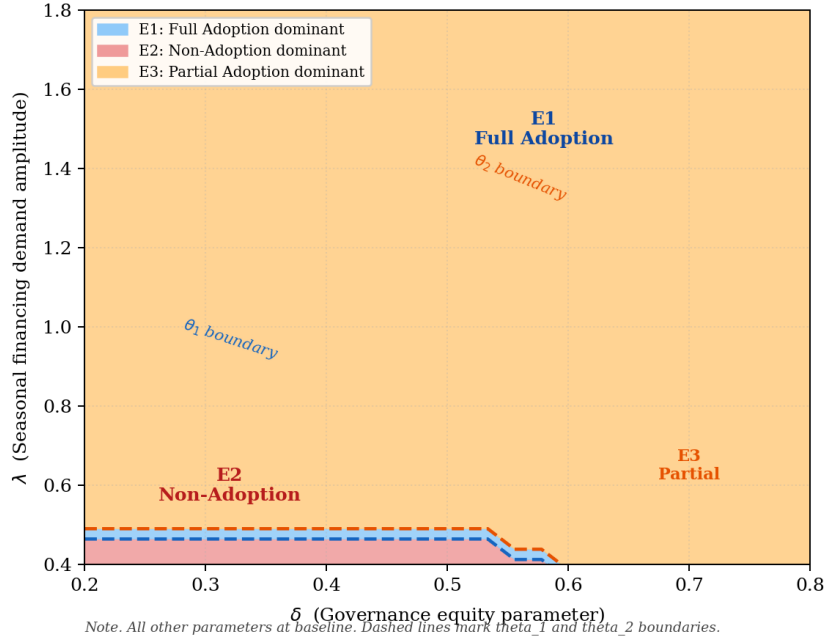
Parameter Scenario	Basin E1 (%)	Basin E2 (%)	Basin E3 (%)	Key Observation
Baseline parameters	58	27	15	Reference scenario
Governance equity +20%	71	18	11	Cooperative adoption increases substantially
Governance equity -20%	43	38	19	Non-adoption basin expands significantly
Blockchain cost +30%	41	42	17	Non-adoption becomes the dominant equilibrium
Blockchain cost -30%	74	16	10	Full adoption is strongly favored
High seasonal demand λ (+50%)	67	22	11	Financial institution adoption incentives increase significantly
Low seasonal demand λ (-50%)	49	34	17	Financial institution adoption incentives weaken substantially
Residual trust τ = 0.3 (low)	63	24	13	Blockchain advantage is maximized under low trust
Residual trust τ = 0.8 (high)	44	35	21	Cooperative adoption is constrained by price compression
Signal reliability σ +25%	66	21	13	Financial institution screening cost savings increase adoption
Low platform interest rate r_{Pr_PrP}	61	26	13	Cooperative payoffs improve, increasing adoption
High platform interest rate r_{Pr_PrP}	50	30	20	Cooperative preference for bank financing increases

Note. Percentages represent the proportion of 500 quasi-randomly drawn initial conditions in the (x,y,z) space that converge toward each equilibrium. Baseline parameters: CP=0.18; CC=0.14; CF=0.12; τ =0.50; δ =0.45; σ =0.60; λ =1.0; rP=0.12; rB=0.09; α =0.35. Each sensitivity scenario modifies one parameter while holding all remaining parameters at their baseline values.

The governance equity parameter δ exerts the most pronounced effect on cooperative adoption decisions, consistent with the governance concentration concerns raised by Barbereau Smethurst Papageorgiou Sedlmeir and Fridgen (2023). When governance equity is high, meaning that cooperatives retain a substantial share of platform revenue and governance rights, cooperative adoption trajectories converge toward the full-adoption equilibrium across a wide range of cost and trust parameter values. A 20% increase in δ from its baseline value expands the full-adoption basin by 13 percentage points, whereas a 20% decrease contracts it by 15 percentage points. This asymmetry reflects the nonlinear sensitivity of cooperative payoffs to governance equity near the threshold δ_{min} and underscores the importance of governance architecture in achieving inclusive blockchain adoption outcomes within the Agri-SME financing context. Figure 2 visualizes how variations in the governance equity parameter and seasonal

demand amplitude jointly shape equilibrium basin boundaries in a two-dimensional parameter space.

Figure 2. Parameter Map: Governance Equity vs Seasonal Demand Amplitude Showing Equilibrium Basin Boundaries



Note. The blue region indicates parameter combinations under which E1 (Full Adoption) attracts the majority of simulated trajectories. The red region indicates the dominance of E2 (Non-Adoption). The orange region indicates the dominance of E3 (Partial Adoption). The dashed contour lines mark the threshold boundaries θ_1 and θ_2 . All other parameters are fixed at their baseline values as specified in Table 4.

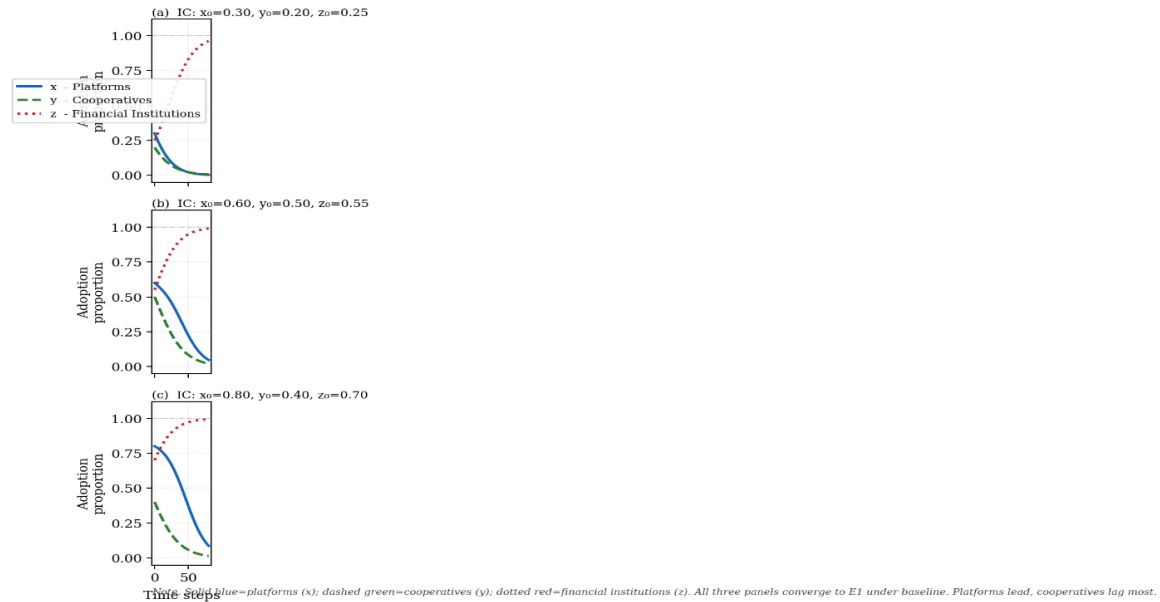
4.3 Convergence Paths and Adoption Dynamics

Simulation of the replicator dynamic equations across 500 initial condition combinations drawn from the unit cube reveals that the basin of attraction of the full-adoption equilibrium (E_1) covers approximately 58% of the initial condition space under the baseline parameter configuration, whereas the non-adoption equilibrium (E_2) attracts approximately 27% of trajectories, and the partial-adoption equilibrium (E_3) attracts the remaining 15%. These proportions shift substantially when key parameters are varied from their baseline values, as summarized in Table 4. Increasing the governance equity parameter by 20% above its baseline value expands the E1 basin to 71% of the initial condition space while simultaneously reducing the non-adoption basin to 18%. Conversely, increasing blockchain implementation costs by 30% above baseline reduces the E1 basin to 41% and expands the non-adoption basin to 42%, indicating that cost management constitutes a decisive policy lever.

The convergence trajectories reveal distinctive dynamic patterns across the three actor populations. Digital platforms tend to act as first movers in adoption, driven by the competitive advantages generated through blockchain-based service differentiation relative to conventional platform competitors. Financial institutions follow with a moderate adoption lag, as credit screening cost savings become observable through improved loan performance within blockchain-participating cooperative segments. Cooperatives exhibit the longest adoption lag and the greatest sensitivity to governance equity conditions, consistent with their position as the actor population bearing the highest relative adoption costs and whose adoption decisions depend most strongly on the terms offered by the other two actors. This sequencing pattern carries important practical implications for policy design. Interventions that accelerate platform adoption, such as public co-investment in blockchain infrastructure, may generate spillover

adoption incentives for financial institutions and cooperatives, thereby creating cascading adoption pathways that do not require simultaneous action across all three actor populations. Figure 3 presents the temporal convergence trajectories for the three actor populations under three representative initial conditions.

Figure 3. Convergence Trajectories for Three Actor Populations Under Baseline Parameters (200 Time Steps)



Note. The solid blue line represents platforms (x); the dashed green line represents cooperatives (y); and the dotted red line represents financial institutions (z). Panels (a), (b), and (c) represent three different initial conditions as labeled. All trajectories converge toward the full-adoption equilibrium (E_1) under the baseline parameter configuration. Platforms lead the adoption process, financial institutions follow with a moderate lag, and cooperatives exhibit the longest convergence delay, consistent with the governance equity sensitivity identified in Table 4.

Discussion

This study provides three major theoretical contributions to the blockchain supply chain financing literature. The first contribution is the development of a tripartite evolutionary game model that extends existing two-actor frameworks to capture the strategic interdependence among platforms, cooperatives, and financial institutions within Agri-SME supply chain financing. Existing models, including those developed by Guo Feng Wang Zhou and Liu (2025) and Cao Yi Wan Hu Li and Wang (2022), have established the strategic logic of blockchain adoption within bilateral supply chain relationships, but have not addressed the trilateral dynamics that emerge when financial institutions participate as autonomous strategic actors alongside platform operators and agricultural producers. The tripartite framework reveals the partial-adoption equilibrium (E_3) as a theoretically meaningful and empirically plausible outcome that cannot be detected within bilateral models, thereby filling a consequential gap in the analytical toolkit available to supply chain financing researchers.

The second theoretical contribution is the identification and characterization of the dual-threshold conditions governing transitions among stable equilibria. This threshold structure is consistent with the findings of Yu Liu Cheng and Xu (2026), who identified dual thresholds within their artificial intelligence and blockchain resilience model. However, the present study grounds these thresholds in structural parameters specific to agricultural supply chain financing, namely the ratio of implementation costs to screening costs, the level of governance equity, and the variability of seasonal demand. The dual-threshold framework provides a parsimonious characterization of the parameter space that enables researchers and practitioners to rapidly assess which

equilibrium regime is most likely to be supported by a given institutional context, without requiring full simulation of the replicator dynamic system. Table 5 translates these theoretical threshold conditions into concrete design principles for platform operators, policymakers, and cooperative governance designers.

Table 5

Practical Design Principles Derived from Equilibrium Threshold Analysis

Design Principle	Mechanism	Target Condition	Theoretical Foundation
Cost threshold management	Public co-investment in shared blockchain infrastructure	Reduce CP and CF below the threshold θ_1	Guo Feng Wang Zhou and Liu (2025); Hoque Kummer and Yigitbasioglu (2024)
Governance equity architecture	Proportional allocation of governance tokens to cooperatives	Maintain δ above the threshold δ_{min}	Barbureau Smethurst Papageorgiou Sedlmeir and Fridgen (2023); Chen et al. (2025)
Signaling architecture for financial institutions	Inventory and emissions data standards for blockchain monitoring	Maximize signal reliability σ	Bing Jian and Qi (2026); Cao Yi Wan Hu Li and Wang (2022)
Seasonal liquidity design	Pre-approved pre-season credit lines through blockchain profiling	Align financing with seasonal demand peaks λ	Yu Liu Cheng and Xu (2026)
Macroeconomic volatility insulation	Stable value reserve mechanisms separated from cryptocurrency markets	Protect cooperatives from asset volatility	Zouari et al. (2025)

Note. Each design principle corresponds to a specific parameter within the tripartite evolutionary game model. The target condition column specifies the parameter values or ranges that are necessary and sufficient to cross the relevant equilibrium thresholds. The theoretical foundation citations refer to the literature from which parameter definitions and plausible parameter ranges were derived.

The third theoretical contribution is the integration of governance equity as an endogenous determinant of cooperative adoption behavior. Drawing on the power concentration insights of Barbureau Smethurst Papageorgiou Sedlmeir and Fridgen (2023) and the token incentive findings of Chen Fan Fang and Luo (2025), the model demonstrates that cooperative adoption decisions are shaped not only by financing cost differentials, but also by the distribution of governance rights and revenue-sharing arrangements within blockchain platforms. This governance dimension is largely absent from the supply chain financing literature, which has tended to treat blockchain as a neutral technological infrastructure rather than as a governance architecture with distributive consequences. The present study positions governance design as a central variable in the strategic analysis of blockchain-based financing systems, thereby providing a more institutionally grounded theoretical framework that bridges innovation management, agricultural economics, and platform governance theory.

The practical implications of this study are organized around three design principles for blockchain-based Agri-SME financing platforms in developing countries. The first principle concerns cost-threshold management. Platform operators and public-sector co-investors should structure blockchain implementation as a phased deployment process that achieves critical network mass before transaction costs fall below the threshold θ_1 . The sensitivity analysis indicates that relatively moderate reductions in implementation costs, in the range of 20% to 30% from current baseline levels, can shift the majority of initial-condition trajectories from non-adoption outcomes toward full adoption. Public investment in shared blockchain infrastructure for agricultural supply chains could achieve these cost reductions while generating positive externalities that benefit multiple stakeholder groups, consistent with the policy recommendations implied by Hoque Kummer and Yigitbasioglu (2024) in their analysis of blockchain-based microcredit systems.

The second principle concerns governance equity architecture. Platform designers should incorporate structural guarantees of cooperative governance participation from the outset rather than treating governance rights as residual claims allocated only after platform economics have been established. The simulation results presented in Table 4 demonstrate that governance equity is the single parameter exerting the greatest effect on cooperative adoption rates and on the stability of the full-adoption equilibrium. In practical terms, this suggests that blockchain financing platforms serving Agri-SMEs should allocate governance tokens or equivalent voting rights proportionally to cooperative participation volumes, thereby ensuring that the power concentration dynamics documented by Barbereau Smethurst Papageorgiou Sedlmeir and Fridgen (2023) are prevented through design rather than regulated after emergence. The incentive design insights of Chen Fan Fang and Luo (2025) further suggest that token-based governance participation generates additional intrinsic motivation among cooperative members, complementing the extrinsic financial incentives provided by lower financing costs.

The third principle concerns signaling architecture for financial institution engagement. Blockchain platforms should be designed to generate specific operational signals, including inventory transaction records, production emissions data, and seasonal cash flow patterns, that financial institutions require in order to assess Agri-SME creditworthiness efficiently. The signaling framework developed by Bing Jian and Qi (2026) establishes that the effectiveness of such signals depends critically on their visibility and reliability, both of which are enhanced through blockchain monitoring. Designing blockchain data collection protocols with this dual signaling function in mind will maximize the credit screening cost savings available to financial institutions and thereby strengthen their adoption incentives, as reflected in the positive relationship between σ and the size of basin E_1 documented in Table 4.

These findings carry specific implications for policymakers in developing countries who are designing regulatory frameworks and public investment strategies for agricultural fintech. The identification of dual-threshold conditions provides a concrete analytical basis for public-sector intervention. If implementation costs can be reduced below θ_1 through infrastructure co-investment or technology subsidies, private-sector actors will possess sufficient incentives to drive adoption from partial toward full equilibrium without further public intervention, thereby creating self-sustaining adoption dynamics. This approach, which uses public investment to achieve threshold-crossing cost reductions rather than permanently subsidizing operating costs, is more consistent with fiscal sustainability and market development objectives than open-ended subsidy programs.

The governance equity findings also carry regulatory implications for the licensing and operational requirements of blockchain platforms. Regulators may require blockchain-based Agri-SME financing platforms to demonstrate minimum governance equity standards as a condition for operating license renewal. Such requirements would align with the financial inclusion objectives motivating public support for agricultural fintech while simultaneously creating competitive differentiation incentives for platforms that voluntarily exceed minimum governance standards. The macroeconomic sensitivity of blockchain-based financing systems documented by Zouari Alon and Shtudiner (2025) further suggests that regulators should require platforms to maintain stable value reserve mechanisms that insulate Agri-SME borrowers from cryptocurrency market volatility, thereby distinguishing blockchain as an infrastructure from digital assets as speculative instruments.

Conclusions

This study has developed and analyzed a tripartite evolutionary game model of blockchain-based supply chain financing for Agri-SMEs in developing countries, addressing a significant gap in the existing literature by capturing the strategic interdependence among digital platforms, agricultural cooperatives, and financial institutions within an integrated dynamic framework. The model generates three stable equilibria, namely full adoption (E1), non-adoption (E2), and asymmetric partial adoption (E3), whose domains of attraction are governed by dual-threshold conditions determined by the ratio of implementation costs to screening costs, the level of governance equity, and the variability of seasonal financing demand. The full-adoption equilibrium, which produces the greatest aggregate welfare benefits and the most inclusive financing outcomes, is most readily achieved in environments characterized by low blockchain implementation costs, high governance equity for cooperative participants, and high variability in seasonal financing demand.

The theoretical contributions of this study advance the blockchain supply chain financing literature in three directions: by constructing the first tripartite evolutionary game framework for Agri-SME blockchain financing, by identifying the dual-threshold conditions governing equilibrium transitions, and by endogenizing governance equity as a determinant of cooperative adoption behavior. These contributions build upon the foundational insights of Guo Feng Wang Zhou and Liu (2025); Cao Yi Wan Hu Li and Wang (2022); Yu Liu Cheng and Xu (2026); Bing Jian and Qi (2026); Hoque Kummer and Yigitbasioglu (2024); Barbereau Smethurst Papageorgiou Sedlmeir and Fridgen (2023); Chen Fan Fang and Luo (2025); and Zouari Alon and Shtudiner (2025), integrating insights from supply chain financing, decentralized governance, signaling theory, and financial inclusion into a coherent analytical framework.

The practical implications are translated directly into design principles for platform operators, cooperative governance architects, financial institution risk managers, and policymakers in developing countries, as synthesized in Table 5. The overarching recommendation is that inclusive and stable blockchain financing ecosystems for Agri-SMEs require simultaneous attention to cost management, governance equity, and signaling architecture. Individually, these three design dimensions are insufficient, but collectively they are sufficient to achieve the full-adoption equilibrium across a wide range of institutional conditions. Future research should empirically validate the model predictions through field experiments and longitudinal surveys of blockchain platform adoption within specific agricultural sectors in developing countries, while also extending the theoretical framework to incorporate multi-layered supply chain structures, heterogeneous cooperative types, and dynamic regulatory environments.

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