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Article

Biomechanics-inspired game analysis of the rural e-commerce ecosystem: An analogy of intercellular interactions among four main entities

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Abstract: Biomechanics is becoming increasingly important in the field of biomedical science, impacting areas such as molecular biology and nanotechnology. This study draws on the principles of biomechanics to analyze the rural e-commerce ecosystem, focusing on the analogy of intercellular interactions among new farmers, e-commerce platforms, logistics companies, and local governments. The purpose of this study is to construct a four-party evolutionary game model that encompasses the dynamic interactions and strategic behaviors within the rural e-commerce ecosystem, aiming to explore the cooperative dynamics and strategic evolution among these four main entities. From a biomechanical perspective, treating these entities as “cells” and market forces as “mechanical signals,” we apply game theory and numerical simulation to analyze their strategic choices and the stability of the ecosystem at different evolutionary stages. The study finds that: government subsidies have a double-edged sword effect, stimulating the adoption of e-commerce, but requiring careful adjustment to prevent market imbalances. Cooperation between e-commerce platforms and logistics companies is crucial for improving supply chain efficiency. The strategic shift of new farmers towards active use of e-commerce is vital for the upward movement of agricultural products. System stability is a dynamic balance influenced by subsidy policies, the degree of cooperation, and the willingness of new farmers to adopt e-commerce. This research provides a new perspective for understanding strategic interactions by introducing biomechanical concepts into the analysis of business ecosystems. In practice, it offers actionable insights for policymakers and industry players to optimize the rural e-commerce ecosystem, promoting agricultural modernization and rural revitalization.

Keywords: biomechanics; rural e-commerce ecosystem; evolutionary game model; intercellular interactions analogy; strategic interactions in agriculture

1. Introduction

In the 21st century, biomechanics plays an increasingly important role in the field of biomedical science [1]. It not only focuses on motion, deformation, and forces within biological systems but also involves cutting-edge scientific fields such as molecular biology, genomic engineering, bioimaging, and nanotechnology [2]. With the rapid development of these technologies, our understanding of the mechanobiology of genes, proteins, cells, tissues, and organs is continuously deepening [3]. This knowledge not only drives the development of new diagnostic tools and treatment methods but also provides us with new insights into ourselves and our interactions with the environment [4].

The interactions and games among the four main entities in the rural e-commerce ecosystem—new farmers, e-commerce platforms, logistics companies, and local governments—are part of a complex dynamic system. New farmers need to adjust production plans according to market demand, e-commerce platforms need to balance product supply and consumer demand, logistics companies need to optimize delivery routes and times, and local governments need to make policy support and financial subsidies to promote rural economic development. The interactions among these entities affect not only the balance of the ecosystem but also the development of the entire rural economy [5].

In the field of biomechanics, the interaction and mechanical response between cells are one of the key research areas. Cells communicate and respond mechanically through the extracellular matrix and intercellular signaling [2]. These interactions determine cell growth, differentiation, and tissue formation. By analogy to the rural e-commerce ecosystem, we can consider new farmers, e-commerce platforms, logistics companies, and government agencies as “cells” in the supply chain, interacting and playing games through “mechanical signals” such as market information and price changes [6]. This analogy not only provides us with a new perspective to understand the game problems in the business ecosystem but also offers an interdisciplinary application scenario for biomechanics research. By applying biomechanical concepts to the management of business ecosystems, we can gain a deeper understanding of the dynamic changes and mechanical responses within the ecosystem, thereby providing new theories and methods for the sustainable development of the ecosystem.

2. Literature review

The integration of e-commerce within the agricultural supply chain, particularly focusing on the upstream movement of agricultural products, has been a subject of increasing scholarly interest. The upstream movement of agricultural products of agricultural products refers to the process of transporting agricultural products from production areas (rural regions) to consumer markets (urban areas), a process that is of significant importance for increasing farmers’ income and promoting economic development in rural areas [7,8]. The primary objective of the interactions and cooperation among various entities in the rural e-commerce ecosystem is to achieve “agricultural products moving from villages to cities.” Under the backdrop of “digital commerce empowering agriculture,” the upstream movement of agricultural products has become a key pathway for advancing the rural revitalization strategy and achieving agricultural modernization [9]. Yet, this process faces numerous challenges, such as an imperfect supply chain system, elevated logistics costs, inadequate coordination among stakeholders, and market information asymmetry [8]. In recent years, research related to the upward movement of agricultural products has predominantly focused on macro-level aspects such as business model innovation [10], supply chain optimization [11], the development of social e-commerce [12], and policy support that drive the upward movement of agricultural products [13]. There is a lack of research that concentrates on the micro-level dynamics of how multiple stakeholders co-evolve within the agricultural product supply chain.

This section reviews the literature that employs evolutionary game theory to analyze the interactions and strategic choices among multiple stakeholders within this complex system. As shown in **Table 1**, we conducted a comparative analysis of the relevant literature from five aspects: research theme, research content, research method, research findings, and the game theory entities analyzed [11,14–21].

Table 1. Comparative analysis of relevant literature.

No.	Research Theme	Research Content	Research Method	Research Findings	player
[11]	Sustainable Development Pathways for Agri-Food Supply Chains	Establishing a sustainable supply chain ecosystem empowered by cross-border e-commerce platforms.	Hybrid grounded theory and DEMATEL-ISM-MICMAC model	Proposes a set of pathways to achieve the sustainability of the supply chain.	Government, platforms, consumers, supply chain participants
[14]	Logistics and Supply Chain Cooperation	Ecological cooperation between logistics platforms and suppliers, emphasizing equilibrium conditions for cooperation.	Game-theoretic model	Highlights the importance of logistics in agricultural product upstreaming.	Logistics platforms, suppliers
[15]	Policy Influence on Agricultural E-commerce	Impact of government subsidies on agricultural e-commerce.	Stackelberg game theory	Direct government subsidies significantly enhance the sales and green credentials of agricultural products.	Government, farmers
[16]	Quality and Safety Traceability	Exploring strategies around quality and safety traceability in rural e-commerce.	Tri-partite evolutionary game model	Emphasizes the importance of quality and safety for the success of agricultural e-commerce.	Producers, supermarkets, e-commerce platforms
[17]	E-commerce Poverty Alleviation Cooperation	Tripartite cooperative mechanism in e-commerce poverty alleviation.	Evolutionary game method	Provides insights on how rural e-commerce can promote development in impoverished areas through multi-party cooperation.	Government, e-commerce enterprises, consumers
[18]	Platform Governance and Product Quality	Constructing a game model between the government, platforms, and merchants to analyze factors affecting product quality optimization in e-commerce.	Evolutionary game theory	Offers guidance on enhancing the quality of agricultural products in rural e-commerce.	Government, platforms, merchants
[19]	E-commerce Platform Construction in Agricultural Wholesale Markets	Analyzing behavior choices of agricultural wholesale markets, local governments, and wholesalers in the construction of e-commerce platforms.	Tri-partite evolutionary game model	Helps understand the interactions and interest coordination among multiple stakeholders in the rural e-commerce ecosystem.	Agricultural wholesale markets, local governments, wholesalers
[20]	Research on Evolutionary Traceability Decision-Making	Constructing a tri-partite evolutionary game model consisting of producers, supermarkets, and e-commerce platforms.	Evolutionary game model	If the benefits of participating in QST exceed the spillover effects of other stakeholders participating in QST, all stakeholders in the dual channel agricultural supply chain will eventually voluntarily participate in QST.	Producers, supermarkets, e-commerce platforms
[21]	Interaction between joining platform blockchain technology and channel encroachment	The interaction between joining the platform blockchain technology strategy and channel encroachment decision for fresh agricultural product firms.	Theoretical model analysis	Demonstrates the dependency of strategies to join the platform blockchain technology on consumer sensitivity to the freshness-keeping effort level of fresh agricultural products, consumer's trust degree of freshness-keeping effort level, and the unit blockchain operation cost.	Suppliers, e-commerce platforms

Current research indicates that the development of rural e-commerce ecosystem is a multidimensional and interdisciplinary field of study, covering a range of themes from sustainable development [11], logistics cooperation [14], policy impact [15], quality and safety traceability [16], to e-commerce poverty alleviation [17]. These researches delves deeply into key issues such as the impact of cross-border e-commerce platforms on supply chain ecosystems, ecological cooperation between logistics platforms and suppliers, and the role of government subsidies in agricultural e-commerce. The research perspective is innovative, covering the interactions and cooperation of multiple stakeholders including governments, e-commerce platforms, consumers, and suppliers, demonstrating the researchers' attempts to understand and solve supply chain issues from various angles. The research methods are scientific, including hybrid grounded theory, DEMATEL-ISM-MICMAC models, game-theoretic models, and others, reflecting the systematic and in-depth nature of the research. The findings are practical, offering guidance and suggestions for the sustainable development of supply chains, policy formulation, platform governance, and product quality optimization [14–21].

However, existing research may have limitations, particularly in terms of attention to small-scale participants such as new farmers and individual farmers who play a foundational role in the supply chain. Additionally, research on consumer behavior may not be sufficiently detailed, with the needs and reactions of different consumer groups potentially being overlooked. Future research can further explore the roles and impacts of more supply chain participants, including new farmers, as well as the diversity of consumer behavior.

Considering the complexity and dynamics of rural e-commerce ecosystems, it may be necessary for existing research to further expand from a biomechanical perspective. A biomechanical perspective can help researchers more accurately simulate and analyze the dynamic interactions and mechanical responses within the supply chain, especially considering how multiple stakeholders interact and compete through mechanical signals such as price, demand, and service levels. This interdisciplinary approach could provide new theoretical and practical guidance for optimizing balance and development of the ecosystem enhancing the practicality and accuracy of research. Therefore, future research could consider combining biomechanical and game-theoretic methods to more comprehensively understand and address issues in the management of rural e-commerce ecosystems.

3. Theoretical framework

From the perspective of biomechanics, we can analogize the interactions among the four main entities in the rural e-commerce ecosystem (new farmers, e-commerce platforms, logistics enterprises, and government departments) to intercellular interaction models, constructing a theoretical framework. **Figure 1** is a theoretical framework based on intercellular interactions, aimed at providing a theoretical basis for studying the game relationships among these entities.

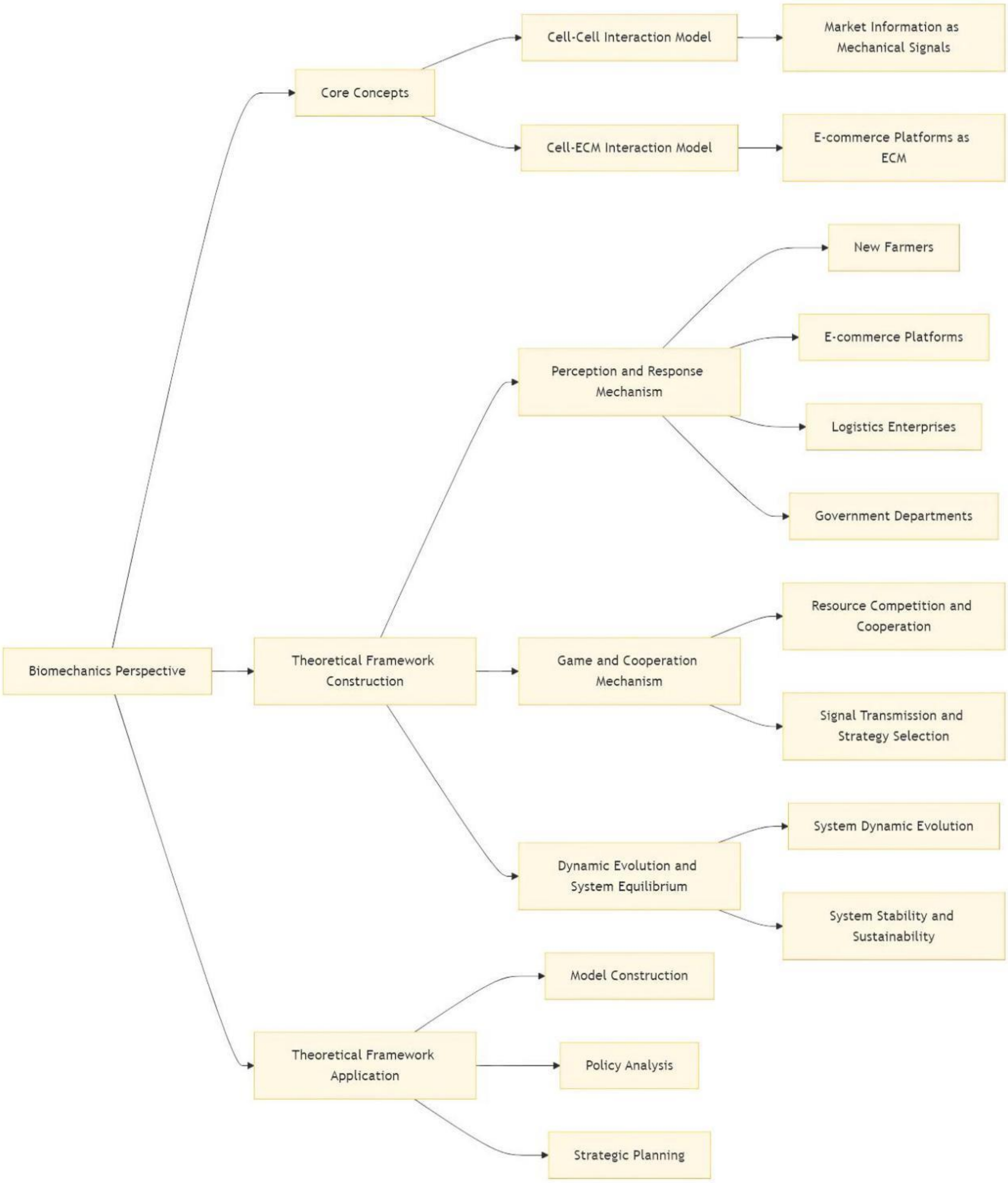

Figure 1. Biomechanical-game theory theoretical analytical framework.

3.1. Core concepts of the theoretical framework

(1) Cell-cell interaction model: In biomechanics, cells communicate and coordinate behavior through mechanical signals (such as traction forces, compression forces, and shear forces). In the rural e-commerce ecosystem, these mechanical signals can be likened to market information (such as price, demand, and policy changes) [1,4].

(2) Cell-extracellular matrix (ECM) interaction model: The interaction between cells and ECM affects cellular behavior and function. In the rural e-commerce ecosystem, e-commerce platforms can be seen as ECM, providing a platform for support and information exchange for new farmers [4].

3.2. Construction of the theoretical framework

(1) Perception and Response Mechanisms

New farmers: As “cells” that perceive market information, new farmers adjust production strategies according to market demand, similar to how cells sense and respond to external mechanical signals [22].

E-commerce platforms: Acting as “ECM,” e-commerce platforms provide market information and trading mechanisms, influencing the behavior of new farmers and other entities, much like ECM influences cell behavior through mechanical signals [23].

Logistics enterprises: As “intercellular connecting structures” that link “cells,” logistics enterprises affect product circulation and market response by optimizing logistics networks and improving delivery efficiency [24].

Government departments: Acting as “signaling molecules” that regulate “cell” behavior, government departments influence the behavior of other entities through policies and regulations, similar to how signaling molecules regulate cellular functions [5].

(2) Game and Cooperation Mechanisms

Resource competition and cooperation: In the rural e-commerce ecosystem, there are relationships of resource competition (such as market share, policy support) and cooperation (such as supply chain collaboration, information sharing) among entities, which can be analyzed using game theory to study these strategic interactions.

Signal transmission and strategy selection: Entities influence each other’s strategy selection by transmitting market information (price, demand changes), akin to cells coordinating behavior by transmitting information through mechanical signals.

(3) Dynamic Evolution and System Equilibrium

System dynamic evolution: As the market environment and policies change, the strategies and behaviors of entities will continue to evolve, forming new market equilibrium states.

System stability and sustainability: By analyzing the interactions and game outcomes among entities, the stability and sustainability of the rural e-commerce ecosystem can be assessed.

3.3. Application of the theoretical framework

(1) Model construction: Based on the above theoretical framework, mathematical models or simulation models can be constructed to simulate the interactions and game processes among entities.

(2) Policy analysis: The theoretical framework can be used to analyze the impact of different policies on the rural e-commerce ecosystem, providing a scientific basis for policy formulation.

(3) Strategic planning: Enterprises can analyze market dynamics based on the theoretical framework and formulate corresponding strategic plans to adapt to market changes.

4. Model construction

4.1. Problem description

Figure 2 illustrates the game relationships among the four stakeholders in the rural e-commerce ecosystem.

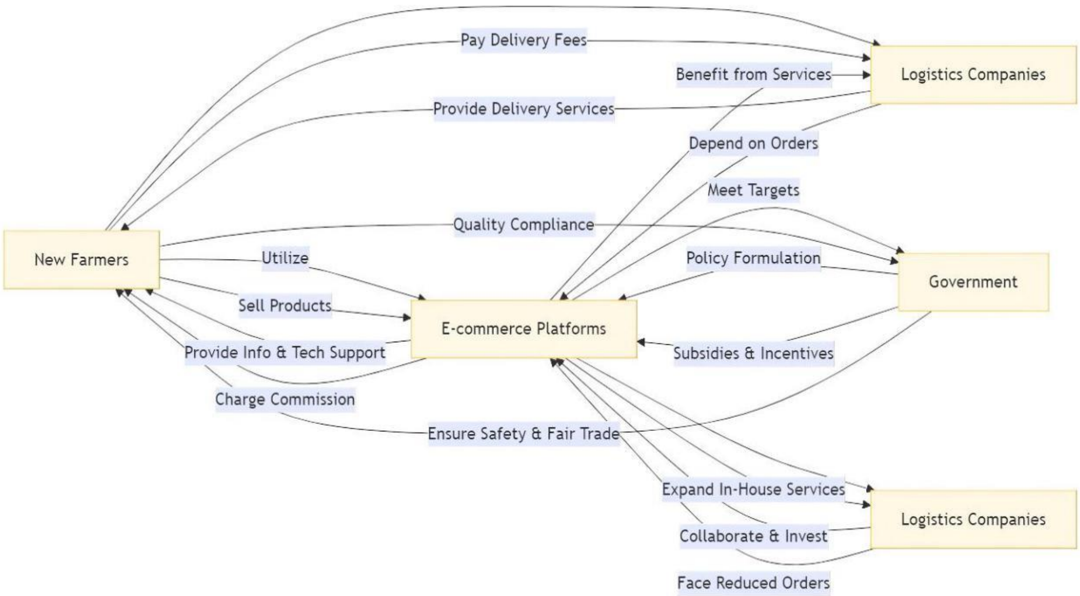

Figure 2. Biomechanical analogy of game relationships in the rural e-commerce ecosystem.

(1) New Farmers and E-commerce Platforms (Cell-ECM Interaction): New farmers, akin to cells, can opt to engage with e-commerce platforms, which act as the extracellular matrix (ECM), facilitating product sales. The ECM (platforms) offers support and connectivity, requiring cooperation, yet conflicts may arise over ‘mechanical signals’ like commission rates and rules [22,23]. Consider “Farmer’s Market,” a collective in Hebei, listing organic vegetables on “Greenery Network.” The platform, while extensive, levies a 10% commission, impacting farmer profits. The ECM (platform) invests in marketing and logistics, balancing commissions with value-added services.

(2) New Farmers and Logistics Companies (Cell-Cell Interaction): New farmers depend on logistics companies for efficient delivery, analogous to cells relying on neighboring cells for transport. The interaction focuses on cost and quality, similar to cells exchanging materials and signals [25]. “Fresh Deliveries” partners with farmers in Jiangsu, where farmers pay a fee that impacts revenue, especially for distant deliveries. The logistics company balances competitive pricing with efficient service to meet expectations and retain clients.

(3) Government and E-commerce Platforms/Logistics Companies (Regulatory Cells and ECM): The government, acting as regulatory cells, influences ECM (platforms and logistics) through policy [5,26]. In 2022, China’s rural e-commerce initiative subsidized platforms like “Rural Connect” to integrate small farmers. The platform, receiving a $500,000 grant, must meet farmer onboarding targets. The government aims to boost rural income, while the platform looks to expand and leverage incentives.

(4) Government and New Farmers (Regulatory Cells and Cellular Compliance): The government's "Quality Assurance Scheme" demands compliance from new farmers, like those in Yunnan's tea cooperatives, to access markets. Farmers gain certification and loans but face regulatory burdens [5]. The government ensures safety and fair trade, while farmers seek market access and support.

(5) E-commerce Platforms and Logistics Companies (ECM and Cellular Dynamics): Platforms and logistics, leveraging their strengths in the agricultural market, exhibit both cooperation and competition [24,27]. "Eco-Shop" and "Swift Drop" collaborate on cold chain management, investing in a logistics hub to reduce delivery times and costs. However, "Eco-Shop's" expansion into in-house delivery challenges "Swift Drop" with reduced orders, prompting a strategic review of their partnership.

4.2. Model assumptions

Assumption 1: Game Players

The evolutionary game involves four primary participants: new farmers, e-commerce platforms, logistics companies, and the government.

Assumption 2: Strategy Choices

New farmers choose between using e-commerce platforms (with probability m) or not (with probability $1 - m$). E-commerce platforms decide between actively supporting farmers (with probability x) or not (with probability $1 - x$). Logistics companies choose to cooperate (with probability y) or not (with probability $1 - y$). The government decides whether to subsidize (with probability z) or not (with probability $1 - z$).

Assumption 3: Benefits and Costs for New Farmers

Not using e-commerce: Benefit R_f, Cost C_1.

Using e-commerce: Benefit $\varDelta R_f$ (where $\Delta > 1$), Increased Cost αC_1 (where $\alpha >$ 1), Commission γ, Logistics Fee H, and Government Subsidy $T1$.

Assumption 4: E-commerce Platform Revenue and Costs

Passive support: Revenue $\gamma \varDelta R_f$, Cost C_2, Sales loss D_e.

Active support: Increased Revenue $\delta\gamma\varDelta R_f$ (where $\delta > 1$), Increased Cost βC_2 (where $\beta > 1$), Government Subsidy $T2$, and Company Image R_e.

Assumption 5: Logistics Company Revenue and Costs

Not cooperating: Cost C_3, Revenue from logistics fees. Losses D_l when not cooperating.

Cooperating: Shared Cost $\kappa\beta C_2$ (where $0 < \kappa < 1$), Shared Revenue $\omega\delta\gamma\varDelta R_f$ (where $0 < \omega < 1$), Additional Benefits R_l, and Risks F_l. Government subsidy for logistics companies $T3$.

Assumption 6: Government Revenue and Costs

No subsidy: Revenue R_g, Cost C_4, Implicit losses D_g for not subsidizing.

Subsidizing: Increased Costs (subsidy costs), Enhanced Revenue ηR_g (where $\eta >$ 1), and Image Benefits I_g.

Assumption 7: Cooperation between E-commerce and Logistics

Cooperating: Shared Costs and Benefits with coefficients κ and ω.

Not cooperating: Fails cooperation, bears costs alone, and enjoys revenues alone.

The parameters in the above assumptions are summarized in **Table 2**.

Table 2. Parameter presentation.

Parameter	explanation	Parameter	explanation
m	Probability new farmers use e-commerce	$T2$	Government subsidy for e-commerce platforms
$1-m$	Probability new farmers do not use e-commerce	R_e	Company image benefit for active support
x	Probability e-commerce platforms actively support	D_e	Sales loss for passive support
$1-x$	Probability e-commerce platforms passively support	F_e	Risk of cooperation between e-commerce and logistics
y	Probability logistics companies cooperate	C_3	Cost for logistics companies not cooperating
$1-y$	Probability logistics companies do not cooperate	κ	Cost-sharing coefficient for logistics ($0 < \kappa < 1$)
z	Probability government subsidizes	ω	Benefit distribution coefficient for logistics ($0 < \omega < 1$)
$1-z$	Probability government does not subsidize	R_l	Additional benefits for logistics cooperation
Δ	E-commerce income factor ($\Delta > 1$)	F_l	Risks of cooperation for logistics
α	Cost factor for using e-commerce ($\alpha > 1$)	D_l	Losses for logistics when not cooperating
γ	Commission rate for using e-commerce ($0 < \gamma < 1$)	$T3$	Government subsidy for logistics companies
H	Logistics service fee rate per unit value	R_g	Government revenue without subsidies
$T1$	Government subsidy for new farmers	C_4	Government cost without subsidies
C_1	Cost for new farmers not using e-commerce	η	Revenue increase factor for subsidies ($\eta > 1$)
C_2	Cost for e-commerce platforms	Ig	Image benefits for government subsidies
β	Cost increase multiple for active support ($\beta > 1$)	Dg	Implicit losses for not subsidizing
δ	Revenue increase multiple for active support ($\delta > 1$)		

4.3. Strategy combinations and payoff matrix

There are a total of 16 strategy combinations among the four entities: new farmers, e-commerce platforms, logistics companies, and the government. A payoff matrix for the game model involving these four parties is established, as shown in **Table 3**, where U_f, U_e, U_l, U_g represent the payoffs of new farmers, e-commerce platforms, logistics companies, and the government under different strategy combinations, respectively.

Table 3. The strategy combination and benefits of each participant.

Strategy combination	The benefits of the new farmers	The revenue of the e-commerce platforms	The profits of logistics enterprises	The benefits of the government
(m, x, y, z)	$U_{f1} = (1-\gamma)\,\Delta R_f + T1\text{-}\alpha C_1$	$U_{e1} = (1-\omega)\,\delta\gamma\Delta R_f + R_e + T2 - (1-\kappa)\,\beta C_2 - F_e$	$U_{l1} = \omega\delta\gamma\Delta R_f + R_l + T3 - \kappa\beta C_2 - F_l$	$U_{g1} = \eta R_g + I_g - C_4 - T1 - T2 - T3$
$(m, x, y, (1-z))$	$U_{f2} = (1-\gamma)\,\Delta R_f - \alpha C_1$	$U_{e2} = (1-\omega)\,\delta\gamma\Delta R_f + R_e - (1-\kappa)\,\beta C_2 - F_e$	$U_{l2} = \omega\delta\gamma\Delta R_f + R_l - \kappa\beta C_2 - F_l$	$U_{g2} = R_g - C_4 - D_g$
$(m, x, (1-y), z)$	$U_{f3} = (1-\gamma)\,\Delta R_f + T1 - \alpha C_1 - H\Delta R_f$	$U_{e3} = \delta\gamma\Delta R_f + R_e + T2 - \beta C_2$	$U_{l3} = H\Delta R_f - C_3 - D_l$	$U_{g3} = \eta R_g + I_g - C_4 - T1 - T2$
$(m, x, (1-y), (1-z))$	$U_{f4} = (1-\gamma)\,\Delta R_f - \alpha C_1 - H\Delta R_f$	$U_{e4} = \delta\gamma\Delta R_f + R_e - \beta C_2$	$U_{l4} = H\Delta R_f - C_3 - D_l$	$U_{g4} = R_g - C_4 - D_g$

Table 3. (*Continued*).

Strategy combination	The benefits of the new farmers	The revenue of the e-commerce platforms	The profits of logistics enterprises	The benefits of the government
$(m, (1-x), y, z)$	$U_{f5} = (1-\gamma)\Delta R_f + T1 - \alpha C_1 - H\Delta R_f$	$U_{e5} = \delta\gamma\Delta R_f - C_2 - D_e$	$U_{l5} = H\Delta R_f + T3 - C_3 - D_l$	$U_{g5} = \eta R_g + I_g - C_4 - T1 - T3$
$(m, (1-x), y, (1-z))$	$U_{f6} = (1-\gamma)\Delta R_f - \alpha C_1 - H\Delta R_f$	$U_{e6} = \delta\gamma\Delta R_f - C_2 - D_e$	$U_{l6} = H\Delta R_f - C_3 - D_l$	$U_{g6} = R_g - C_4 - D_g$
$(m, (1-x), (1-y), z)$	$U_{f7} = (1-\gamma)\Delta R_f + T1 - \alpha C_1 - H\Delta R_f$	$U_{e7} = \delta\gamma\Delta R_f - C_2 - D_e$	$U_{l7} = H\Delta R_f - C_3 - D_l$	$U_{g7} = \eta R_g + I_g - C_4 - T1$
$(m, (1-x), (1-y), (1-z))$	$U_{f8} = (1-\gamma)\Delta R_f - \alpha C_1 - H\Delta R_f$	$U_{e8} = \delta\gamma\Delta R_f - C_2 - D_e$	$U_{l8} = H\Delta R_f - C_3 - D_l$	$U_{g8} = R_g - C_4 - D_g$
$((1-m), x, y, z)$	$U_{f9} = R_f - C_1 - D_f - HR_f$	$U_{e9} = R_e + T2 - (1-\kappa)\beta C_2 - F_e$	$U_{l9} = HR_f + R_l + T3 - \kappa\beta C_2 - F_l$	$U_{g9} = \eta R_g + I_g - C_4 - T2 - T3$
$((1-m), x, y, (1-z))$	$U_{f10} = R_f - C_1 - D_f - HR_f$	$U_{e10} = R_e - (1-\kappa)\beta C_2 - Fe$	$U_{l10} = HR_f + R_l - \kappa\beta C_2 - F_l$	$U_{g10} = R_g - C_4 - D_g$
$((1-m), x, (1-y), z)$	$U_{f11} = R_f - C_1 - D_f - HR_f$	$U_{e11} = R_e + T2 - C_2$	$U_{l11} = HR_f - C_3 - D_l$	$U_{g11} = \eta R_g + I_g - C_4 - T2$
$((1-m), x, (1-y), (1-z))$	$U_{f12} = R_f - C_1 - D_f - HR_f$	$U_{e12} = R_e - C_2$	$U_{l12} = HR_f - C_3 - D_l$	$U_{g12} = R_g - C_4 - D_g$
$((1-m), (1-x), y, z)$	$U_{f13} = R_f - C_1 - D_f - HR_f$	$U_{e13} = -C_2 - D_e$	$U_{l13} = HR_f + T_3 - C_3 - D_l$	$U_{g13} = \eta R_g + I_g - C_4 - T3$
$((1-m), (1-x), y, (1-z))$	$U_{f14} = R_f - C_1 - D_f - HR_f$	$U_{e14} = -C_2 - D_e$	$U_{l14} = HR_f - C_3 - D_l$	$U_{g14} = R_g - C_4 - D_g$
$((1-m), (1-x), (1-y), z)$	$U_{f15} = R_f - C_1 - D_f - HR_f$	$U_{e15} = -C_2 - D_e$	$U_{l15} = HR_f - C_3 - D_l$	$U_{g15} = \eta R_g + I_g - C_4$
$((1-m), (1-x), (1-y), (1-z))$	$U_{f16} = R_f - C_1 - D_f - HR_f$	$U_{e16} = -C_2 - D_e$	$U_{l16} = HR_f - C_3 - D_l$	$U_{g16} = R_g - C_4 - D_g$

5. Policy analysis

5.1. Game model analysis for each participant

Referring to the evolutionary game analysis method by Friedman [28], we calculate the replicator dynamics equations for new farmers, e-commerce platforms, logistics companies, and the government based on the payoff matrix presented in **Table 3**. The replicator dynamics equation for new farmers is:

$$F(m) = \frac{dm}{dt} = m(1-m)\left[zT1 + xy(U_{f2} - U_{f4}) + (U_{f8} - U_{f16})\right] = m(1-m)\left[zT1 + xyH\Delta R_f + (U_{f8} - U_{f16})\right] \quad (1)$$

The replicator dynamics equation for the e-commerce platform is:

$$\begin{aligned} F(x) = \frac{dx}{dt} &= x(1-x)\begin{Bmatrix} zT2 + my(U_{e2} - U_{e4} - U_{e10} + U_{e12}) \\ +m(U_{e4} - U_{e12} - U_{e8} + U_{e16}) \\ +y(U_{e10} - U_{e12}) + (U_{e12} - U_{e16}) \end{Bmatrix} \\ &= x(1-x)\begin{Bmatrix} zT2 - my\left[\omega\delta\gamma\Delta R_f - (\beta-1)C_2\right] \\ -m((\beta-1)C_2 \\ -y[(1-\kappa)\beta C_2 + F_e] + R_e + D_e \end{Bmatrix} \end{aligned} \quad (2)$$

The replicator dynamics equation for the logistics company is:

$$F(y) = \frac{dy}{dt} = y(1-y)\begin{Bmatrix} zT3 + mx[U_{l2} - U_{l6} - (U_{l10} - U_{l14})] \\ +x(U_{l10} - U_{l14}) \end{Bmatrix} \quad (3)$$

The replicator dynamics equation for the government is:

$$F(z)=\frac{dz}{dt}=z(1-z)\left[-yT3-xT2-mT1+(U_{g15}-U_{g16})\right]=z(1-z)\begin{bmatrix}-yT3-xT2-mT1+\eta R_g\\+I_g-C_4-(R_g-C_4-D_g)\end{bmatrix} \tag{4}$$

5.2. Stability strategy analysis

Building upon the aforementioned analysis, we further discuss the evolutionary stable strategy combinations under the joint action of new farmers, e-commerce platforms, logistics companies, and the government. By simultaneously considering the replicator dynamics Equations (1) to (4) for each party, we can construct a replicator dynamic system for the rural e-commerce ecosystem involving all four parties:

$$\begin{cases}F(m)=m(1-m)\left[zT1+xyH\Delta R_f+(U_{f8}-U_{f16})\right]\\ F(x)=x(1-x)\begin{bmatrix}zT2+my(U_{e2}-U_{e4}-U_{e10}+U_{e12})\\+m(U_{e4}-U_{e12}-U_{e8}+U_{e16})\\+y(U_{e10}-U_{e12})+(U_{e12}-U_{e16})\end{bmatrix}\\ F(y)=y(1-y)[zT3+mx(U_{l2}-U_{l6}-U_{l10}+U_{l14})+x(U_{l10}-U_{l14})]\\ F(z)=z(1-z)\left[-yT3-xT2-mT1+(U_{g15}-U_{g16})\right]\end{cases} \tag{5}$$

Setting $F(m)=0$, $F(x)=0$, $F(y)=0$, and $F(z)=0$ simultaneously yields 16 pure strategy equilibrium points. Following the method of Friedman [28], the evolutionarily stable strategies (ESS) of the differential equation system can be determined by analyzing the local stability of the Jacobian matrix of the system. The local stability of the Jacobian matrix can be assessed by examining its eigenvalues. The Jacobian matrix for the system, derived from the replicator dynamics equations, is:

$$J=\begin{bmatrix}\partial F(m)/\partial m & \partial F(m)/\partial x & \partial F(m)/\partial y & \partial F(m)/\partial z\\ \partial F(x)/\partial m & \partial F(x)/\partial x & \partial F(x)/\partial y & \partial F(x)/\partial z\\ \partial F(y)/\partial m & \partial F(y)/\partial x & \partial F(y)/\partial y & \partial F(y)/\partial z\\ \partial F(z)/\partial m & \partial F(z)/\partial x & \partial F(z)/\partial y & \partial F(z)/\partial z\end{bmatrix}$$

$$=\begin{bmatrix}(1-2m)\begin{bmatrix}zT_1+xy(U_{f2}-U_{f4})\\+(U_{f8}-U_{f16})\end{bmatrix} & m(1-m)y(U_{f2}-U_{f4}) & m(1-m)x(U_{f2}-U_{f4}) & m(1-m)T_1\\ -x(1-x)\begin{bmatrix}y(U_{e2}-U_{e4}-U_{e10}+U_{e12})\\+(U_{e4}-U_{e12}-U_{e8}+U_{e16})\end{bmatrix} & (1-2x)\begin{bmatrix}zT_2+my(U_{e2}-U_{e4}-U_{e10}+U_{e12})\\+m(U_{e4}-U_{e12}-U_{e8}+U_{e16})\\+y(U_{e10}-U_{e16})+(U_{e12}-U_{e16})\end{bmatrix} & -x(1-x)\begin{bmatrix}m(U_{e2}-U_{e4}-U_{e10}+U_{e12})\\+(U_{e10}-U_{e16})\end{bmatrix} & x(1-x)T_2\\ y(1-y)[x(U_{l2}-U_{l6}-U_{l10}+U_{l14})] & y(1-y)\begin{bmatrix}m(U_{l2}-U_{l6}-U_{l10}+U_{l14})\\+(U_{l10}-U_{l14})\end{bmatrix} & (1-2y)\begin{bmatrix}zT_3+x(U_{l10}-U_{l14})\\+mx(U_{l2}-U_{l6}-U_{l10}+U_{l14})\end{bmatrix} & y(1-y)T_3\\ -z(1-z)T_1 & -z(1-z)T_2 & -z(1-z)T_3 & (1-2z)\begin{bmatrix}-yT_3-xT_2-mT_1\\+(U_{g15}-U_{g16})\end{bmatrix}\end{bmatrix}$$

According to Lyapunov's first theorem, if all eigenvalues are negative, the equilibrium point is an evolutionarily stable strategy (ESS) point for the system; if at least one eigenvalue is positive, the point is an unstable point. The stability of the 16 equilibrium points is shown in **Table 4**. As can be seen from **Table 2**, the four-party evolutionary game system for the rural e-commerce ecosystem may stabilize at nine strategy combinations, namely (1, 1, 1, 1), (1, 1, 1, 0), (1, 1, 0, 1), (1, 1, 0, 0), (1, 0, 1, 1), (0, 1, 1, 1), (0, 1, 1, 0), (0, 1, 0, 1), and (0, 1, 0, 0).

Table 4. Stability analysis of the 16 pure strategy equilibrium points.

equantequation	characteristic value	symbol	stability	stability conditions
(1, 1, 1, 1)	$\lambda_1 = -(T1 + U_{f2} - U_{f4} + U_{f8} - U_{f16})$; $\lambda_2 = -\{T2 + [(U_{e2} - U_{e8}) + (U_{e12} - U_{e16})]\}$; $\lambda_3 = -(T3 + U_{l2} - U_{l6})$; $\lambda_4 = -(U_{g15} - U_{g16} - T1 - T2 - T3)$	uncertainty	ESS	$U_{f8} > U_{f16}; U_{e2} > U_{e8}$ $U_{l1} > U_{l6}; U_{g1} > U_{g2}$
(1, 1, 1, 0)	$\lambda_1 = -(U_{f2} - U_{f4} + U_{f8} - U_{f16})$; $\lambda_2 = -[(U_{e2} - U_{e8}) + (U_{e12} - U_{e16})]$; $\lambda_3 = -(U_{l2} - U_{l6})$; $\lambda_4 = U_{g15} - U_{g16} - T1 - T2 - T3$	uncertainty	ESS	$U_{f8} > U_{f16}; U_{e2} > U_{e8}$ $U_{l2} > U_{l6}; U_{g1} < U_{g2}$
(1, 1, 0, 1)	$\lambda_1 = -(T1 + U_{f8} - U_{f16})$ $\lambda_2 = -[T2 + (U_{e4} - U_{e8})]$ $\lambda_3 = (T3 + U_{l2} - U_{l6})$ $\lambda_4 = -(U_{g15} - U_{g16} - T1 - T2)$	uncertainty	ESS	$U_{f8} > U_{f16}; U_{e3} > U_{e8}$ $U_{l1} < U_{l6}; U_{g1} > U_{g2}$
(1, 1, 0, 0)	$\lambda_1 = -(U_{f8} - U_{f16}); \lambda_2 = -(U_{e4} - U_{e8})$; $\lambda_3 = U_{l2} - U_{l6}; \lambda_4 = U_{g15} - U_{g16} - T1 - T2$	uncertainty	ESS	$U_{f8} > U_{f16}; U_{e4} > U_{e8}$ $U_{l2} < U_{l6}; U_{g1} < U_{g2}$
(1, 0, 1, 1)	$\lambda_1 = -(T1 + U_{f8} - U_{f16})$; $\lambda_2 = T2 + [(U_{e2} - U_{e8}) + (U_{e12} - U_{e16})]$; $\lambda_3 = -T3; \lambda_4 = -(U_{g15} - U_{g16} - T1 - T3)$	uncertainty	ESS	$U_{f8} > U_{f16}; U_{g1} > U_{g2}$ $U_{e8} - U_{e1} > R_e + D_e$
(1, 0, 1, 0)	$\lambda_1 = -\left(U_{f8} - U_{f16}\right)$; $\lambda_2 = (U_{e2} - U_{e8}) + (U_{e12} - U_{e16})$; $\lambda_3 = 0; \lambda_4 = (U_{g15} - U_{g16} - T1 - T3)$	Have a positive	instability	
(1, 0, 0, 1)	$\lambda_1 = -(T1 + U_{f8} - U_{f16}); \lambda_2 = T2 + (U_{e4} - U_{e8})$ $\lambda_3 = T3; \lambda_4 = -(U_{g15} - U_{g16} - T1)$	Have a positive	instability	
(1, 0, 0, 0)	$\lambda_1 = -(U_{f8} - U_{f16}); \lambda_2 = U_{e4} - U_{e8}$ $\lambda_3 = 0; \lambda_4 = U_{g15} - U_{g16} - T1$	Have a positive	instability	
(0, 1, 1, 1)	$\lambda_1 = T1 + U_{f2} - U_{f4} + U_{f8} - U_{f16}$ $\lambda_2 = -\{T2 + [(U_{e10} - U_{e16}) + (U_{e12} - U_{e16})]\}$ $\lambda_3 = -(T3 + U_{l10} - U_{l14})$ $\lambda_4 = -(U_{g15} - U_{g16} - T2 - T3)$	Have a negative value	ESS	$U_{f16} > U_{f1}$; $U_{l9} > U_{l14}$; $U_{g9} > U_{g16}$.
(0, 1, 1, 0)	$\lambda_1 = U_{f2} - U_{f4} + U_{f8} - U_{f16}$; $\lambda_2 = -[(U_{e10} - U_{e16}) + (U_{e12} - U_{e16})]$; $\lambda_3 = -(U_{l10} - U_{l14})$; $\lambda_4 = U_{g15} - U_{g16} - T2 - T3$.	Have a negative value	ESS	$U_{f16} > U_{f8} + H\Delta R_f$; $U_{l10} > U_{l14}$; $U_{g9} < U_{g16}$
(0, 1, 0, 1)	$\lambda_1 = T1 + U_{f8} - U_{f16}$; $\lambda_2 = -[T2 + (U_{e12} - U_{e16})]$; $\lambda_3 = T3 + (U_{l2} - U_{l6})$; $\lambda_4 = -(U_{g15} - U_{g16} - T2)$.	Have a negative value	ESS	$U_{f7} < U_{f16}$; $U_{l1} < U_{l6}$; $U_{g11} > U_{g16}$.
(0, 1, 0, 0)	$\lambda_1 = U_{f8} - U_{f16}$; $\lambda_2 = -(U_{e12} - U_{e16})$; $\lambda_3 = U_{l10} - U_{l14}$; $\lambda_4 = U_{g15} - U_{g16} - T2$.	Have a negative value	ESS	$U_{f8} < U_{f16}$; $U_{l10} < U_{l14}$; $U_{g11} < U_{g16}$.
(0, 0, 1, 1)	$\lambda_1 = T1 + U_{f8} - U_{f16}$; $\lambda_2 = T2 + [(U_{e10} - U_{e16}) + (U_{e12} - U_{e16})]$; $\lambda_3 = -T3; \lambda_4 = -(U_{g15} - U_{g16} - T3)$	Have a positive	instability	
(0, 0, 1, 0)	$\lambda_1 = U_{f8} - U_{f16}$; $\lambda_2 = [(U_{e10} - U_{e16}) + (U_{e12} - U_{e16})]$ $\lambda_3 = 0; \lambda_4 = U_{g15} - U_{g16} - T3$	Have a positive	instability	
(0, 0, 0, 1)	$\lambda_1 = T1 + U_{f8} - U_{f16}$; $\lambda_2 = (T2 + (U_{e12} - U_{e16})$ $\lambda_3 = T3; \lambda_4 = U_{g15} - U_{g16}$	Have a positive	instability	
(0, 0, 0, 0)	$\lambda_1 = U_{f8} - U_{f16}; \lambda_2 = U_{e12} - U_{e16}$ $\lambda_3 = 0; \lambda_4 = U_{g15} - U_{g16}$	Have a positive	instability	

Based on the stability conditions of the nine potential equilibrium points of the system's strategy combinations, it is clear that the payoffs associated with different strategies determine the choices of the four stakeholders. Utilizing the economic life cycle theory and supported by pertinent literature [29–31], the evolutionary process of the rural e-commerce ecosystem is delineated into three distinct phases: the initial phase, the development phase, and the maturity phase. The following analysis examines the stability of system equilibrium points across these varying evolutionary stages.

Corollary 1 Initial Stage: During this phase, akin to cells in their nascent state, new farmers are not fully aware of the income-increasing effects of e-commerce platforms, hence they opt for the strategy of "Not Using" e-commerce platforms. To capture market share in rural e-commerce, e-commerce platforms, like pioneering cells, take the lead in expanding into rural areas, followed by cooperation from logistics companies. Therefore, e-commerce platforms initially choose the "Active Support" strategy in this stage. After a period of operation, local governments also recognize the role of rural e-commerce development in promoting rural economic growth, shifting their strategy from "No Subsidies" to "Subsidies." Consequently, the system evolution equilibrium points in this stage may include (0, 1, 1, 1), (0, 1, 1, 0), (0, 1, 0, 1), and (0, 1, 0, 0), with (0, 1, 1, 1) being the ideal evolutionary state for this phase. According to **Table 4**, for the system to stabilize at point (0, 1, 1, 1), three conditions must be met simultaneously under government subsidies: ① $U_{f16} > U_{f1}$: The net benefit for new farmers "Not Using" e-commerce platforms is greater than their net benefit from "Using" e-commerce platforms; ② $U_{l9} > U_{l14}$: The net benefit for logistics companies choosing to "Cooperate" is greater than that from "Not Cooperating"; ③ $U_{g9} > U_{g16}$: The net benefit for the government subsidizing e-commerce platforms and logistics companies is greater than without subsidies.

Corollary 2 Development Stage: At this stage, new farmers, having experienced the income-enhancing effects of e-commerce platforms, begin to earnestly acquire e-commerce skills, selling agricultural products through online stores and short video live streaming on e-commerce channels. This is similar to cells maturing and specializing in response to their environment. After a period of rural e-commerce development, local governments increase their support for new farmers and the proactive engagement of e-commerce platforms and logistics companies in rural e-commerce activities. Consequently, by the end of this stage, new farmers opt for the "Use" strategy for e-commerce platforms, e-commerce platforms choose "Active Support," logistics companies select "Cooperate," and the government adopts the "Subsidize" strategy. The potential equilibrium points for this stage are (1, 1, 0, 1), (1, 1, 0, 0), (1, 0, 1, 1), and (1, 1, 1, 1), with the most ideal system evolutionary equilibrium point being (1, 1, 1, 1). As indicated in **Table 4**, for the system to stabilize at point (1, 1, 1, 1), four conditions must be met simultaneously under government subsidies: ① $U_{f8} > U_{f16}$: The net benefit for new farmers using e-commerce platforms is greater than not using them; ② $U_{e2} > U_{e8}$: The net benefit for e-commerce platforms actively supporting new farmers is greater than providing passive support; ③ $U_{l1} > U_{l6}$: The net benefit for logistics companies choosing to "Cooperate" is greater than "Not Cooperating"; ④ $U_{g1} > U_{g2}$:The net benefit for the government after subsidizing new farmers, e-commerce platforms, and logistics companies is greater than not providing subsidies.

Corollary 3 Maturation Stage: When e-commerce platforms, logistics companies, and new farmers are all actively engaged in the agricultural product upstreaming project, and the movement of agricultural products from villages to cities proceeds smoothly, the economic utility of government subsidies to these three entities has been minimized. This is akin to a mature cellular system where external stimuli have less influence. There is no need for the government to continue increasing subsidies. Therefore, the system equilibrium point corresponding to this stage is (1, 1, 1, 0). As indicated in **Table 4**, the stability of this equilibrium point requires the fulfillment of four conditions under the scenario where the government does not provide subsidies: ① $U_{f8} > U_{f16}$: The net benefit for new farmers using e-commerce platforms is greater than not using them; ② $U_{e2} > U_{e8}$: The net benefit for e-commerce platforms actively supporting new farmers is greater than providing passive support; ③ $U_{l1} > U_{l6}$: The net benefit for logistics companies choosing to "Cooperate" is greater than "Not Cooperating"; ④ $U_{g1} < U_{g2}$: The net benefit for the government after subsidizing new farmers, e-commerce platforms, and logistics companies is less than not providing subsidies.

6. Numerical simulation

In this section, we will build upon the previous analysis and use MATLAB software to conduct simulation experiments on the evolutionary changes in strategy choices of the four stakeholders across different evolutionary stages. From a biomechanical perspective, we can liken this process to the dynamic balance and interactions within biological systems. Just as the mechanical behavior and interactions of cells determine their functionality and adaptability in biomechanics, similarly, in a business ecosystem, the strategic choices and interactions of stakeholders determine the stability and evolutionary path of the system.

Considering the stability conditions at each stage, we assign initial values to the parameters, and the resulting evolutionary stability simulation outcomes are presented in **Figure 3**. The following discussion, in conjunction with **Figure 3**, will focus on the simulation experiments for different evolutionary stages, with particular emphasis on analyzing the impact of government subsidy policies on system stability and the strategic choices of the stakeholders.

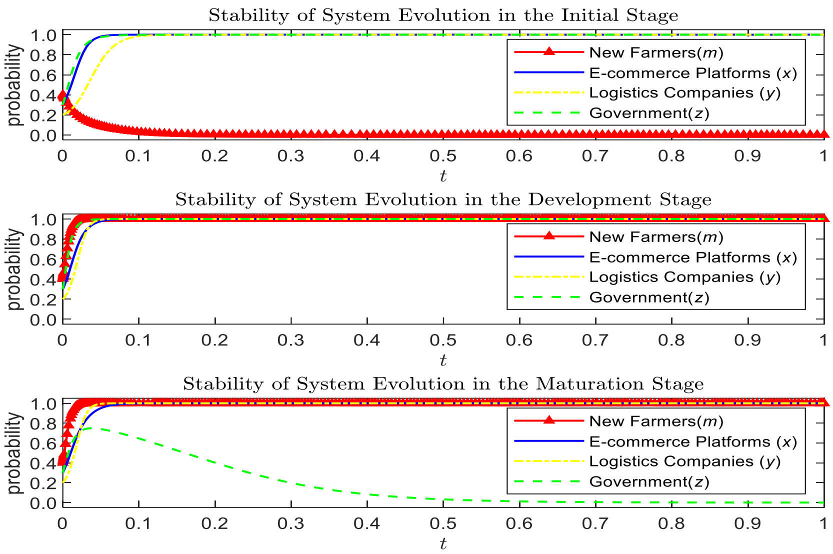

Figure 3. Evolutionary stability of the system at different stages with the initial values.

6.1. Analysis of system evolutionary stability in the initial stage

In line with the actual conditions of the initial stage, initial values are assigned to the parameters as shown in **Table 5**.

Table 5. Table of initial parameter of starting parameters.

parameter	R_f	Δ	C_1	α	γ	T_1	H	D_f	C_2	D_e	R_e	β	T_2	F_e
assignment	100	1.1	50	3	0.05	60	0.02	10	55	20	50	2	60	10
parameter	C_3	κ	ω	δ	R_l	F_l	D_l	T_3	R_g	η	I_g	D_g	C_4	
assignment	50	0.8	0.5	1.5	40	10	10	60	100	2	50	20	55	

We begin by examining the evolutionary path of the system in the initial phase. As illustrated in **Figure 4**, when the conditions $U_{f16} > U_{f1}$, $U_{l9} > U_{l14}$, and $U_{g9} > U_{g16}$ are met simultaneously, new farmers, facing higher net benefits from not using e-commerce platforms compared to using them, ultimately opt for the "Do Not Use" e-commerce platform strategy. However, given that the government has chosen the "Subsidize" strategy, if the financial subsidies provided by the government are sufficiently high, it ensures that the net benefits for e-commerce platforms to actively support new farmers are always greater than those for passively supporting them. Furthermore, if the net benefits for logistics companies to "Cooperate" with e-commerce platforms in building a rural e-commerce logistics system exceed the benefits of "Not Cooperating," then e-commerce platforms will ultimately adopt the "Active Support" strategy, and logistics companies will ultimately choose the "Cooperate" strategy.

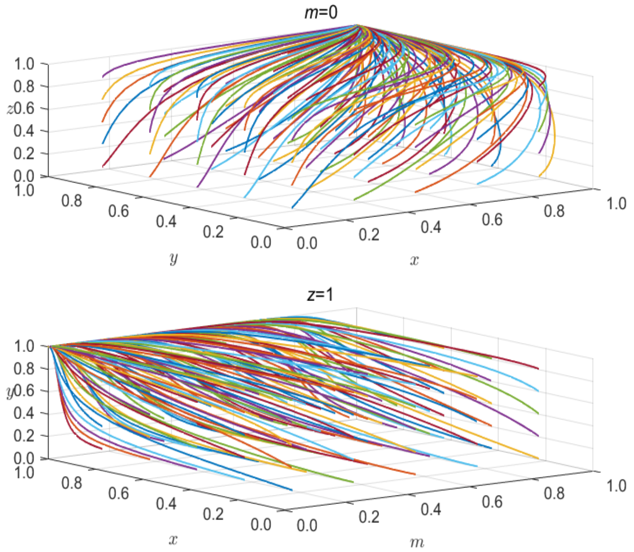

Figure 4. Evolutionary paths of strategy choices for four parties in the initial stage.

Figure 4 illustrates the evolutionary paths of strategies for e-commerce platforms, logistics companies, and the government when new farmers do not utilize e-commerce platforms (i.e., $m = 0$) in the upper half, and the evolutionary paths of strategies for new farmers, e-commerce platforms, and logistics companies under the condition of government subsidies (i.e., $z = 1$) in the lower half. As can be seen from **Figure 3**, the equilibrium point for the system's evolution at this stage is (0, 1, 1, 1). This simulation outcome confirms Corollary 1.

To further examine the impact of policy subsidies on system stability, we varied the initial value of T1 and observed the subsequent changes in stability, as illustrated in **Figure 5**. **Figure 5** demonstrates that a moderate increase in government subsidies for new farmers to utilize e-commerce platforms can elevate the probability of their adoption. However, should the subsidy level surpass a critical threshold (e.g., $T1 = 85$ in this case), it may lead to new farmers vacillating between using and not using e-commerce platforms, plunging the entire system into a state of instability.

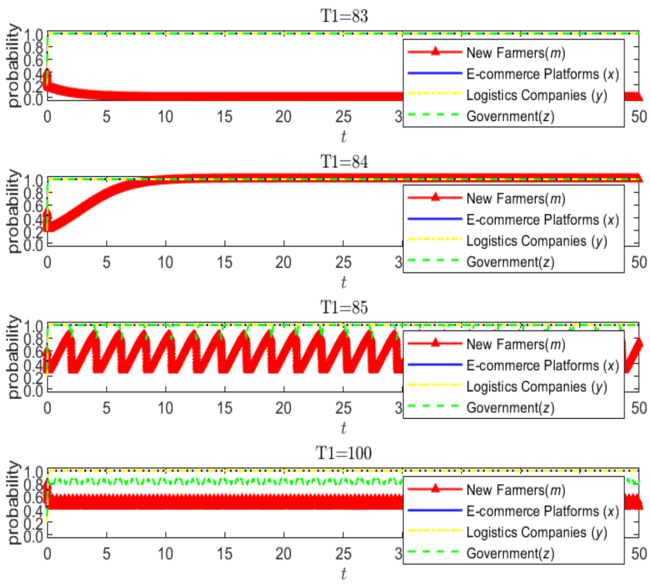

Figure 5. The impact of $T1$ variation on system stability in the initial stage.

Managerial Implications: In the initial stage, the primary reason new farmers do not utilize e-commerce platforms is that government subsidies have not reached a sufficient level, akin to an insufficient stimulus for cellular activity in biomechanics. Appropriately increasing financial subsidies for their use of e-commerce platforms can encourage a shift towards adopting such platforms, thereby facilitating the evolution of the rural e-commerce ecosystem towards the development phase, similar to how adequate mechanical signals can stimulate cellular responses and lead to tissue development. However, the amount of government subsidies should not exceed a critical threshold; excessive financial support may lead to behavioral fluctuations between new farmers and the government, resulting in an unstable system, much like how excessive mechanical stress can disrupt homeostasis in biological systems.

6.2. Analysis of system evolutionary stability in the development phase

Based on the parameter assignments from the initial stage and considering the actual conditions of the development phase, we adjust certain parameter values for the development phase as follows: setting $\Delta = 3$, $\alpha = 1.35$, $T_1 = 70$, $D_f = 20$, $\beta = 1.2$, $T_2 = 70$, $C_3 = 60$, $\kappa = 0.5$, $R_l = 80$, $T_3 = 70$, $\eta = 3$, $I_g = 80$, ensuring that the adjusted parameters satisfy the conditions $U_{f8} > U_{f16}$, $U_{e2} > U_{e8}$, $U_{l1} > U_{l6}$, and $U_{g1} > U_{g2}$ simultaneously. The evolutionary path of the system in this phase is shown in **Figure 6**. The upper half of **Figure 6** illustrates the evolutionary paths of strategies for e-commerce platforms, logistics companies, and the government when new farmers use e-commerce platforms (i.e., $m = 1$). The lower half of **Figure 6** displays the evolutionary paths of strategies for new farmers, e-commerce platforms, and logistics companies under the condition of government subsidies (i.e., $z = 1$).

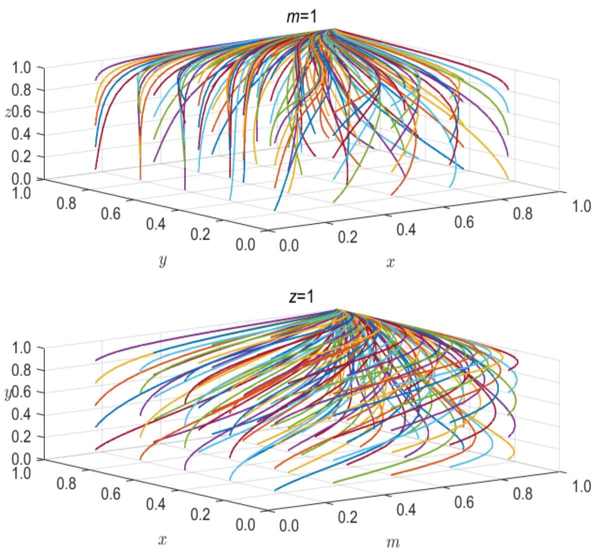

Figure 6. Evolutionary paths of strategy selection in the development phase.

From **Figure 6**, it is evident that under the initial parameter settings, the system stabilizes at the equilibrium point (1, 1, 1, 1), as all four conditions under government subsidy scenarios are met simultaneously: the net benefit for new farmers using e-commerce platforms is greater than not using them, the net benefit for e-commerce platforms actively supporting new farmers is greater than passive support, the net benefit for logistics companies cooperating with e-commerce platforms to build a rural e-commerce logistics system is greater than not cooperating, and the net benefit for the government with subsidies is greater than without subsidies. These simulation results confirm Corollary 2.

In this phase, by adjusting the government subsidies $T1$, $T2$, and $T3$ for the other three parties and observing the system's evolutionary stability, the simulation outcomes are depicted in **Figure 7**.

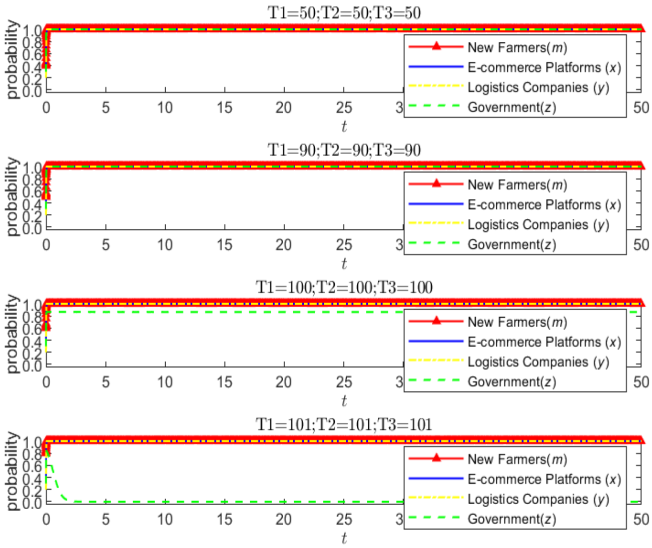

Figure 7. The impact of variations in $T1$, $T2$, and $T3$ on system stability in the development phase.

From **Figure 7**, it is evident that within a certain range, the strategic choices of the four stakeholders remain unchanged regardless of whether the government increases or decreases subsidies, demonstrating a strong stability in the system. However, if the financial subsidies provided by the government exceed a certain threshold (for example, $T1$, $T2$, $T3$ = 101 in this experiment), and the government further increases the subsidy amount, the economic utility has already been minimized. Consequently, the government will adopt a "No Subsidy" strategy, thereby prompting the system to evolve towards the maturation phase and achieving the ideal stable state of the system.

Maintaining the initial values of other parameters in this phase, while adjusting the commission ratio γ charged by e-commerce platforms to new farmers and the service fee rate H charged by logistics companies to new farmers, the simulation results are shown in **Figure 8**. As indicated by **Figure 8**, increasing or decreasing the commission ratio and logistics service fee rate has minimal impact on the overall stability of the system. However, raising the commission ratio and logistics service fee rate can enhance the revenue of e-commerce platforms and logistics companies, thereby providing an incentive for both parties.

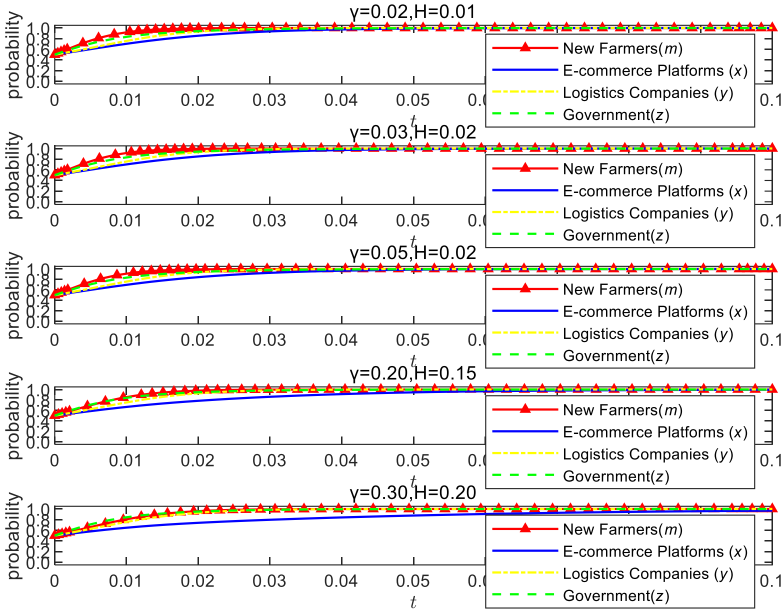

Figure 8. Effect of the changes in γ and H on the system stability during the developmental stage.

Managerial Implications: In the development phase, analogous to a biological system reaching a critical mass for cellular growth, once government subsidies reach a threshold level, the subsidy policy no longer serves as the primary driver for the strategic decisions of new farmers, e-commerce platforms, and logistics companies. Thus, further escalation of government financial support is not imperative in this phase. However, to effectively encourage e-commerce platforms and logistics companies to collaborate in developing a robust rural e-commerce logistics infrastructure, similar to how cells adjust their interactions within a tissue, it is reasonable to permit a moderate increase in the commission ratio γ and service fee rate H during this phase. This approach mirrors the biological mechanism where cells respond to changes in their microenvironment, such as variations in mechanical stress, to optimize their functions and interactions within the system.

6.3. System evolutionary stability in the maturation phase

Based on the stability conditions of the maturation phase and estimates of actual situations, further adjustments are made to some parameters for the maturation phase, building upon the parameter assignments from the development phase. Considering that as the system enters the maturation phase, the proportion of government revenue enhancement due to promoting the upward movement of agricultural products begins to decrease compared to the development phase, the value of η is reduced from 3 in the development phase to 2. The adjusted parameters are made to simultaneously satisfy the four conditions: $U_{f8} > U_{f16}$, $U_{e2} > U_{e8}$, $U_{l1} > U_{l6}$, $U_{g1} < U_{g2}$. The evolutionary path of the system in this phase is depicted in **Figure 9**. The upper half of **Figure 8** illustrates the strategic evolutionary path of new farmers, e-commerce platforms, and logistics enterprises when z = 0, that is, under the condition of no government subsidies; the lower half of **Figure 9** illustrates the strategic evolutionary path among e-commerce platforms, logistics enterprises, and the government when new farmers have determined to use e-commerce platforms (m = 1).

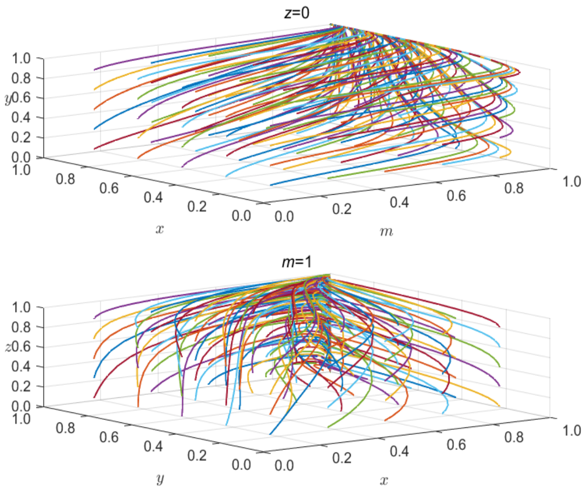

Figure 9. Evolutionary path of strategy choices for the four main subjects in the maturity stage.

Simulation results have validated Proposition 3. That is, in the maturation phase of the rural e-commerce ecosystem, the utility of government subsidies has reached its peak; further implementation of fiscal subsidies has an insignificant incentive effect on the other three parties, and the revenue obtained from government subsidies is lower than the revenue without subsidies. Therefore, in this phase, the government has chosen the "no subsidy" strategy, and the system stabilizes at the equilibrium point (1, 1, 1, 0).

Upon entering the maturation phase, the income-increasing factor of rural e-commerce has reached a certain height. Thus, this phase focuses on examining the impact of the e-commerce income-increasing factor $\mathit{\Delta}$ and the cost-increasing factor α for new farmers using e-commerce platforms on system stability.

Adjustments were made to the value of the rural e-commerce income-increasing factor Δ, as well as the commission ratio γ paid by new farmers to e-commerce platforms. The simulation results are shown in **Figure 10**. Observations from **Figure 10** reveal that when the e-commerce income-increasing factor $\mathit{\Delta}$ is raised to a certain level, the strategy choice of e-commerce platforms shifts from active support to passive support. This indicates that when the benefits for new farmers using e-commerce platforms increase to a certain extent, a dependency effect on e-commerce platforms is generated. Even if e-commerce platforms no longer actively support or even increase commission ratios, new farmers still choose to use e-commerce platforms, and logistics enterprises continue to adopt a "cooperative" strategy. At this point, the government may receive incomplete information, thus falling into a subsidy dilemma. When $\mathit{\Delta}$ = 8 and γ = 0.2, the probability of active support from e-commerce platforms begins to fluctuate, and the government tends towards a subsidy strategy; when $\mathit{\Delta}$ = 9 and γ = 0.5, e-commerce platforms quickly shift to a passive support strategy, and the government also rapidly shifts to a subsidy strategy, leading the system to a stable state. However, if the government still chooses not to subsidize at this point, as shown in the last layer of **Figure 10**, the system can still achieve a stable state with a stable equilibrium point of (1, 0, 1, 0).

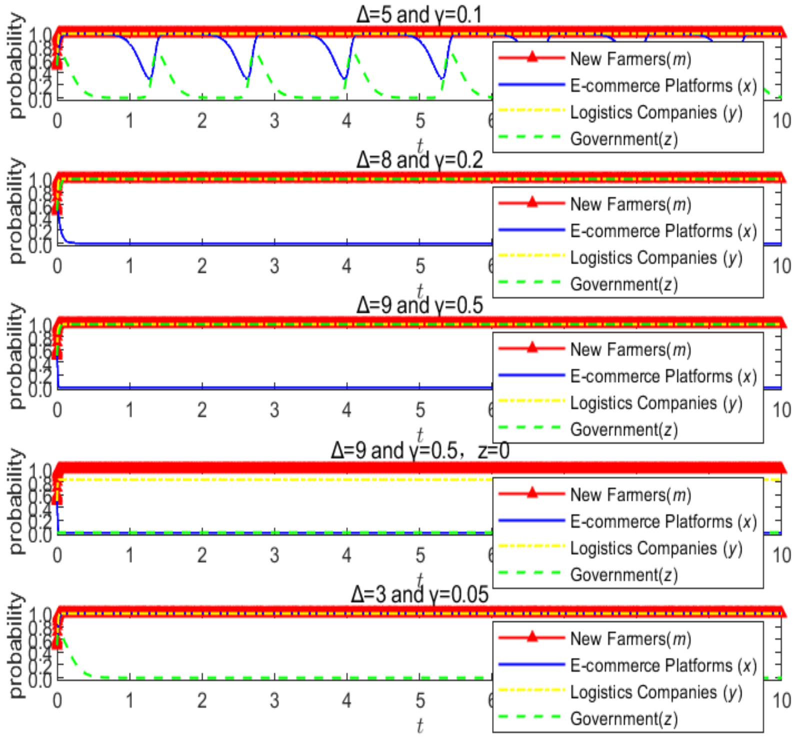

Figure 10. The impact of increasing the e-commerce increment factor *Δ* on system stability.

Managerial Implications: As the rural e-commerce ecosystem transitions into the maturation phase, akin to the adaptation of biological systems to stable environmental conditions, e-commerce platforms can implement support strategies that are commensurate with the income-increasing factor of rural e-commerce. To prevent the government from encountering a subsidy dilemma due to the escalation of the income-increasing factor, a rational analysis mirroring the homeostatic mechanisms in biomechanics can guide the government in formulating effective subsidy strategies. By understanding the development trends of the agricultural product upscaling system and the income situation of new farmers, the government can make strategic choices that ensure a stable and balanced ecosystem, much like how biological systems maintain mechanobiological stability.

Adjusting the value of α and further observing the simulation results, as shown in **Figure 11**, when the cost-increasing factor α for new farmers using e-commerce platforms increases to between 5.5 and 6 times, the strategy choices of new farmers and the government will oscillate, and the system becomes highly unstable. However, when the value of α increases to 6.5, the strategy choice of new farmers stabilizes at m = 1 after a period of fluctuation, and the system stabilizes at the point (1, 1, 1, 1), which belongs to the system evolution to the development phase. Continuing to increase the value of α to 6.6, 7, 7.5, the system's stable equilibrium point tends towards (0, 1, 1, 1), which belongs to returning to the initial phase. This indicates that if the multiple increase of costs for new farmers using e-commerce platforms in terms of technological learning and business management reaches a certain range (such as between 5.5 and 6.5 in this example), new farmers will waver between using and not using e-commerce platforms, leading to fluctuations in the government's strategy choices and an unstable system state.

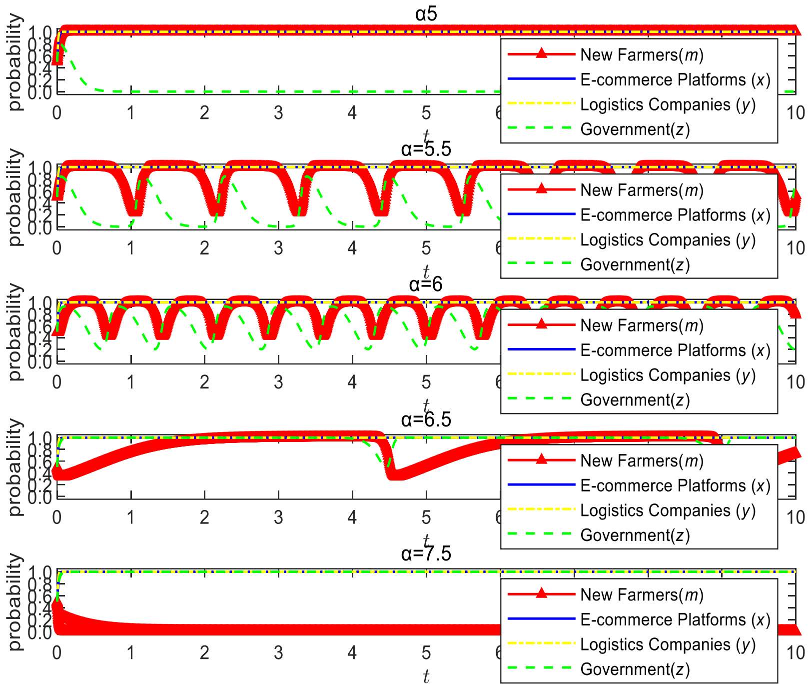

Figure 11. The impact of α variation on system stability.

Managerial Implications: As the rural e-commerce ecosystem transitions into the maturation phase, similar to the adaptation of biological systems to stable environmental conditions, e-commerce platforms can implement support strategies that are commensurate with the income-increasing factor of rural e-commerce. In the face of external factors such as technological changes or business model innovation, which are akin to perturbations in the biomechanical environment, these factors will inevitably increase the costs for new farmers to use e-commerce platforms. If the multiplier of this cost increase is high, akin to a significant mechanical stressor in biomechanics, the government may need to reactivate the subsidy mechanism. This is similar to how biological systems respond to increased stress by activating regulatory mechanisms. The government should design an appropriate subsidy amount based on the increased cost multiples that new farmers face in the new environment to achieve stability, mirroring the homeostatic responses in biological systems that maintain equilibrium under varying conditions.

7. Case analysis: Practices of the Alibaba ecosystem

7.1. Introduction to Alibaba group

Alibaba Group is one of China's leading internet companies, with businesses spanning e-commerce, cloud computing, digital media, and entertainment. In promoting the development of rural e-commerce, Alibaba Group has integrated multiple business sectors to build a comprehensive rural e-commerce service system [32]. This aims to facilitate the upward movement of agricultural products, increase farmers' income, and drive rural revitalization.

7.2. Analysis of the construction of Alibaba's rural e-commerce ecosystem based on model assumptions

Alibaba Group's practices in the field of rural e-commerce align closely with the model and assumptions constructed in this paper. Here are several key points:

(1) Digital Production and Supply Chain Optimization: Alibaba promotes the digital transformation of agricultural production by establishing digital agriculture bases. These bases monitor the growth conditions of agricultural products through IoT devices, achieving precise agricultural management, which echoes the government subsidies and new farmers' e-commerce platform usage behavior mentioned in the model.

(2) E-commerce Platform Support Strategy: Alibaba's e-commerce platforms, such as Taobao and Tmall, provide a direct channel for agricultural products to reach consumers. New models like Taobao Live allow farmers to participate directly in sales, increasing their income, which is consistent with the e-commerce platform support strategy in the model.

(3) Logistics Enterprise Cooperation Behavior: Alibaba has established a nationwide logistics system through Cainiao Network, addressing the "last mile" issue in agricultural product logistics and distribution. This logistics cooperation model matches the assumptions about logistics enterprise cooperation behavior in the model.

(4) Government Subsidy Policies: Alibaba collaborates with the government to integrate multiple businesses through the Digital Agriculture Office, creating new infrastructure for digital agriculture. This public-private partnership model reflects the government's important role in the upward movement of agricultural products and corresponds to the assumptions about government subsidy strategies in the model.

(5) Agricultural Product Upward Movement and Income Increase for Farmers: Alibaba's practices show that with the support of e-commerce platforms and logistics networks, agricultural products can enter the market more quickly, increasing sales channels and income for farmers, which is consistent with the assumptions about new farmers' strategic shifts and system stability in the model.

7.3. Effects of Alibaba group in optimizing the agricultural product upward supply chain and assisting agricultural product upward movement

Alibaba Group's rural e-commerce practices have achieved significant results in the following areas:

(1) Increasing Farmers' Income: Data from Alibaba's platform shows that over the past eight years, the total sales of agricultural products on the platform has reached 10 trillion yuan, helping 832 national-level poor counties achieve over 270 billion yuan in online sales.

(2) Enhancing Agricultural Product Branding and Marketization: Agricultural product brands have been promoted through channels like Taobao Live, where farmers sell agricultural products via live broadcasts, increasing brand exposure and sales.

(3) Promoting the Construction of Rural E-commerce Ecosystem: Alibaba has built a collaborative, innovative, and efficient rural e-commerce ecosystem, promoting high-quality development of rural e-commerce and providing strong support for rural revitalization.

In summary, Alibaba Group's rural e-commerce practices have not only optimized the supply chain for agricultural product upward movement but also effectively supported the upward movement of agricultural products by building a rural e-commerce ecosystem, increasing farmers' income, and promoting rural revitalization. These practices provide strong case support for the application of the model in practice.

8. Conclusion

8.1. Summary

The study has yielded significant insights into the complex dynamics of the rural e-commerce ecosystem. Drawing from the principles of biomechanics, we have analogized the interactions among new farmers, e-commerce platforms, logistics companies, and local governments to intercellular communications within a biological system. Our research reveals that these entities, akin to cells, respond to 'mechanical signals' such as market demands and price fluctuations, which influence their strategic decisions and the ecosystem's stability. The findings indicate that government subsidies, when optimally balanced, can stimulate the adoption of e-commerce platforms by new farmers, while cooperation between e-commerce platforms and logistics companies enhances supply chain efficiency. Furthermore, as new farmers become more adept at leveraging e-commerce platforms, they contribute to the upward movement of agricultural products, a pivotal factor in rural economic development.

8.2. Policy recommendations

Based on our conclusions, we propose the following policy recommendations:

Dynamic Subsidy Adjustments: Governments should implement dynamic subsidy policies that respond to market feedback, ensuring support is provided where needed without creating dependency.

Enhanced Public-Private Partnerships: Encourage collaboration between e-commerce platforms and logistics companies to reduce costs and improve service quality for new farmers.

Capacity Building for New Farmers: Invest in education and training programs to enhance new farmers' e-commerce skills, enabling them to better compete in the digital marketplace.

Monitoring and Regulation: Establish mechanisms to monitor the balance between revenue-increasing and cost-increasing factors in the ecosystem to maintain stability and prevent market fluctuations.

8.3. Limitations

While our research provides valuable insights, it is not without limitations. The model assumptions may not capture all the nuances of real-world interactions, and the generalizability of our findings may be constrained by the specific context of rural China. Additionally, the dynamic nature of e-commerce and the rapid evolution of technology may render some aspects of our analysis subject to change. Future research should aim to refine the model by incorporating more detailed data on stakeholder interactions and by exploring the long-term effects of policy interventions in this ecosystem.

In conclusion, our biomechanics-inspired game analysis has illuminated the complex interplay among the key entities within the rural e-commerce ecosystem, highlighting the critical role of balanced strategies for sustainable development. As biomechanics continues to advance, our comprehension of its applications in intricate systems, such as rural e-commerce, will deepen, unveiling new opportunities for both research and practical implementation.

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