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EDITED BY
Siphe Zantsi,
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REVIEWED BY
Zehra Alakoç Burma,
Mersin University, Türkiye
Xueli Ma,
Yantai University, China

*CORRESPONDENCE
Huiyang Hu
✉ huhuiyang0504@163.com

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Strategic research on the digital transformation of agricultural businesses based on evolutionary game theory

Mei Rong, Huiyang Hu* and Zhaozhuo Qu

Faculty of Economics and Management, Qilu University of Technology (Shandong Academy of Sciences), Jinan, China

The rapid progress of the digital economy has established digital transformation as a fundamental strategy for enterprises seeking to ensure sustainability, enhance competitiveness, and achieve sustained growth. Compared to other industries, the agricultural sector lags significantly in adopting digital transformation, requiring substantial efforts to bridge the existing gap. This paper constructs an evolutionary game model to analyze the strategic interactions and system evolution among agricultural businesses, digital enablers, and the government. It examines how strategic decisions, initial willingness, and parameter variations affect the dynamics of the system. Furthermore, the study utilizes Matlab2023b to simulate and analyze the evolutionary behaviors of the three parties, offering insights into their decision-making processes and mutual adaptations. The results of the study show that: (1) The internal drive of agricultural businesses is the primary factor influencing their active digital transformation strategy, while digital enablers assist in this process, primarily motivated by their own interests. Meanwhile, the government assumes a critical role in guiding and promoting the digital transformation of agricultural businesses; (2) Enhancing the initial willingness of stakeholders in the game, combined with fostering the synergistic benefits of collaborative transformation between agricultural businesses and digital enablers, significantly strengthens their motivation to actively engage in the transformation process. However, this dynamic tends to slow down the evolution of the government's adoption of an active regulatory strategy; (3) Government subsidies, paired with a structured system of rewards and penalties for agricultural businesses and digital enablers, effectively foster active engagement in the transformation process. Nevertheless, excessively generous subsidies and rewards risk undermining the government's ability to effectively execute its primary responsibility of proactive regulation. The findings elucidate the intrinsic logical interconnections between government regulation, digital enablers support, and agricultural enterprise transformation during the digitization process. Additionally, they illuminate the factors shaping the strategic decisions of these three parties, with the overarching goal of advancing the digital transformation of agricultural businesses.

KEYWORDS

agricultural businesses, digital transformation, government, evolutionary game, simulation analysis

1 Introduction

Digital transformation facilitates real-time monitoring and intelligent management of agricultural production, spanning the entire value chain from cultivation to consumption (Oliveira et al., 2025; Yuan et al., 2025; Begishev et al., 2024). By leveraging advanced technologies and optimizing processes (Zhang et al., 2022), it significantly boosts the competitiveness of agricultural businesses' products (Li and Yang, 2021) and enhances the efficiency of their production and operational activities (Tang et al., 2025; Peng and Tao, 2022). Furthermore, it strengthens their overall market competitiveness (Wu et al., 2021b; Miklosik and Krah, 2023; Li et al., 2025). However, compared to other industries, the digitization of agricultural businesses in China faces significant challenges, such as heightened information resource and financing constraints (Wang et al., 2024) and insufficient policy and financial support (Restrepo-Morales et al., 2024). Consequently, it remains in a relatively underdeveloped state in terms of both development level and growth rate (Yin et al., 2020). There is an urgent need to foster a stronger sense of responsibility and urgency to accelerate digital transformation (Qiang, 2021). Realizing the digital transformation of agricultural businesses is a multifaceted and methodical undertaking (Matt et al., 2015). This process requires the coordinated efforts of agricultural businesses, digital enablers, and government departments, with joint efforts aimed at advancing agriculture toward digitization and intelligent development.

The digital transformation of agricultural businesses requires the active engagement of the enterprises themselves. The primary constraint on the transformation lies not in the specific challenges of the transformation process, but in a lack of recognition of its significance and the insufficient willingness and awareness of enterprises to undergo transformation (Zhang et al., 2025; Xia et al., 2024). As the primary entities in agricultural production, agricultural businesses hold a pivotal role in advancing agricultural and rural modernization. They must fully leverage their position as the "main force" by embedding digital technologies across all facets of production, operations, and service delivery (Wang and Zhang, 2024). This process not only helps agricultural businesses to improve their market responsiveness (Li and Dai, 2024) and resource utilization efficiency (Xia et al., 2024), but also optimizes their business performance (Dimitrov, 2016; Wang and Yan, 2024), and thus promotes the construction of agricultural modernization.

The digital transformation of agricultural businesses necessitates collaborative support from digital enablers. Insufficient transformation capabilities and limited resources are common challenges faced by enterprises undergoing digital transformation (Li et al., 2018; Niu, 2024). These challenges are particularly pronounced for agricultural businesses, which frequently reflects an inadequate understanding of the complexities inherent in digital transformation (Zhang J. et al., 2024) and face more significant constraints in their external environment (Shi et al., 2021). Embracing digital technologies to enhance processes, products, and infrastructures is a fundamental prerequisite for achieving enterprise digital transformation (Hoessler and Carbon, 2024). Consequently, the provision of technical expertise by digital technology providers is crucial for driving the digital transformation of agricultural businesses (Ardolino et al., 2018). Digital enablers convene cross-industry, multifaceted enterprises to collaborate. Leveraging their resource reserves and integration capabilities (Mazumder and Garg, 2021; Ngwenya et al., 2025), they guide enterprises toward collaborative innovation (Nambisan et al., 2018). By optimizing resource allocation (Yang and Wang, 2022), they offer professional digital solutions and promote complementary innovation (Jacobides et al., 2018), thereby empowering the digital transformation of agricultural businesses.

The successful digital transformation of agricultural businesses depends on effective guidance and support from government departments. Amid the rapid progress of digital economy, many enterprises face challenges such as "not knowing how to transform" due to limited transformation capabilities, "unwillingness to transform" due to high costs, and "hesitation to transform" because of prolonged adjustment periods (Liu et al., 2021). Therefore, it is imperative for the government to intervene and address these issues. Consequently, government intervention is critically required to address these challenges (Chen et al., 2021; Sun et al., 2023). Government subsidies represent a critical component of government regulation (Zhao et al., 2024). Subsidizing agricultural businesses can facilitate their digital transformation by alleviating financial pressures and mitigating managerial myopia (Wang and Feng, 2025). Furthermore, government subsidies can effectively produce a signaling effect (Li et al., 2024), advancing digital transformation through mechanisms such as reducing information asymmetry, alleviating financing constraints (Wu et al., 2021a; Kong et al., 2024; Liu et al., 2025), and enhancing industry-academia-research collaboration (Zhang and Ma, 2023).

Research applying game theory to analyze multi-agent interaction strategies in enterprise digital transformation has gained traction in recent years. At the enterprise-government level, extant research predominantly examines interactions between policy instruments—such as subsidies (Xu et al., 2025; Dong and Dai, 2023; Shi and He, 2024), taxation (Zhang et al., 2023), and regulation (Zheng et al., 2024)—and corporate digital transformation strategies. Empirical findings indicate that regulatory stringency and subsidy-penalty frameworks constitute primary determinants of digital transformation adoption. At the enterprise-digital enablers level, scholars have investigated determinants of collaborative transformation and trust dynamics (Zhou et al., 2024) between technology adopters and providers. Within the agricultural sector, research predominantly examines dyadic game-theoretic interactions: subsidy-regulation dynamics involving agricultural businesses and government (Sun et al., 2024), and technology collaboration games between agricultural businesses and digital enablers (Huang and Tang, 2025).

In summary, prior research conducted by both domestic and international scholars in this field focuses predominantly on the current state of progress, the involvement of key stakeholders, and their respective roles, thereby establishing a comprehensive and well-supported theoretical framework for the present study. However, the interests of agricultural businesses, digital enablers, and the government are closely intertwined, with changes in the behavior of any party exerting significant impacts on the system. Existing research employing evolutionary game theory to analyze agricultural businesses' digital transformation has predominantly concentrated on two-party interactions. Few studies, however, have incorporated all three parties into a unified analytical framework to examine the balance of interests and the dynamics of their game relationships. Accordingly, utilizing evolutionary game theory, this study exploration of an evolutionary game model, which incorporates interactions between digital enablers and government institutions. The model is simulated to analyze the strategic choices of game participants and the impact of parameter changes on the strategy evolution path, aiming to provide valuable insights for facilitating the digital transformation of agricultural businesses.

The marginal contribution of this study is 2-fold: First, from a research perspective, this study innovatively applies three-party evolutionary game theory to investigate the digital transformation of agricultural businesses. Departing from the prevailing literature's emphasis on two-party interactions or single-entity analyses. This study develops a three-party game model that incorporates agricultural businesses, digital enablers, and the government, examining the evolution of strategies and the equilibrium outcomes for each party under various strategic scenarios. This approach illuminates the interaction dynamics among stakeholders and enhances the theoretical framework of digital transformation. Second, this study examines the government's crucial role in advancing the digitization of agricultural businesses and evaluates its strategic evolution. This paper explores how the government leverages incentives and penalties to encourage the adoption and integration of digital technologies. Furthermore, the paper investigates the conditions under which the government might adopt a "conservative regulation" strategy and examines the factors that influence its decision-making process. This analysis offers valuable insights for developing policies aimed at agricultural digital transformation, thereby improving their precision and effectiveness. Third, this study establishes plausible parameter ranges and conducts iterative simulation analyses, graphically demonstrating how variations in critical parameters influence evolutionary trajectories of tripartite strategies and system equilibria. This approach significantly enhances the visual representation and interpretability of findings, thereby furnishing a quantitative basis for calibrating policy-relevant parameters.

2 Evolutionary game model construction

2.1 Model construction

The digital transformation of agricultural businesses is a collaborative process involving agricultural businesses, digital enablers, and the government. This collaboration occurs through interactive digital transformation models, technical support from digital enablers, and a system of rewards and penalties implemented by the government.

Agricultural businesses play the role of both initiators and beneficiaries in digital transformation, enhancing their production, management, and marketing capabilities through this process. Simultaneously, they contribute to the modernization of the agricultural industry. As an illustrative example, the leading agricultural conglomerate New Hope Liuhe has strategically invested in smart farm development, leading to significant improvements in resource efficiency and product quality (Liu et al., 2023). Agricultural businesses decide whether to engage in digital transformation based on factors such as the policy environment, their internal conditions, industry competition, and available technical support.

Digital enablers assist agricultural businesses in overcoming challenges during the transformation process by offering expertise, technical support, and innovative solutions. Their willingness to support agricultural businesses in digital transformation is shaped by government policies on incentives and penalties. They decide whether to assist based on their objective to maximize their own benefits. In this context, the government's policy orientation and the self-interest considerations of service providers collectively determine their willingness to support agricultural businesses in digital transformation. As an example, JD Farms leverages JD.com's advanced technological capabilities to facilitate digital transformation across the agricultural product value chain. By integrating upstream and downstream stakeholders, the initiative establishes an agricultural ecosystem—specifically, a smart agriculture collective—where stakeholder engagement intensity correlates strongly and positively with local governments' fiscal incentives and dedicated project funding (Wu et al., 2023).

Governmental support for the digitization of agricultural businesses is evident in two primary domains: First, through policy guidance, including the development of a specialized plan for agricultural digital transformation that outlines a clear development path and key tasks; Second, by introducing subsidies, incentives, and penalties for agricultural businesses actively participating in the digital transformation process, as well as for digital enablers, to stimulate progress in digital transformation. China's "Internet Plus" Agricultural Products Outbound Program, promoted by the Ministry of Agriculture and Rural Affairs, and complemented by local subsidies for establishing and operating smart agriculture demonstration zones, exemplifies the government's catalytic role in accelerating agricultural modernization (Ruan et al., 2020).

This study develops an evolutionary game model, grounded in prior theory, to analyze the interactions of three key stakeholders: agricultural businesses, digital enablers, and the government. All three actors make strategic decisions under the assumption of bounded rationality, as illustrated in Figure 1.

2.2 Model assumptions

Assumption 1: agricultural businesses is the main participant 1, digital enablers is the main participant 2, and the government is the main participant 3. During the digital transformation process, it is assumed that the three stakeholders are boundedly rational actors. In the game, each participant prioritizes strategies that maximize their respective interests, leading to a gradual convergence toward an optimal equilibrium.

Assumption 2: The strategy set of the agricultural businesses is (positive transition, negative transition). The probability of selecting a positive transition is denoted by x, while the probability of selecting a negative transition is $1 - x$, where $0 \leq x \leq 1$. The strategy set of the digital enablers is (assist, do not assist).

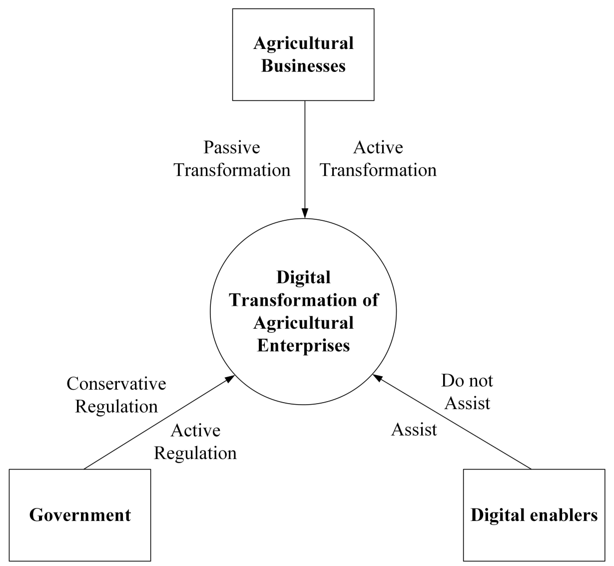

FIGURE 1
Diagram of the game interaction relationships.

The probability of selecting to assist is denoted by y, while the probability of selecting not to assist is $1 - y$, where $0 \leq y \leq 1$. The strategy set of the government is (positive regulation, conservative regulation). The probability of adopting positive regulation is represented by z, while $1 - z$ denotes the probability of adopting a conservative regulatory approach, where $0 \leq z \leq 1$.

Assumption 3: agricultural businesses pursuing digital transformation face significant initial capital investment requirements. Their production and operational costs, denoted as C_1, include expenditures for replacing smart agricultural equipment, training digital talent, and managing data (Rabhi et al., 2025). The basic benefits, denoted as R_1, including the improvement of economic efficiency and production efficiency (Zhan and Jin, 2024). Due to market competition, agricultural businesses that passively engage in digital transformation will face a certain degree of potential loss, denoted as C_g (Wang and Jia, 2025). The longer the interval of inaction, the higher the potential loss value, where $C_g > C_1$.

Assumption 4: Digital enablers and agricultural businesses act as key stakeholders in the digital transformation process. The digital enablers provide relevant technical support and consulting services for the digital transformation of agricultural businesses, and its production cost is C_2. When the digital enablers avoid assisting in agricultural digital transformation, the base revenue from service sales is denoted as R_2, while the additional cost (i.e., concession cost) incurred by adopting a assist strategy is represented by C_t (Yang et al., 2022). For example, JD Farms incurs investment-related expenditures when providing end-to-end digital services across the agricultural value chain, including the development of tailored solutions for agribusinesses, the delivery of enhanced technical training programs, and the provision of extended operations and maintenance support cycles. When the government actively facilitates the process, the synergistic benefits arising from the collaborative digital transformation of agricultural businesses and digital enablers are represented by R_0.The coefficient of synergy gain distribution for the digital enablers is b, where $0 \leq b \leq 1$. Consequently, the synergy gains obtained by the digital enablers and agricultural businesses are bR_0 and $(1-b)R_0$, respectively (Feng and Ma, 2022). However, under conservative government regulation, the synergy gains of both parties are reduced by J, where $R_0 > J$ and $b(R_0 - J) < C_t$.

Assumption 5: To facilitate digitization of agricultural businesses and incentivize active engagement from digital enablers, the government offers innovation subsidies. The innovation subsidy allocated to actively transforming agricultural businesses is denoted as Q_1. Common forms include farm machinery purchase subsidies, such as China's subsidies for Beidou navigation-enabled agricultural machinery (Ministry of Agriculture Rural Affairs, 2023). Consequently, the subsidy aimed at encouraging the participation of digital enablers is represented as Q_2. The incentives here include both direct financial incentives provided by the government and the quantification of non-financial incentives, such as policy guidance, marketing support, and procurement priority. For example, Anhui Province facilitates digital transformation service providers in delivering solutions to local enterprises. The provincial government promotes the development of specialized "industry brain platforms." Qualified service providers are eligible for a one-time subsidy of up to 1 million yuan, contingent upon quantifiable service metrics and demonstrated impact (General Office of the People's Government of Anhui Province, 2024). Under active government regulation, if a digital enabler fails to support agricultural businesses that are actively engaged in digital transformation, the provider will be penalized an amount F by the government. The penalties are not monetary in nature but instead quantify the pressures on the digital enablers' reputation, market competitiveness, and social responsibility, among other factors.

Assumption 6: The government's cost of adopting an active participation strategy is C_3, includes expenditures on constructing digital infrastructure for agriculture, regulating agricultural markets, and promoting information technology to facilitate the digitization of agricultural businesses (Li et al., 2024). The positive social benefits arising from active government regulation, driven by improvements in public service levels and social credibility, are S, manifested through improved agricultural productivity, enhanced institutional credibility, and greater social equity (Zhang W. et al., 2024). The government derives additional incremental benefits, denoted as W, from the collaboration between agricultural businesses and digital enablers in facilitating digital transformation. If the government adopts conservative regulations regarding the digital transformation of agricultural businesses, it will incur significant social costs. These include delays in agricultural modernization, reduced agricultural productivity and quality, an expanding disparity in development between urban and rural regions, and diminished government credibility, collectively represented as K, which $S - C_3 - Q_2 > -K$. As illustrated in Table 1.

2.3 Constructing payment matrices

Building on the foundational assumptions and variable relationships established in the preceding model, this study

TABLE 1 Main variables and descriptions.

Variable	Description
C_1	Costs of positive transformation of agricultural businesses
R_1	Gains from positive transformation of agricultural businesses
C_2	Production costs for digital enablers
R_2	Production gains for digital enablers
C_g	Potential losses in agricultural businesses producing in the traditional way
C_3	Costs of active government regulation
C_t	The cost of concessions for digital service providers to assist with agricultural businesses transformation
R_0	Synergistic benefits of transformation of agricultural businesses in partnership with digital enablers under active government guidance
J	Reduced synergistic gains for both sides under conservative government regulation
b	Coefficient of distribution of synergistic benefits of digital enablers
Q_1	Innovation subsidies for actively transforming agricultural businesses under active government regulation
Q_2	Incentives for digital enablers to assist in transformation under active government regulation
F	Penalties under active government regulation for digital enablers who do not assist actively transforming businesses
S	Positive social benefits of active government regulation
W	Incremental benefits to government from agricultural businesses transformation with digital enablers
K	Social costs and loss of credibility due to conservative government regulation

constructs a game revenue matrix involving agricultural businesses, digital enablers, and the government, as illustrated in Table 2.

2.4 Constructing a three-way replicated dynamic equation for the evolutionary game

2.4.1 A replicated dynamic equation for strategy choice of agricultural businesses

The expected return of an agricultural enterprise engaged in digital transformation is represented by E11, the expected return for an agricultural enterprise resisting digital transformation is represented by E10, and the average expected return be $\overline{E}_1$, then:

$$E_{11} = yz\left[R_1 + \left(1-b\right)R_0 + Q_1 - C_1 + C_t\right] + y\left(1-z\right)\left[R_1 + \left(1-b\right)\left(R_0 - J\right) - C_1 + C_t\right] + \left(1-y\right)z\left(R_1 + Q_1 - C_1\right) + \left(1-y\right)\left(1-z\right)\left(R_1 - C_1\right)$$

$$E_{10} = yz\left(-C_g\right) + y\left(1-z\right)\left(-C_g\right) + \left(1-y\right)z\left(-C_g\right) + \left(1-y\right)\left(1-z\right)\left(-C_g\right)$$

$$\overline{E_1} = xE_{11} + \left(1-x\right)E_{10}$$

The replicated dynamic equation for agricultural businesses strategy choice is:

$$F\left(x\right) = \frac{dx}{dt} = x\left(E_{11} - \overline{E_1}\right) = x\left(1-x\right)\left[C_g - C_1 + R_1 + y\left(C_t - J + R_0 + bJ - bR_0\right) + zQ_1 + yz\left(J - bJ\right)\right]$$

2.4.2 A replicated dynamic equation for strategy choice of digital enablers

The expected return of a digital enabler aiding an agricultural enterprise's digital transformation is denoted by E_{21}, the expected return of a digital enabler not assisting in an agricultural enterprise's digital transformation is represented by E_{20}, and the average expected return be $\overline{E}_2$, then:

$$E_{21} = xz\left(R_2 - C_t - C_2 + bR_0 + Q_2\right) + \left(1-x\right)z\left(Q_2 - C_2\right) + x\left(1-z\right)\left[R_2 - C_2 - C_t + b\left(R_0 - J\right)\right] + \left(1-x\right)\left(1-z\right)\left(-C_2\right)$$

$$E_{20} = xz\left(R_2 - C_2 - F\right) + \left(1-x\right)z\left(-C_2\right) + x\left(1-z\right)\left(R_2 - C_2\right) + \left(1-x\right)\left(1-z\right)\left(-C_2\right)$$

$$\overline{E}_2 = yE_{21} + \left(1-y\right)E_{20}$$

The replicated dynamic equation for digital enablers strategy choice is:

$$F\left(y\right) = \frac{dy}{dt} = y\left(E_{21} - E_2\right) = y\left(1-y\right)\left[zQ_2 + x\left(bR_0 - C_t - bJ\right) + xz\left(F + bJ\right)\right]$$

2.4.3 A replicated dynamic equations for strategy choice of government

The expected return from active government regulation of agricultural digital transformation is denoted by E_{31}, the expected return from conservative government regulation of agricultural digital transformation is denoted by E_{30}, and the average expected return be $\overline{E}_3$, then:

$$E_{31} = xy(S + W - C_3 - Q_1 - Q_2) + \left(1-x\right)y\left(-C_3 - Q_2 + S\right) + x\left(1-y\right)\left(F + S - C_3 - Q_1\right) + \left(1-x\right)\left(1-y\right)\left(-C_3 + S\right)$$

$$E_{30} = xy\left(W - K\right) + \left(1-x\right)y\left(-K\right) + x\left(1-y\right)\left(-K\right) + \left(1-x\right)\left(1-y\right)\left(-K\right)$$

$$\overline{E}_3 = zE_{31} + \left(1-z\right)E_{30}$$

TABLE 2 Revenue matrix of three parties.

Gaming party	Strategic choice	Gaming party	Strategic choice	Agricultural businesses	
				Positive transformation (x)	Negative transformation (1−x)
Digital enablers	Assistance (y)	Governments	Positive regulation (z)	$R_1+(1-b)R_0+Q_1-C_1+C_t$	$-C_g$
				$R_2-C_t-C_2+bR_0+Q_2$	Q_2-C_2
				$S+W-C_3-Q_1-Q_2$	$-C_3-Q_2+S$
			Conservative regulation (1−z)	$R_1-C_1+C_t+(1-b)(R_0-J)$	$-C_g$
				$R_2-C_2-C_t+b(R_0-J)$	$-C_2$
				$W-K$	$-K$
	Do not assistance (1−y)	Governments	Positive regulation (z)	$R_1+Q_1-C_1$	$-C_g$
				R_2-C_2-F	$-C_2$
				$F+S-C_3-Q_1$	$-C_3+S$
			Conservative regulation (1−z)	R_1-C_1	$-C_g$
				R_2-C_2	$-C_2$
				$-K$	$-K$

The replication dynamic equation for government strategy choice is:

$$F(z)=\frac{dz}{dt}=z\left(E_{31}-E_3\right)=z(1-z)\left[S+K-C_3+x(F-Q_1)-yQ_2-xyF\right]$$

3 Game player strategy stability analysis

3.1 Game player strategy stability analysis

3.1.1 Strategic stability analysis of agricultural businesses

Based on the previous analysis, the setup:

$$G(y)=G(z)=C_g-C_1+R_1+y(C_t-J+R_0+bJ-bR_0)+zQ_1+yz(J-bJ)$$

Then :$dF(x)/dx=(1-2x)G(y)$

In consonance with the stability theorem pertaining to differential equations, the conditions that define evolutionary stable strategies are as follows: $F(x)=0$ and $dF(x)/dx<0$. The equations reveal that agricultural businesses' strategic evolution is shaped by digital enablers and the government. This section analyzes strategy stability from these two perspectives:

When $y=\frac{C_1-C_g-R_1-zQ_1}{C_t-J+R_0+bJ-bR_0+zJ-zbJ}=y^*$, $G(y)=0$, $F(x)\equiv 0$, $dF(x)/dx\equiv 0$, then x can take any value, and agricultural businesses achieve an evolutionary stable state where the strategic balance between "active transformation" and "passive transformation" remains constant over time. Since $\frac{\partial G(y)}{\partial y}>0$, then $G(y)$is an increasing function of y. When $y<y^*$, $G(y)<0$, then $dF(x)/dx|_{x=0}<0$ and $F(x)|_{x=0}=0$, so $x=0$ is the evolutionary stabilization strategy of the agricultural businesses, and the result shows that the final choice of the agricultural businesses in this condition is "negative transition." Similarly, when $y>y^*$, $x=1$ is the evolutionary stable strategy of the agricultural businesses, and the result shows that the final choice of the agricultural businesses in this condition is "positive transformation."

When $z=\frac{C_1-C_g-R_1-y(C_t-J+R_0+bJ-bR_0)}{Q_1+y(J-bJ)}=z^*$, $G(z)=0$, $F(x)\equiv 0$, $dF(x)/dx\equiv 0$, then z can take any value, and the agricultural businesses are in an evolutionary stable state, meaning that, regardless of the initial proportions of enterprises adopting "active transformation" or "passive transformation," the strategy remains stable and does not change over time. Since $\frac{\partial G(z)}{\partial z}>0$, then $G(z)$ is an increasing function of z. When $z<z^*$, $G(z)<0$, then $dF(x)/dx|_{x=0}<0$ and $F(x)|_{x=0}=0$, so $x=0$ is the evolutionary stable strategy of the agricultural businesses, and the result shows that the final choice of the agricultural businesses in this condition is "negative transition." Similarly, when $z>z^*$, $x=1$ is the evolutionary stable strategy of the agricultural businesses, and the result shows that the final choice of the agricultural businesses strategy under this condition is "positive transformation."

Thus, the evolutionary phase diagram of agricultural businesses‘ strategy choices was plotted (see Figure 2), where the probability of active transformation for agricultural businesses is represented by the volume of A_2, and the probability of passive transformation is represented by the volume of A_1. The evolution path of the ESS is indicated by the arrows in Figure 2.

Proposition 1: The probability that the agricultural enterprise adopts an active transformation strategy is positively correlated with both the likelihood of receiving assistance from a digital enablers and the probability of active government regulation.

Proof: When $z<z^*$, $y<y^*$, the evolutionary stable strategy for agricultural businesses is passive transformation; conversely, when $z>z^*$, $y>y^*$, the evolutionary stable strategy is

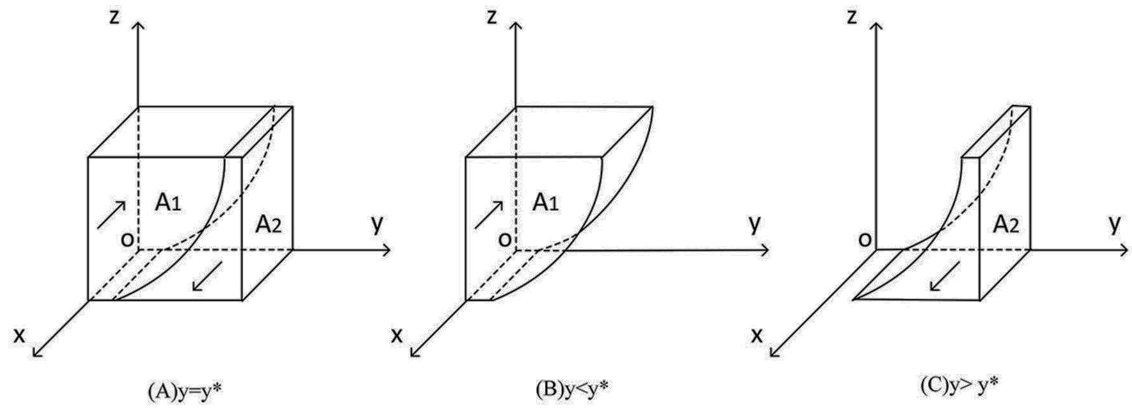

FIGURE 2
Agricultural businesses evolutionary phase diagram. **(A)** y = y*, **(B)** y > y*, **(C)** y < y*.

active transformation. Therefore, as the likelihood of assistance from digital enablers and the probability of active regulation by government authorities increase, the decision-making of agricultural businesses shifts from adopting passive transformation to opting for active transformation.

Proposition 1 indicates: The strategic decisions made by digital enablers and government regulators significantly impact the stable strategy formulation of agricultural businesses. agricultural businesses are more likely to adopt "active transformation" as their stable strategy when digital enablers provide proactive support for their digital transformation and when government authorities implement active regulatory measures to oversee this process. Promoting the digital transformation of agricultural businesses necessitates both active regulatory involvement by government agencies—including the formulation of relevant policies, establishment of dedicated funds, and provision of financial subsidies—and the innovation of technologies tailored to the agricultural sector by digital enablers. digital enablers should provide robust technical support and implement favorable policies, while fostering strong collaborative partnerships with agricultural businesses.

Proposition 2: When other parameters remain unchanged, agricultural businesses tend to adopt a "passive transformation" strategy as C_1, b, and J increase. Conversely, when C_g, R_1, and Q_1 increase, agricultural businesses are more likely to adopt an "active transformation" strategy.

Proof: By calculating the first-order partial derivatives of the variable y^* with respect to each variable, we obtain $\frac{\partial y^*}{\partial C_1} > 0$, $\frac{\partial y^*}{\partial b} > 0$, $\frac{\partial y^*}{\partial J} > 0$, $\frac{\partial y^*}{\partial C_g} < 0$, $\frac{\partial y^*}{\partial R_1} > 0$, $\frac{\partial y^*}{\partial Q_1} > 0$, Therefore, as the values of C_1, b, and J increase, the value of y^*also increases, causing the volume of A_1 to grow, which leads to a decrease in agricultural businesses' willingness to adopt active transformation. Conversely, as the values of C_g, R_1, and Q_1 increase, the value of y^* decreases, resulting in an increase in the volume of A_2, which enhances agricultural businesses' willingness to pursue active transformation.

Proposition 2 indicates: The probability of agricultural businesses adopting active transformation is positively correlated with the potential losses from traditional production methods, the benefits of active transformation, and the innovation subsidies provided under active government regulation. It is negatively correlated with the costs of active transformation, the coordination benefit distribution coefficient between digital enablers, and the reduction in coordination benefits under conservative government regulation.

3.1.2 Strategic stability analysis of digital enablers

Based on the previous analysis, the setup:

$$G(z) = zQ_2 + x\left(bR_0 - C_t - bJ\right) + xz\left(F + bJ\right)$$

Then: $dF\left(y\right)/dy = \left(1 - 2y\right) G\left(z\right)$

In consonance with the stability theorem pertaining to differential equations, the conditions that define evolutionary stable strategies are as follows: $F\left(y\right) = 0$ and $dF\left(y\right)/dy < 0$. When $z = \frac{x\left(bJ + C_t - bR_0\right)}{Q_2 + xF + xbJ} = z^{**}$, $G(z) = 0$, $F\left(y\right) \equiv 0$, $dF\left(y\right)/dy \equiv 0$, then y can take any value, and digital enablers achieve an evolutionary stable state where the distribution of "assist" or "do not assist" strategies remains consistent over time. Since $\frac{\partial G(z)}{\partial z} > 0$, then $G(z)$ is an increasing function of z. When $z < z^{**}$, $G(z) < 0$, then $dF\left(y\right)/dy\big|_{y=0} < 0$ and $F\left(y\right)\big|_{y=0} = 0$, so $y = 0$ the evolutionary stable strategy of agricultural businesses. Consequently, this result indicates that under these conditions, the digital enablers' final strategic choice is "do not assist." Similarly, when $z > z^{**}$, $y = 1$ is the evolutionary stable strategy of the digital enablers, the result shows that the final choice strategy of the digital enablers under this condition is "assist." This generates the evolutionary phase diagram illustrating the strategy choices of digital enablers (see Figure 3), where the probability of assisting is depicted by the volume of B_2, while the probability of not assisting is depicted by the volume of B_1. The evolutionary path of the evolutionary Stable Strategy (ESS) is indicated by the arrows in Figure 3.

Proposition 3: The probability of digital enablers choosing the "assist" strategy is positively correlated with the probability of the government implementing an active regulation strategy.

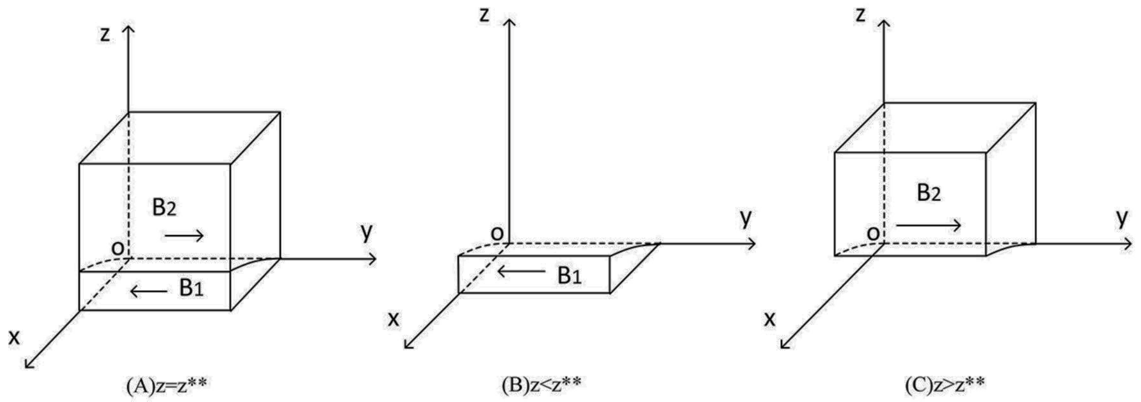

FIGURE 3
Digital enablers evolutionary phase diagram. **(A)** z = z**, **(B)** z < z**, **(C)** z > z**.

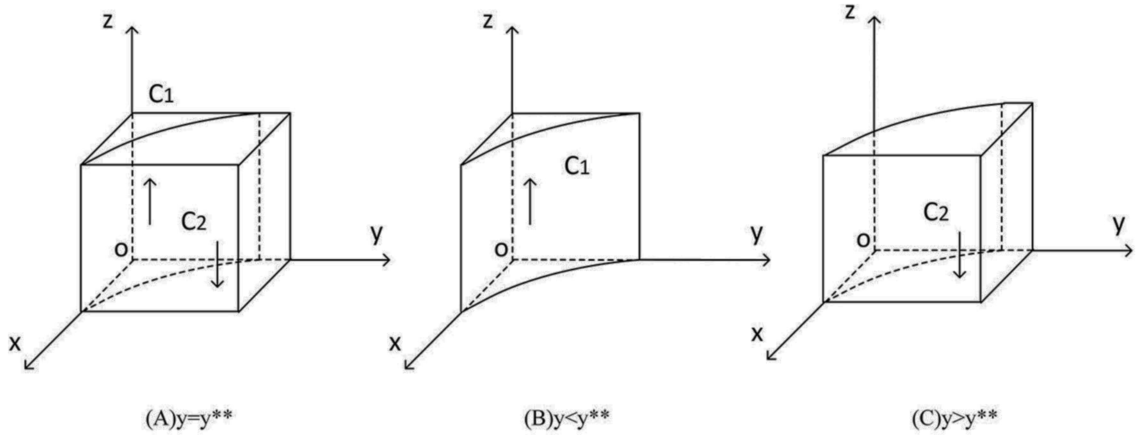

FIGURE 4
Government evolutionary phase diagram. **(A)** y = y**, **(B)** y < y**, **(C)** y > y**.

Proof: When the probability is $z < z^{**}$, the evolutionary stable strategy for digital enablers is "not assist." Conversely, when the probability is $z > z^{**}$, their evolutionary stable strategy shifts to "assist." Therefore, as the probability of active government regulation increases, digital enablers' decisions transition from "do not assist" to "assist."

Proposition 3 indicates: Increasing the probability of active government regulation encourages digital enablers to adopt "assist" as their stable strategy. Therefore, the government can promote the participation of digital enablers in the digitization of agricultural businesses by strengthening their sense of social responsibility and implementing effective fiscal reward and penalty measures.

Proposition 4: All other parameters being equal, the digital enablers prefers the "do not assist" strategy when C_t and J increase, and the "assist" strategy when Q_2FR_0 and b increase.

Proof: By calculating the first-order partial derivatives of the variable z^* with respect to each variable, we obtain $\frac{\partial z^{**}}{\partial Q_2} < 0$, $\frac{\partial z^{**}}{\partial F} < 0$, $\frac{\partial z^{**}}{\partial R_0} < 0$, $\frac{\partial z^{**}}{\partial b} < 0$, $\frac{\partial z^{**}}{\partial C_t} > 0$, $\frac{\partial z^{**}}{\partial J} > 0$ (s.t.$Q_2 - C_t > -F$). Therefore, as the value of $C_{t'}J$ increases, the value of z^{**} also increases, causing the volume of B1 to expand, which reduces the willingness of digital enablers to assist. Conversely, when the value of $Q_{2'}F_{'}R_{0'}b$ increases, the value of z^{**} decreases, leading to an expansion in the volume of B_2, which enhances the willingness of digital enablers to assist.

Proposition 4 indicates: The likelihood of a digital enablers adopting the "assist" strategy is inversely proportional to the concession costs of facilitating the transformation and the reduction in collaborative benefits caused by the government's conservative regulatory policies. It is positively correlated with the collaborative benefits, the proportion of collaborative benefits allocated to the digital enablers, the penalties imposed on non-assisting service providers under active government regulation, and the rewards granted to assisting service providers.

3.1.3 Stability analysis of government strategies

Based on the previous analysis, the setup:

$$G(y) = S + K - C_3 + x(F - Q_1) - yQ_2 - xyF$$

Then: $\mathrm{dF}(\mathrm{z})/\mathrm{dz} = (1 - 2\mathrm{z})\,\mathrm{G}(\mathrm{y})$

In consonance with the stability theorem pertaining to differential equations, the conditions that define evolutionary stable strategies are as follows: $F(z) = 0$ and $dF(z)/dz < 0$. When $\mathrm{y} = \frac{\mathrm{x(F-Q_1)-C_3+S+K}}{\mathrm{Q_2+xF}} = \mathrm{y}^{**}$, $G(y) = 0$, $F(z) \equiv 0$, $dF(z)/dz \equiv 0$, then z can take any value, and the government reaches an evolutionarily stable state, signifying that regardless of the initial proportion of "active regulation" and "conservative regulation" strategies, the equilibrium strategy remains constant over time. Since $\frac{\partial G(y)}{\partial y<}$ 0, then $G(y)$ is a decreasing function of y. When $y < y^{**}$, $G(y) > 0$, then $\left. dF(z)/dz \right|_{z=1} < 0$ and $\left. F(z) \right|_{z=1} = 0$, so $z = 1$ is the government's evolutionary stabilization strategy, and this result shows that the government's final choice of strategy under this condition is "active regulation." Similarly, when $y > y^{**}$, $z = 0$ is the evolutionary stable strategy of government, and the results indicate that under these conditions, the government's final choice of strategy is "conservative regulation." This generates the evolutionary phase diagram illustrating the strategy choices of government (see Figure 4). In this diagram, the probability of active regulation for government is represented by the volume of C_1, while the probability of conservative regulation is depicted by the volume of C_2. The evolutionary path of the ESS is illustrated by the arrows in Figure 4.

Proposition 5: During the evolutionary process, the likelihood of the government adopting active regulation is inversely correlated with the probability of digital enablers choosing to assist.

Proof: When $y < y^{**}$ occurs, the evolutionary stable strategy of government is active regulation; conversely, when $y > y^{**}$ occurs, the government's evolutionary stable strategy is conservative regulation. Therefore, as the probability of digital enablers assisting increases, the decision of government shifts from choosing active regulation to opting for conservative regulation.

Proposition 5 indicates: The likelihood of active regulation by government regulatory departments is determined by the strategic choices made by digital enablers. When digital enablers take a proactive stance and offer substantial assistance to agricultural businesses in their digital transformation, government regulatory departments may relax their intervention policies, rationalize costs, improve resource efficiency, and fully leverage the role of market participants.

Proposition 6: All other parameters being equal, the government prefers the "active regulation" strategy when S, K and F increases ; the government prefers the "conservative regulation" strategy when C_3, Q_1 and Q_2 increases.

Proof: By calculating the first-order partial derivatives of the variables with respect to variable y^{**}, we can obtain $\frac{\partial y^{**}}{\partial C_3} < 0$, $\frac{\partial y^{**}}{\partial Q_1} < 0$, $\frac{\partial y^{**}}{\partial Q_2} < 0$, $\frac{\partial y^{**}}{\partial F} > 0$ (s.t.$Q_2 + xQ_1 + C_3 - S - K > 0$), $\frac{\partial y^{**}}{\partial S} > 0$, $\frac{\partial y^{**}}{\partial K} > 0$. Therefore, as the values of S, K and F increase, the value of y^{**} also increases, leading to a larger volume of C_1, which implies that the government's tendency to adopt active regulation intensifies. Conversely, as the values of C_3, Q_1 and Q_2 increase, the value of y^{**} decreases, resulting in a larger volume of C_2, indicating a reduced willingness of the government to choose active regulation.

Proposition 6 indicates: The likelihood of the government adopting active regulation is inversely correlated with the costs associated with active regulation, the subsidies provided for agricultural businesses undergoing transformation, and the rewards allocated to digital enablers that assist in the transformation. It is positively correlated with the social benefits generated by active regulation, the penalties imposed on digital enablers that fail to assist in the transformation, and the social costs and loss of public trust associated with conservative regulation.

3.2 System equilibrium points stability analysis

Following the analysis of individual strategy stability, the stability of the equilibrium points in the three-party evolutionary game system are examined in greater detail. The system's equilibrium points can be derived from $F(x) = 0$, $F(y) = 0$, $F(z) = 0$. As asymmetric games require the ESS to be a strict Nash equilibrium, it suffices to analyze the stability of the eight pure strategy equilibrium points: E_1 (0, 0, 0), E_2 (0, 1, 0), E_3 (0, 0, 1), E_4 (0, 1, 1), E_5 (1, 0, 0), E_6 (1, 1, 0), E_7 (1, 0, 1), E_8 (1, 1, 1) .

The Jacobi matrix for the three-way evolutionary game system can be calculated as:

$$J = \begin{bmatrix} J_1 & J_2 & J_3 \\ J_4 & J_5 & J_6 \\ J_7 & J_8 & J_9 \end{bmatrix} = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix}$$

According to Lyapunov's First Method, an equilibrium point is considered an evolutionary stable strategy (ESS), if all eigenvalues of the Jacobi matrix derived from the dynamic equations of the three strategies have negative real parts. Table 3 provides the asymptotic stability analysis results for the eight pure strategy equilibrium points, summarizing their stability under different conditions.

Using the data from Table 3, the signs of the eigenvalues for the Jacobian matrix associated with the equilibrium points of the three-party pure strategy combinations were calculated and their signs analyzed. The results indicate that under certain conditions, E_5 (1, 0, 0), E_7 (1, 0, 1), E_8 (1, 1, 1) and may become ESS. Other strategies are considered unstable if they possess at least one eigenvalue with a positive real part or an eigenvalue with a real part equal to zero. The subsequent sections present inferences derived from various scenarios and conditions.

Corollary 1: When $F - C_3 + K - Q_1 + S < 0$, the stabilization point is E_5 (1, 0, 0). Owing to the net negative difference between the benefits and costs of the government's active regulation, coupled with the loss of public credibility associated with conservative regulation, the government typically adopts a conservative regulatory strategy to mitigate fiscal pressure. Simultaneously, under the government's conservative regulation, the collaborative benefits generated by digital enablers assisting agricultural businesses in their digital transformation are outweighed by the concession costs. Consequently, digital enablers frequently opt not to assist agricultural businesses in their digital transformation to maximize their own profits. However, faced with intensifying market competition, agricultural businesses must adopt digital transformation to enhance efficiency, streamline

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TABLE 3 Eigenvalues and stability analysis of system equilibrium points.

Equilibrium point	Eigenvalue	Stability conclusions	Prerequisite
E_1 (0, 0, 0)	$C_g - C_1 + R_1, 0, K - C_3 + S$	Point of instability	–
E_2 (0, 1, 0)	$C_g - C_1 + C_t - J + R_0 + R_1 + bJ - bR_0, 0, K - C_3 - Q_2 + S$	Point of instability	–
E_3 (0, 0, 1)	$C_g - C_1 + Q_1 + R_1, Q_2, C_3 - K - S$	Point of instability	–
E_4 (0, 1, 1)	$C_g - C_1 + C_t + Q_1 + R_0 + R_1 - bR_0, -Q_2, C_3 - K + Q_2 - S$	Point of instability	–
E_5 (1, 0, 0)	$C_1 - C_g - R_1, bR_0 - bJ - C_t, F - C_3 + K - Q_1 + S$	ESS	①
E_6 (1, 1, 0)	$C_1 - C_g - C_t + J - R_0 - R_1 - bJ + bR_0, C_t + bJ - bR_0, K - C_3 - Q_1 - Q_2 + S$	Point of instability	–
E_7 (1, 0, 1)	$C_1 - C_g - Q_1 - R_1, F - C_t + Q_2 + R_0 b, C_3 - F - K + Q_1 - S$	ESS	②
E_8 (1, 1, 1)	$C_1 - C_g - C_t - Q_1 - R_0 - R_1 + R_0 b, C_t - F - Q_2 - R_0 b, C_3 - K + Q_1 + Q_2 - S$	ESS	③

①$F - C_3 + K - Q_1 + S < 0$; ②$R_1 + Q_1 > C_1, F - C_t + Q_2 + R_0 b < 0, S + F - C_3 - Q_1 > -K$; ③$C_1 - C_g - C_t - Q_1 - R_0 - R_1 + R_0 b < 0, C_t - F - Q_2 - R_0 b < 0, C_3 - K + Q_1 + Q_2 - S < 0$.

processes, drive product and service innovation, and attract as well as retain customers to sustain their competitiveness. Consequently, agricultural businesses actively opt for digital transformation. Under these circumstances, the stable strategy combination at equilibrium is (active transformation, do not assist, conservative regulation).

Corollary 2: When $R_1 + Q_1 > C_1$, $F - C_t + Q_2 + R_0 b < 0$, $S + F - C_3 - Q_1 > -K$, the stabilization point is E_7 (1, 0, 1). Since the net benefits of active government regulation exceed the loss of public credibility associated with conservative regulation, the government chooses active regulation. Simultaneously, under active government regulation, the benefits of agricultural businesses participating in the transformation exceed the associated costs, prompting agricultural businesses to adopt an active transformation strategy. However, the costs of assisting enterprises in digital transformation exceed the benefits, combined with financial penalties imposed by the government for non-participation, digital enablers prioritize protecting their financial interests and opt not to assist. This highlights the need for policy changes to incentivize collaboration. Consequently, under these conditions, the stable equilibrium strategy combination is (active transformation, do not assist, active regulation).

Corollary 3: When $C_1 - C_g - C_t - Q_1 - R_0 - R_1 + R_0 b < 0$, $C_t - F - Q_2 - R_0 b < 0$, $C_3 - K + Q_1 + Q_2 - S < 0$, the stabilization point is E_8 (1, 1, 1). In this equilibrium, all three parties derive greater benefits from adopting active or assisting strategies compared to refraining from participating in the transformation. Consequently, agricultural businesses and digital enablers will adopt strategies that maximize their respective benefits, while the government will pursue active regulation to increase fiscal revenue and improve the overall competitiveness of the agricultural sector. At this point, the equilibrium strategy combination is (active transformation, assist, active regulation). Moreover, according to the payoff matrix, when all three parties actively participate, the overall system benefit is maximized, making E_8 (1, 1, 1) the ideal state.

In summary, regardless of the strategic choices made by digital enablers and the government, the evolutionary stable strategy for agricultural businesses remains "active transformation." In driving digital transformation, agricultural businesses not only reap the commercial and social benefits of transformation but also act as key drivers, playing a leading role in the process. Meanwhile, digital enablers base their strategies primarily on maximizing their own interests, opting for approaches that yield the highest returns. The government, motivated by goals such as increasing fiscal revenue, enhancing its service and governance capabilities, and fostering comprehensive rural economic development, actively invests in the digitization of agricultural businesses. To foster a favorable transformation ecosystem, the government can establish flexible regulatory frameworks to reduce regulatory costs and facilitate a transition from equilibrium E_5(1, 0, 0) to E_7(1, 0, 1). agricultural businesses and digital enablers can enhance the level of digitization to make collaborative transformation more advantageous, ensuring that the providers' collaborative benefits exceed their concession costs. Additionally, the government can implement robust incentive and penalty mechanisms to constrain and encourage digital enablers, ultimately guiding the system from equilibrium E_7(1, 0, 1) to E_8(1, 1, 1). This approach will elevate and optimize the overall equilibrium, fostering a sustainable and efficient digital transformation ecosystem.

4 Simulation analysis

To assess the stability of the three-party evolutionary game, this study combines the stability outcomes derived from the constructed evolutionary game model with parameter assignments and performs simulation analysis using MATLAB 2023b software. Drawing on the research of Yu et al. (2024) and other scholars, this paper sets the initial probabilities of the different behaviors of agricultural businesses, digital enablers, and the government at 0.5. As this study aims to analyze the evolutionary game process of digital enablers assisting agricultural businesses in their digital transformation under government guidance and to explore strategies for fostering positive interactions among the three parties, this section adopts the system's desirable stable state E_8(1,1,1) (Condition ③) as the basis. Based on the implementation rules of Hefei City's "Strengthening Agriculture, Strengthening Rural Areas, and Increasing Farmer Incomes" policy, which stipulates subsidies of CNY 200,000 to 1 million for agricultural businesses establishing qualified digital infrastructure, and Anhui Province's one-time subsidy of up to CNY 1 million for suppliers providing solutions to local manufacturing enterprises, we set

$Q_1 = 7.5$ and $Q_2 = 7$. Referring to the regret cost assigned to non-transforming agricultural businesses in the two-party evolutionary game model for agricultural digital transformation under government-enterprise collaboration by Hai et al. (2024), we set $C_g = 6$. Drawing on the parameter assignment methodology from Sun, Miao, Xie and Wu's (2024) two-party evolutionary game model between agricultural businesses and digital technology service provider, we assign $C_1 = 10, R_1 = 15, C_2 = 15, R_2 = 20$. Other parameters are set by integrating approaches from Yang et al. (2022), Li and Gao (2022), and others, with the following assumed values: $C_3 = 5, C_t = 3, R_0 = 6, J = 5, b = 0.5, F = 8, S = 15, W = 5, K = 6$.

4.1 The impact of variations in the initial intention of the three parties on the system's evolution

This paper adopts the methodology proposed by Liu et al. (2019) for setting initial willingness parameters, as outlined in his study on the evolution of corporate carbon emissions within a dual governance framework, as well as Wang, Xu, Zhang and Wang's (2022) method for defining initial willingness parameters for e-commerce platforms, entrepreneurs, and government in his research on the tripartite evolutionary game promoting rural e-commerce entrepreneurial ecosystems. Accordingly, the initial willingness of agricultural businesses to actively participate in the digital transformation, the digital enablers to assist in the transformation of agricultural businesses, and the government's active regulation are set at three levels: x, y, z ε Ω (0.2, 0.5, 0.8). The evolutionary trends of behavioral strategies are depicted in Figures 5–7.

4.1.1 The impact of variations in the initial intention of subjects on the evolution of behavioral strategies in agricultural businesses

As illustrated in Figure 5, the differing levels of initial willingness among stakeholders have varying degrees of impact on the evolution of behavioral strategies within agricultural businesses. Variations in the initial willingness of digital enablers to adopt cooperative strategies exert minimal impact on the direction and pace of the evolution of agricultural businesses' strategies. Nonetheless, as the initial willingness of service providers to cooperate increases, the rate at which agricultural businesses evolve toward active transformation experiences a slight acceleration. This suggests that the assistance offered by digital enablers can, to some extent, facilitate the digitization of agricultural businesses, as depicted in Figure 5A. The government's initial willingness to implement active regulatory strategies does not alter the evolutionary trajectory of agricultural businesses' strategies but significantly affects the speed at which they transition toward an "active transformation" strategy. As the government's initial commitment to active regulation grows, the pace at which agricultural businesses transition toward active transformation increases. And that, the lower initial willingness of agricultural businesses to pursue transformation, the stronger the acceleration effect observed. This highlights the crucial role of government subsidies, strategic policymaking, and effective regulations in promoting the digitization of agricultural businesses, as illustrated in Figure 5B. Simulation results demonstrate that proactive governmental guidance is indispensable for motivating agricultural businesses to overcome inertia or hesitancy during the initial phase of digital transformation, particularly when intrinsic motivation is insufficient. Government subsidies, policy support, and regulatory frameworks substantially reduce agricultural businesses' perceived risks while elevating expected returns, thus effectively catalyzing transformation. In contrast, while increased willingness of digital enablers to assist positively influences agricultural businesses' digital transformation, this effect remains contingent on either the collaborative environment established by the government or agricultural businesses' own transformation commitment. Consequently, policymakers should prioritize establishing comprehensive incentive and guidance frameworks targeting agricultural businesses' transformation decisions, supplemented by enabling measures to facilitate digital enablers' participation.

4.1.2 The impact of variations in the initial intention of subjects on the evolution of behavioral strategies in digital enablers

As depicted in Figure 6, changes in the initial willingness of agricultural businesses and the government to pursue specific strategies have varying impacts on the evolution strategies of digital enablers. Variations in the initial willingness of agricultural businesses have a limited impact on the direction and speed of digital enablers' strategic evolution, as their decisions are predominantly driven by government regulation and self-interest, as shown in Figure 6A. In comparison to changes in the initial willingness of agricultural businesses, the strategic decisions made by the government have a much greater influence on digital enablers. Although variations in the government's initial willingness to adopt an "active regulation" strategy do not influence the direction of service providers' strategic evolution, they substantially impact the rate at which service providers evolve toward a "cooperative" strategy. As the government's initial commitment to active regulation grows, digital enablers transition toward cooperation at an accelerated rate. This highlights that strong government interventions, including rewards, penalties, and regulatory measures, play a significant role in encouraging digital enablers to assist in the digitization of agricultural businesses, as depicted in Figure 6B. Simulation results indicate that the primary driver for digital enablers' active participation in agricultural business transformation stems from economic viability and risk mitigation enabled by governmental regulation, rather than agricultural businesses' unilateral transformation willingness. This underscores the government's pivotal role as both "rule-setter" and "market mediator" in the agricultural digital transformation ecosystem. As rational market actors, digital enablers' behavior is significantly influenced by government-established policy frameworks. Consequently, to strategically leverage technology service resources for the agricultural sector, the government must

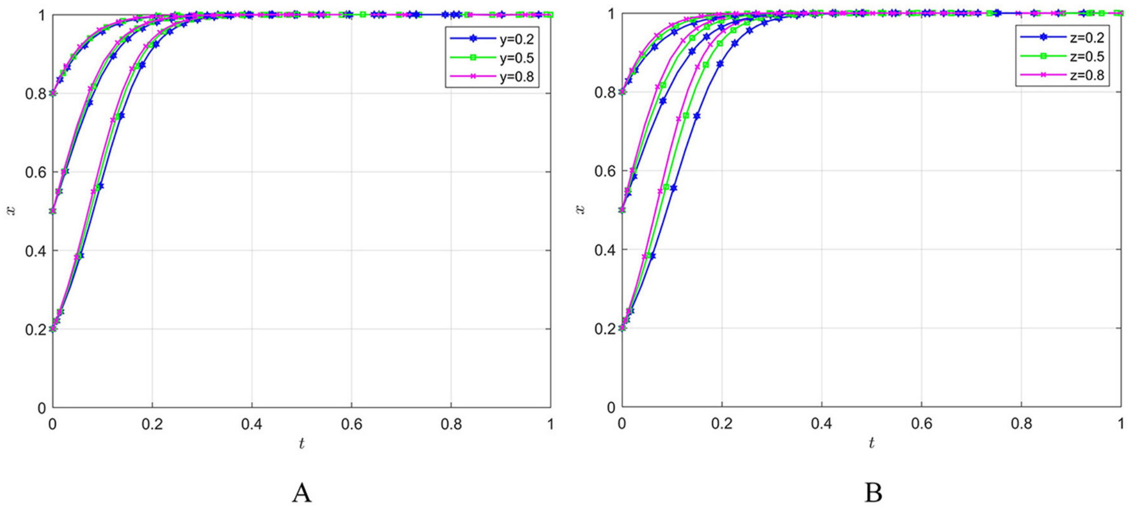

FIGURE 5
Evolutionary trajectory of agricultural businesses behavioral strategies under different levels of initial intention of the subject. **(A)** Impact of y on the evolutionary of the agricultural businesses' behavioral strategies. **(B)** Impact of z on the evolutionary of the agricultural businesses' behavioral strategies.

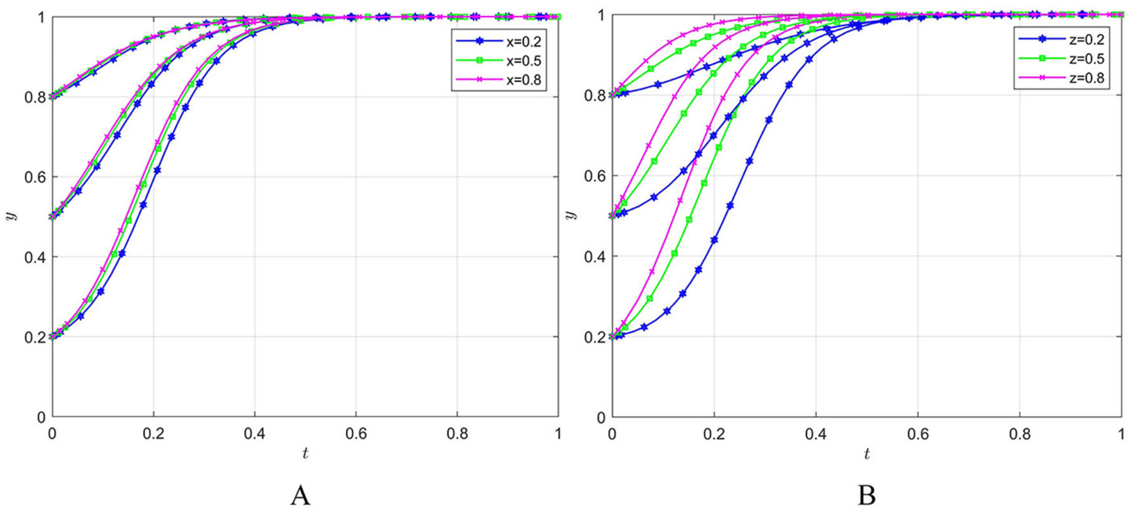

FIGURE 6
Evolutionary trajectory of behavioral strategies of digital enablers under different initial intention levels of the subject. **(A)** Impact of x on the evolutionary of the digital enablers' behavioral strategies. **(B)** Impact of z on the evolutionary of the digital enablers' behavioral strategies.

design sufficiently attractive and enforceable reward-penalty mechanisms, explicitly signaling support for cooperation while sanctioning non-participation.

4.1.3 The impact of variations in the initial willingness of subjects on the evolution of behavioral strategies in government

As shown in Figure 7, changes in stakeholders' initial willingness have varying impacts on the evolution of government strategies. Given varying initial intentions regarding the government's strategy selection, a rise in the initial intention of agricultural businesses to adopt an "active transformation" strategy slightly slows the government's evolution toward an "active regulation" strategy. This suggests that as agricultural businesses increase their willingness to pursue digital transformation, the government moderately relaxes its intervention policies. However, the overall impact remains relatively minor, as illustrated in Figure 7A. Compared to agricultural businesses, variations in the initial willingness of digital enablers exert a more significant influence on the evolution of government strategies. Given varying initial intentions regarding the government's strategy selection, an increase in the initial intention of service providers to pursue a "assist" strategy significantly decelerates the government's evolution

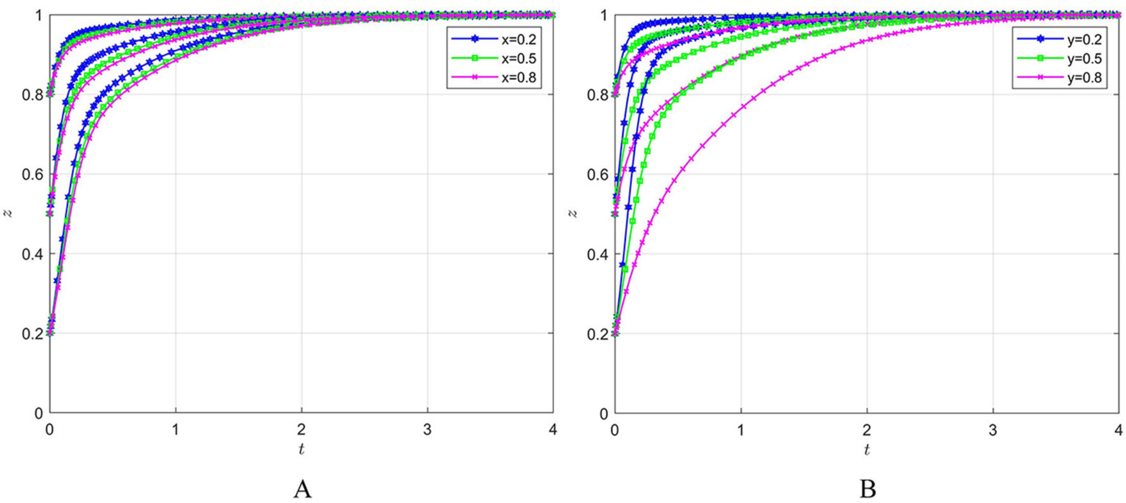

FIGURE 7
Evolutionary trajectory of government behavioral strategies under varying levels of initial intention among stakeholders. **(A)** Impact of x on the evolutionary of government's behavioral strategies. **(B)** Impact of y on the evolutionary of government's behavioral strategies.

toward an "active regulation" strategy. The lower the initial intention of the government, the more pronounced the slowdown in its evolution. Since digital enablers possess key resources such as technology, software development capabilities, and technical talent essential for digital transformation, they play a critical role in facilitating this process. When service providers are inclined to assist enterprises in their transformation, the government tends to relax its intervention policies. However, ultimately, the government's strategy will evolve toward "active regulation," as illustrated in Figure 7B. Simulation results demonstrate the dynamic adaptability of governmental regulatory strategies. When digital enablers exhibit high assistance willingness, the government strategically reduces regulatory intensity, diminishing direct intervention and ceding greater operational space to market mechanisms and autonomous stakeholder collaboration. The objective of governmental regulation is not perpetual high-intensity involvement but rather to ignite endogenous market momentum through initial guidance and rule-setting. Once market mechanisms function effectively, resources are progressively reallocated toward macro-level supervision, standard formulation, and market failure mitigation. Concurrently, the government's statistically insignificant responsiveness to enhanced enterprise willingness substantiates that intrinsic motivation alone cannot substitute governmental indispensability in overcoming systemic barriers, such as technological accessibility constraints and prohibitive initial costs.

In summary, increasing the initial willingness of all three parties accelerates digital transformation, with the government's willingness having the most significant impact. This indicates that the government assumes a pivotal role in guiding the digital transformation of agricultural businesses. For instance, the "Internet Plus" Agricultural Products Outbound Project, spearheaded by the Ministry of Agriculture and Rural Affairs, has effectively mobilized agricultural businesses and digital enablers through proactive governmental guidance and investment. This initiative has catalyzed a preliminary multi-stakeholder collaboration framework for advancing rural digital transformation. By establishing a favorable environment, promoting technological innovation and application, cultivating a collaborative ecosystem, and enhancing regulation and support, the government offers strong backing for the digitization of agricultural businesses.

4.2 The impact of parameter variations on system evolution under varying initial intention levels of the three parties

Building on the above analysis, to further explore the effect of parameters F, R_0, Q_1 and Q_2– which were not the focus of the theoretical discussion—on the system's evolution, the values of F, R_0, Q_1, and Q_2 were adjusted according to the assignment methods of scholars such as Cao et al. (2018). And we follow Luo et al. (2024) tripartite evolutionary game study on e-commerce transformation in agricultural wholesale markets. The resulting evolutionary trajectories of strategies under different initial willingness levels of agricultural businesses, digital enablers, and the government, with varying values of $F \in \Omega(2, 8, 14)$, $R_0 \in \Omega(2, 6, 10)$, $Q_1 \in \Omega(5.5, 7.5, 9.5)$, $Q_2 \in \Omega(5, 7, 9)$ are shown in Figures 8–10.

4.2.1 The impact of variations in the initial intentions of the three parties on the system's evolution with respect to F changes

As illustrated in Figure 8, variations in the value of F significantly influence the evolutionary strategies of digital enablers and the government but exert minimal impact on the behavioral evolution of agricultural businesses. This is because government penalty actions involve only digital enablers and the government,

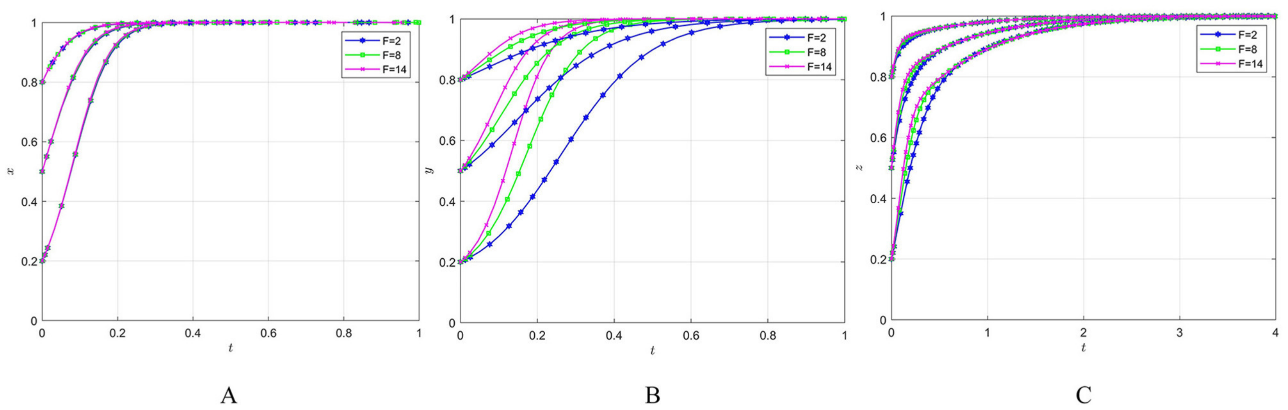

FIGURE 8
Systematic evolutionary trajectory of F under varying initial intention levels of the three parties. **(A)** Impact of F on the evolution of behavioral strategies in agricultural businesses. **(B)** Impact of F on the evolution of behavioral strategies in digital enablers. **(C)** Impact of F on the evolution of behavioral strategies in government.

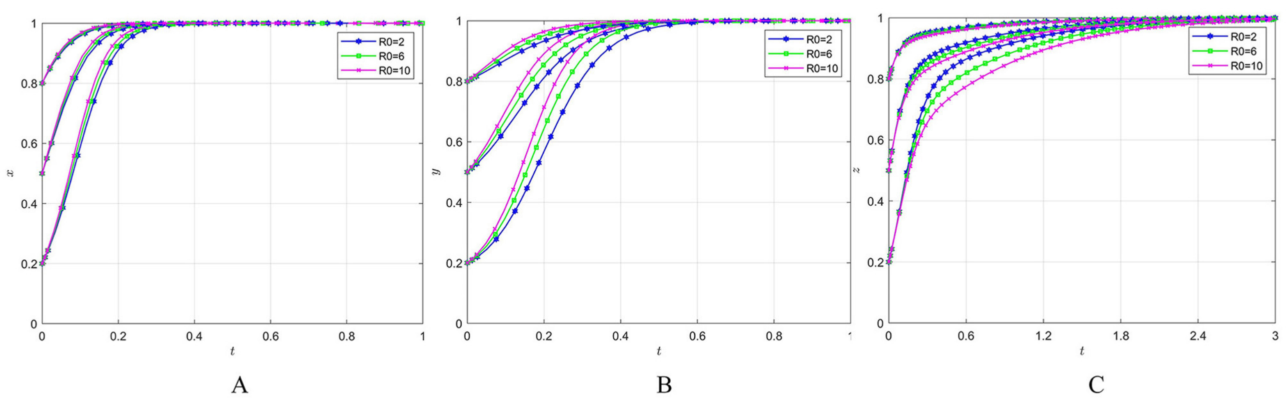

FIGURE 9
Systematic evolutionary trajectory of R0 change under different initial intention levels of three subjects. **(A)** Impact of R0 on the evolution of behavioral strategies in agricultural businesses. **(B)** Impact of R0 on the evolution of behavioral strategies in digital enablers. **(C)** Impact of R0 on the evolution of behavioral strategies in government.

and these penalties have no direct impact on the strategic choices of agricultural businesses. As depicted in Figure 8B, an increase in F accelerates the rate at which digital enablers evolve toward the "assist" strategy. Additionally, lower initial willingness among digital enablers to assist in the transformation leads to a more pronounced impact. As shown in Figure 8C, an increase in F slightly accelerates the government's evolution toward an "active regulation" strategy. In summary, establishing and strictly enforcing punitive mechanisms for non-participation by digital enablers not only directly expedites their adoption of assistance strategies but also indirectly enhances the legitimacy of proactive governmental regulation. Such penalties serve not solely as cost deterrents but, more critically, as strategic signals conveying the state's commitment to advancing digital transformation and policy credibility. This effectively corrects market failures by preventing digital enablers from neglecting their social responsibility to support agricultural transformation and long-term market opportunities in pursuit of short-term gains. Therefore, governments should implement sufficiently stringent penalty mechanisms. Appropriately calibrated penalties for digital technology service providers failing to actively assist in agricultural transformation can incentivize their participation in enterprise digitalization, thereby promoting convergence toward the desired equilibrium state $E_8(1, 1, 1)$.

4.2.2 The impact of variations in the initial intentions of the three parties on the system's evolution with respect to R_0 changes

As illustrated in Figure 9, variations in the value of the collaborative benefit R_0 between agricultural businesses and digital enablers influence the evolution of the three-party system. As R_0 increases, the rate at which agricultural businesses and digital enablers evolve toward the "active transformation" and "assist" strategies accelerates, with a more pronounced effect observed in the evolutionary speed of digital enablers. Consequently, the

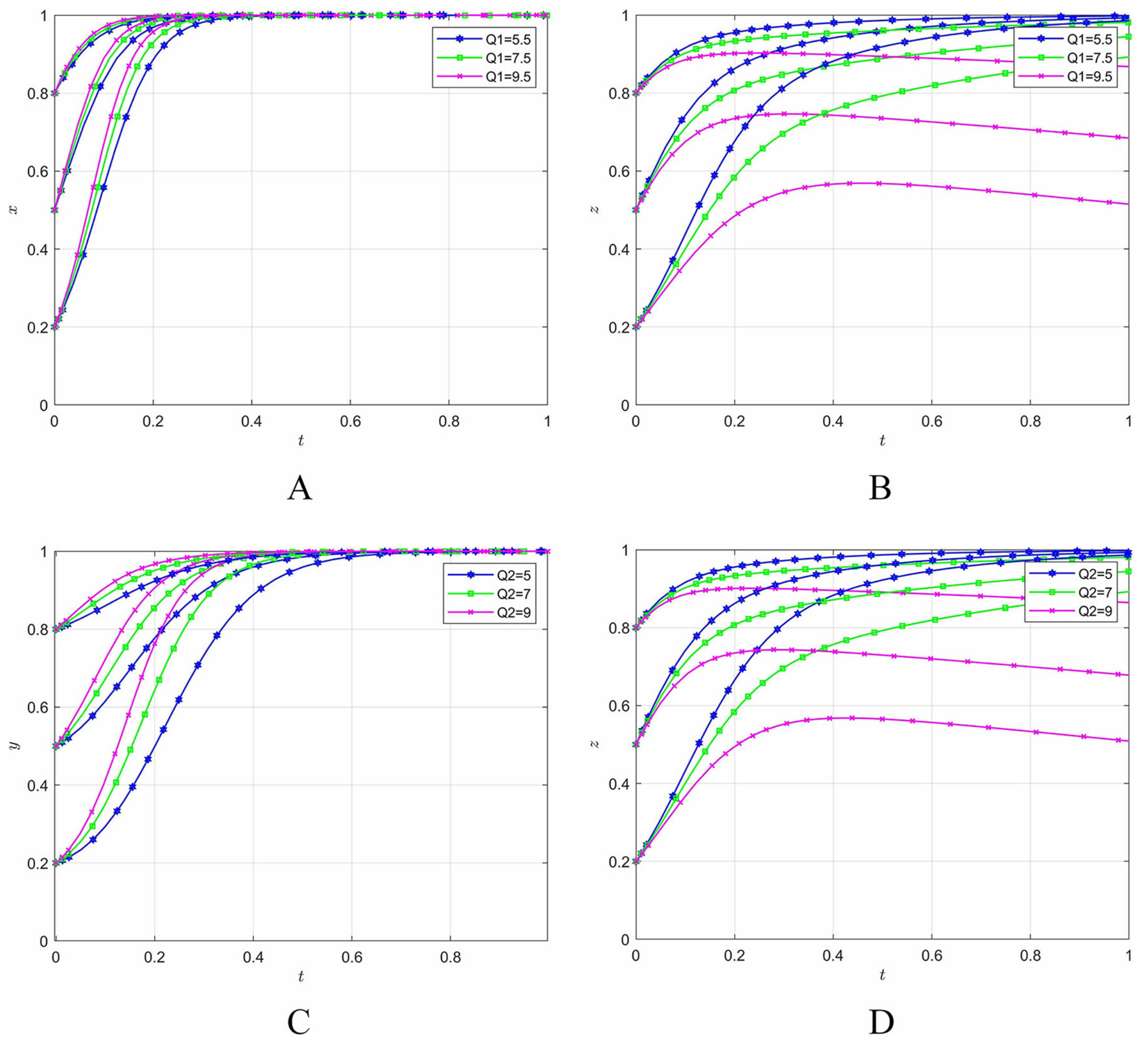

FIGURE 10
Systematic evolutionary trajectory of government subsidies and incentives changes under different initial willingness levels of subjects. **(A)** Impact of Q1 on the evolution of behavioral strategies in agricultural businesses. **(B)** Impact of Q1 on the evolution of behavioral strategies in government. **(C)** Impact of Q2 on the evolution of behavioral strategies in digital enablers. **(D)** Impact of Q2 on the evolution of behavioral strategies in government.

increase in collaborative benefits promotes cooperation between agricultural businesses and digital enablers during the digital transformation process, as illustrated in Figures 9A, B. As R_0 increases, both agricultural businesses and digital enablers exhibit a stronger tendency to collaborate in the transformation process. Consequently, the government, seeking to enhance the role of market participants and ease fiscal pressure, tends to reduce the intensity of its active regulation, as illustrated in Figure 9C. In summary, agricultural businesses and digital enablers should enhance their level of digitization and continuously expand the scope and depth of their collaborative transformation, thereby making collaboration more mutually beneficial. By enhancing collaborative benefits, they can create a positive momentum for fostering cooperation in digital transformation. For example, the collaboration between Wens Group and Huawei in developing smart farming solutions has not only enhanced Wens' production efficiency and precision management capabilities but also enabled Huawei to accumulate valuable expertise and industry-specific solutions in smart agriculture. This significant synergistic effect serves as the core driver for sustained partnership deepening. The magnitude of collaborative benefits represents the primary endogenous driver for establishing stable, proactive partnerships between agricultural businesses and digital enablers. Simulations demonstrate that elevated R_0 not only accelerates the adoption of proactive strategies by both parties but also enhances strategic alignment and mutual gains in their decision-making calculus. When collaboration generates substantially tangible incremental returns, transformation motivation transitions from passive policy compliance to active pursuit of cooperative engagement. Consequently, policy frameworks should transcend conventional subsidy-based incentives and prioritize institutional innovation alongside technological enablement to significantly amplify the incremental value created through collaborative agricultural transformation. Simultaneously, the observed attenuation of

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governmental regulatory intensity following R_0 enhancement reaffirms the governance principle of strategic intervention relaxation when market momentum achieves self-sustainability, enabling resource reallocation toward fostering collaborative ecosystems rather than sustaining high-intensity regulation.

4.2.3 The impact of government subsidies and incentives on system evolution under varying initial willingness levels of stakeholders

As illustrated in Figure 10, an increase in government subsidies and rewards for actively transforming agricultural businesses accelerates the rate at which agricultural businesses and digital enablers evolve toward the "active transformation" and "assist" strategies. Furthermore, lower initial willingness among agricultural businesses and digital enablers amplifies the impact on the transformation process. Since agricultural businesses require significant financial investment in the initial phases of digital transformation, government subsidies can reduce their financial burden and incentivize them to proactively participate in digital transformation. Moreover, providing a certain level of rewards increases the net benefits of digital enablers assisting in the transformation, making them greater than the net benefits when they choose not to assist. This, in turn, enhances their willingness to cooperate in the transformation, as illustrated in Figures 10A, C. However, excessively high government subsidies and rewards may not always yield better outcomes. As subsidies for actively transforming agricultural businesses and rewards for digital enablers assisting in the transformation increase, the government's willingness to pursue "active regulation" gradually decreases. Excessive subsidies and rewards impose a financial burden on the government, diminishing its willingness to support the digitization of agricultural businesses and ultimately hindering the progression of the comprehensive transformation, as illustrated in Figures 10B, D. This dynamic is evidenced in the evolution of China's Agricultural Machinery Purchase Subsidy Program. While initial subsidies significantly boosted mechanization rates, excessive subsidy ratios later triggered issues such as subsidy fraud, increasing fiscal burdens and regulatory costs. Consequently, later policy iterations prioritized targeting accuracy and operational efficiency. Government subsidies and rewards are critical during the initial transformation phase, effectively overcoming startup barriers and significantly accelerating participation rates among agricultural businesses and digital enablers. However, simulations also reveal that excessive subsidies and rewards intensify fiscal burdens on governments, diminishing their willingness and capacity for proactive regulation. This ultimately jeopardizes the long-term healthy development of the broader transformation ecosystem. Consequently, subsidy and reward policies should target key transformation bottlenecks and genuinely incentivizable entities, with quantum calibrated to mobilize participation while avoiding dependency or fiscal unsustainability. Furthermore, as transformation deepens and market mechanisms mature, governments should design exit or tapering mechanisms to redirect resources toward cultivating endogenous momentum and optimizing the business environment.

4.3 Model stability test

Based on the conditions outlined in condition ③, 50 simulation runs were performed using Matlab 2023b software. As seen in Figure 11, the system exhibits a stable point at (1, 1, 1), meaning the evolutionary stable strategy combination for agricultural businesses, digital enablers, and government departments is (active transformation, assist, active regulation), which aligns with the theoretical result in Corollary 3. This confirms that the stability analysis of the strategies and the simulation results are consistent and valid, demonstrating the model's stability.

5 Conclusions and suggestions

5.1 Conclusions

This paper investigates the digital transformation of agricultural businesses by the evolutionary game model involving agricultural businesses, digital enablers, and government. It explores how strategic decisions, initial willingness, and parameter variations affect the dynamics of the system. Furthermore, the study utilizes Matlab2023b to simulate and analyze the evolutionary behaviors of the three parties. The conclusions of the study are as follows:

This evolutionary game system has three potential evolutionary stable strategy combinations: (active transformation, do not assist, conservative regulation) (active transformation, do not assist, active regulation), and (active transformation, assist, active regulation). Among these, increasing the level of collaboration in digital transformation between agricultural businesses and digital enablers, as well as the government's adoption of flexible regulatory models and effective incentive and penalty measures, are key to stabilizing the system at the (active transformation, assist, active regulation) strategy combination. In the initial phases of digital transformation, agricultural businesses, motivated by intensifying market competition, are likely to actively adopt digital transformation strategies to sustain their competitiveness. However, given their limited transformation capabilities, agricultural businesses rely on technical support from digital enablers and effective guidance from the government to address the challenges of transformation.

Variations in the initial intention of the three parties—agricultural businesses, digital enablers, and government—substantially affect the rate at which their strategic decisions evolve. An increase in the initial intention of the three parties expedites the rate at which agricultural businesses and digital enablers actively take part in digital transformation. Meanwhile, the government, acting as both regulator and policymaker, relaxes its interventionist policies and enables market forces to play a more prominent role when the other two parties demonstrate a willingness to collaborate in the transformation process. Among these factors, the strategic decisions of digital enablers are particularly sensitive to changes in the willingness of government to participate. This highlights the government's pivotal role in steering the digital transformation of agricultural businesses by empowering them with policy incentives and support.

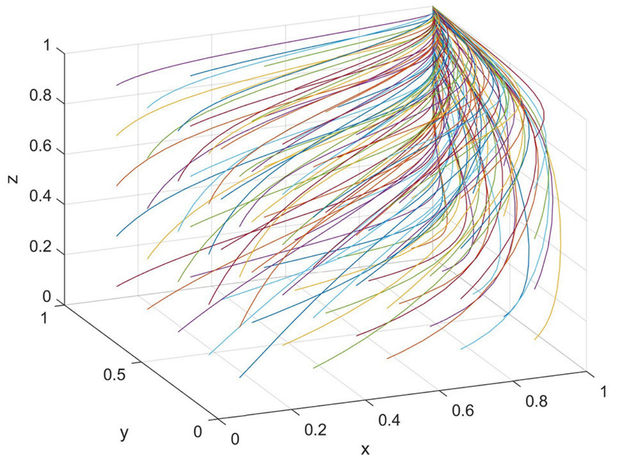

FIGURE 11
Result of array evolution 50 times.

The varying levels of government rewards and penalties for agricultural businesses and service providers, along with the synergistic benefits of their collaborative transformation within the model, influence the pace of evolution in the stakeholders' behavioral strategies. An increase in the synergistic benefits of collaborative transformation between agricultural businesses and digital enablers motivates both parties to cultivate a stronger willingness to transform. When both parties demonstrate a willingness to collaborate, the government will appropriately relax its interventionist policies, enable market forces to play a more prominent role, and enhance resource allocation efficiency. Furthermore, appropriately increasing subsidies and incentives for agricultural businesses and digital enablers can foster their collaboration in digital transformation. However, excessively high subsidies and incentives may impose significant financial burdens on the government, reducing its motivation to regulate digital transformation and ultimately hindering the overall progress of agricultural businesses' digital transformation. Imposing higher penalties on digital enablers who fail to assist agricultural businesses in their digital transformation motivates them to actively engage in providing support. A stringent regulatory mechanism imposes constraints on the overall system, promoting the digital transformation of agricultural businesses.

5.2 Suggestions

(1) Agricultural businesses should fully acknowledge the significance of digital transformation in enhancing production efficiency, lowering costs, and expanding market opportunities. They must recognize that digital transformation is an inevitable trend and actively assume a leadership role in the process. By utilizing digital technologies, they can enhance the digital transformation of the entire value chain, encompassing production, processing, distribution, and services. This approach will enhance the informatization and intelligence of rural industries. Furthermore, agricultural businesses should build long-term partnerships with digital enablers to collaboratively develop solutions tailored to their unique needs.

(2) Digital enablers should improve the level of digitization in collaborative transformation, lower transformation costs through technological innovation, and consistently expand the scope and depth of collaboration to fully realize its advantages. For instance, service providers can deliver structured training programs to agricultural businesses, strengthen initiatives to cultivate digital talent in agriculture, and improve the digital literacy and skill sets of agricultural workers. Furthermore, digital enablers can develop platforms dedicated to agricultural digital transformation, integrating advanced technological resources such as big data, internet of things, and the cloud computing. These initiatives will enhance collaborative benefits, allowing both parties to optimize their respective interests while actively engaging in digital transformation, thereby driving the development of new productive forces.

(3) To foster a favorable environment for transformation, the government should recognize the necessity and benefits of agricultural businesses' digital transformation and establish stringent reward and penalty mechanisms alongside diverse promotion strategies. For instance, the government can raise awareness about the significance of digital transformation for agricultural businesses through diverse channels, such as organizing seminars, forums, and related events. By extensively promoting successful examples of digital transformation in agriculture, more enterprises can recognize its value and be encouraged to actively engage in the transformation process. At the outset of digital transformation, the government can provide increased subsidies to agricultural businesses pursuing transformation and offer incentives to digital enablers that actively support the process. Furthermore, penalties for service providers that fail to support the transformation should be increased. These measures will enhance the motivation of both digital enablers and agricultural businesses to actively engage in the transformation, thereby advancing the overall progress of digital transformation in agriculture. Furthermore, the government can create dedicated funds to support agricultural businesses that effectively implement digital transformation. By offering financial subsidies, tax incentives, low-interest loans, and other preferential policies, the government can help reduce the financial burdens enterprises encounter during the initial stages of transformation. However, overly generous subsidies and rewards can impede the progress of digitization in agricultural businesses. Therefore, the government can increase subsidies and rewards within reasonable limits to facilitate effective collaboration between agricultural businesses and digital enablers during the transformation process.

While this study provides insights into the strategic interactions driving agricultural digital transformation using evolutionary game theory, several promising avenues for future research emerge. First, the current model primarily focuses on agricultural businesses, digital enablers, and the government. In the future, the scope of the study can be further expanded to consider the impact of other critical actors such as farmers, cooperatives, consumers, financial institutions, or logistics providers to capture a more comprehensive ecosystem perspective and understand how their strategies influence the overall transformation dynamics. Second, our model assumes certain parameters are relatively static. Future research should integrate dynamic elements, simulating how these parameters evolve over time and how technological advancements themselves reshape the strategic landscape and payoff structures. Finally, current studies frequently employ homogeneous decision-making frameworks, despite significant divergences between smallholder farms and large agribusinesses regarding resource acquisition capacities, risk tolerance thresholds, and technology adoption behaviors. Future research should refine existing models to accurately capture variations in digital transformation patterns across operations of differing scales, geographic contexts, and technological capabilities.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MR: Data curation, Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing. HH: Methodology, Software, Writing – original draft, Writing – review & editing. ZQ: Methodology, Software, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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