frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 25 June 2024
DOI 10.3389/fsufs.2024.1398319

OPEN ACCESS

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RECEIVED 09 March 2024
ACCEPTED 03 June 2024
PUBLISHED 25 June 2024

CITATION
Zheng Y, Mei L and Chen W (2024) Does government policy matter in the digital transformation of farmers' cooperatives?—A tripartite evolutionary game analysis.
Front. Sustain. Food Syst. 8:1398319.
doi: 10.3389/fsufs.2024.1398319

Does government policy matter in the digital transformation of farmers' cooperatives?—A tripartite evolutionary game analysis

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Farmers' cooperatives, as one of the new types of agricultural businesses, are an effective carrier for the digital transformation of agriculture, yet existing studies have paid less attention to how farmers' cooperatives realize digital transformation. As agricultural economic organizations embedded in social networks, the digital transformation of farmers' cooperatives requires the joint efforts of governments and companies. Based on the evolutionary game theory, this paper constructs a tripartite evolutionary game model of the government, digital technology companies and farmers' cooperatives, and simulates and analyzes the behavioral decisions of different participants in the digital transformation of farmers' cooperatives from the perspective of government policy. The results show: Medium government subsidies can effectively promote the digital transformation of farmers' cooperatives, and strong subsidy policies increase the government's financial burden, which is not conducive to policy sustainability. Strong government regulation facilitates digital technology companies to actively provide high-quality services for the digital transformation of farmers' cooperatives, but government regulation does not have a significant impact on the strategic choices of the government and farmers' cooperatives. When farmer cooperatives and digital technology companies are in a medium or high level of cooperative trust or when the number of labors saved by digital transformation reaches a certain level, farmers' cooperatives opt for digital transformation even if the government withdraws from policy intervention.

KEYWORDS

farmers' cooperatives, digital transformation, government policy, evolutionary game, simulation

1 Introduction

Agricultural modernization is an important support for rural revitalization (Qu et al., 2018; Fengan, 2020; Chen et al., 2022). Facing the challenges of uncertain factors such as public health emergencies and the external political environment, promoting agricultural modernization requires seeking new momentum for quality change, efficiency change, and power change (Jiang et al., 2020; Han and Lin, 2021). The limited nature of agricultural resources, the differences in regional factor endowments, and the short-term stability of the endowment structure determine that agricultural modernization cannot rely solely on resource-factor-intensive inputs, and that it is necessary to explore new mechanisms for improving agricultural production efficiency in theoretical research and policy practice. Digital technology provides an effective path to break through resource and environmental constraints and achieve agricultural modernization (Jiang et al., 2022). On the one hand, data on farmland, meteorology, crops, livestock and poultry are collected, monitored and analyzed through digital technologies such as sensors, remote sensing technology and the IoT devices, and the accumulation and sharing of such agricultural data enables new types of agricultural businesses, agribusinesses and governments to better understand and respond to the needs and challenges of agricultural production (Khanna et al., 2022). On the other hand, the integration of agriculture with emerging technologies such as the IoT, big data and artificial intelligence has led to a closer connection between agricultural production and processing, logistics, markets and other links, improved the quality of agricultural products and optimized the supply chain of agricultural products, and facilitated the comprehensive upgrading of and value-added to the agricultural industry (Fountas et al., 2020; Hackfort, 2021). Digital technological transformation has become an important force in promoting information sharing, resource integration and interconnection of elements in agricultural production, providing more development space and growth momentum for the upgrading of the agricultural industry chain and industrial integration (Khanna et al., 2022).

In recent years, the Chinese government has introduced a series of policies to provide top-level support for the digital transformation of agriculture. At the policy planning level, in 2019, the General Office of the Central Committee of the Communist Party of China (CPC) and the General Office of the State Council issued the Outline of the Strategy for the Development of Digital Rural Areas,[1] which puts forward ten key tasks for the construction of digital rural areas, and explicitly states that it is necessary to "promote the digital transformation of agriculture." In 2020, the Ministry of Agriculture and Rural Development and the Office of the Central Network Security and Informatization Committee jointly issued the "Digital Agriculture and Rural Development Plan (2019–2025)",[2] which clearly puts forward the five key tasks of "constructing a basic data resource system, accelerating the digitalization of production and operation, advancing the digitalization of management services, reinforcing the key technologies and equipments, and strengthening the construction of major projects." It strives that by 2025 China's agricultural digital economy will account for 15 percent of the value added of agriculture, the e-tailing of agricultural products will account for 15 percent of the total turnover of agricultural products, and the Internet penetration rate in rural areas will reach 70 percent. At the policy implementation level, the No. 1 Document of the Central Government in 2019[3] strongly encourages the further integration of modern information technology with agriculture. To a certain extent, this has accelerated the research and development of related agricultural digital equipment, and pushed forward the transformation of agricultural development from increasing production to improving quality. In 2021, the No. 1 Document of the Central Government[4] explicitly proposed accelerating agricultural modernization and fostering standard "frontrunners" in leading agricultural companies, further reflecting the urgency and importance of agricultural companies to use digital transformation to improve their own development. In 2022, the Central Internet Information Office and other departments jointly promulgated the "Key Points of Digital Rural Development in 2022",[5] focusing on accelerating the completion of shortcomings in digital infrastructure and vigorously promoting the construction of smart agriculture. The "Key Points of Digital Rural Development in 2023"[6] proposes to promote the digital transformation of the entire grain industry chain and accelerate the construction of a digital regulatory platform for agriculture.

The above-mentioned favorable policies provide a good opportunity to promote the integrated development of digital technology and agricultural production. However, digital technology-driven agricultural digital transformation is a systematic project. The current digital infrastructure construction of agricultural digital transformation has not yet achieved wide coverage (Wen and Chen, 2020), there is still a serious disconnect between digital technology and the actual needs of agricultural production (Xin et al., 2020), and the application and maintenance costs of digital technology are high (Chen and Yan, 2020). At the same time, the overall low quality of all kinds of talents serving the development of agriculture seriously restricts the development of agricultural digitalization (Sun et al., 2019). Data from the Third China Agricultural Census show that the aging of the agricultural labor force is high and the labor force is seriously weakened, specifically, 82.4% of agricultural production and management personnel are 36 years old or older, of which 32.6% are 55 years old or older, and 93.0% have an education level of less than junior high school (Li, 2020). At present, the labor productivity and resource utilization rate of Chinese agriculture are still low, and the level of informationization, digitization and intelligence of agricultural production is low, which seriously impedes the development of agricultural modernization. Compared with industry (37.8%) and services (19.5%), the penetration of the digital economy in agriculture is still relatively low at 8.2%. In the context of the high-quality development of agriculture, there is a need to focus on how to achieve the digital transformation of agriculture, which is of great practical significance for the realization of modernized agriculture.

The digital transformation of agriculture is not only one of the urgent priorities for government departments to achieve high-quality development of agriculture, but also one of the topics of growing concern in the academic community, with existing research focusing on four main areas. First, the necessity and strategic significance of digital transformation in agriculture. The digitalization of agriculture is of strategic significance and practical value for achieving high-quality agricultural development and is a new impetus for rural

1 *The Outline of the Strategy for the Development of Digital Rural Areas* can be found at https://www.gov.cn/zhengce/2019-05/16/content_5392269.htm.

2 *Digital Agriculture and Rural Development Plan (2019–2025)* can be found at http://www.moa.gov.cn/govpublic/FZJHS/202001/t20200120_6336316.htm.

3 *The No. 1 Document of the Central Government in 2019* can be found at http://www.moa.gov.cn/ztzl/jj2019zyyhwj/2019zyyhwj/.

4 *The No. 1 Document of the Central Government in 2021* can be found at http://www.moa.gov.cn/ztzl/jj2021zyyhwj/2021nzyyhwj/.

5 *Key Points of Digital Rural Development in 2022* can be found at https://www.cac.gov.cn/2022-04/20/c_1652064650196835.htm.

6 *Key Points of Digital Rural Development in 2023* can be found at https://www.cac.gov.cn/2023-04/13/c_1683027266482224.htm.

revitalization (Qin et al., 2022). Bacco et al. (2019) argued that the wider introduction of information and communication technology in agriculture is important for the economic development of agriculture in the EU region. Second, the application scenario of digital transformation in agriculture. Digital technologies are widely used in production, sales, and operations (Büchi et al., 2018), and digital agriculture involves monitoring, controlling, forecasting, and logistics in the agricultural production process (Dayioğlu and Turker, 2021). The combination of satellite remote sensing technology and network technology can realize real-time monitoring of crops and their growing environment parameters (Ray, 2016). Agricultural supply chain finance can be digitally transformed with digital technologies such as e-commerce platforms, big data and cloud computing (Xu and Zhang, 2020). Third, the problems of digital transformation in agriculture. Currently, the digital transformation of agriculture is faced with insufficient application capacity of agricultural operators (Hackfort, 2021), insufficient investment of resources (Mamai et al., 2020), and low level of application and management of agricultural big data (Sarker et al., 2019; Newton et al., 2020).At the same time, the digital transformation of agriculture is more oriented towards large farmers, and small farmers may not be able to fully share the dividends of digitization, leading to "elite capture" (Basso and Antle, 2020), and the process of digitization of agriculture may reduce biodiversity and disengage farmers from their traditional culture of agriculture (Lioutas et al., 2021). Fourth, the path to achieve digital transformation in agriculture. On the one hand, legislators developing policies for digital transformation in modern agriculture should pay more attention to external dimensions including economy, government, and sustainability. Farmers seeking to implement digital transformation should pay more attention to internal dimensions including infrastructure, technology, collaboration, change, and people/knowledge/skills (Mendes et al., 2022). Specifically, driving agricultural modernization through precision agriculture emphasizes the application of "3S" technologies in smart agriculture. Leveraging "blockchain + Internet of Things" technology to overcome existing weaknesses in the agricultural industry, actively promoting the integration of agricultural industries, nurturing new integrated entities, constructing a full industry chain digital agricultural operation model, and guiding integrated entities towards moderate scaling and intensification of development (Patil et al., 2012; Mohanta et al., 2021; Avşar and Mowla, 2022). On the other hand, agricultural policies need to ensure that digitalization is carried out in an ethical, fair and inclusive manner, protecting farmers' rights to their own data, controlling the trajectory of digitalization and intervening when needed to prevent negative impacts (Lioutas et al., 2021). In summary, research on digital transformation in agriculture has achieved some theoretical results and practical experience, but there are some gaps in existing research: First, existing research on agricultural digital transformation mostly analyzes from a single subject and lacks systematic analysis; Second, although existing research has paid attention to the role of government policies in agricultural digital transformation, they have been analyzed more from a static perspective and less from a dynamic perspective. Third, existing research analyzes agricultural digital transformation more from the macro level and pays less attention to farmers' cooperatives, a new type of agricultural businesses, from the micro level.

Evolutionary game theory first originated as a game analysis of conflict and cooperative behavior in animals and plants by genetic ecologists such as Fisher, Hamilton and Tfive. Smith and Price (1973) first proposed the concept of evolutionary stable strategy, which marked the official birth of evolutionary game theory. In recent years, with the expansion of the application field of evolutionary game theory, some scholars have studied the problems of companies digital transformation based on evolutionary game theory. Zhang et al. (2023) argued that the problem of low digitization in China's construction industry is relatively prominent, constructed a tripartite evolutionary game model of the government, service providers, and construction companies, explored the influencing factors of the digital transformation of construction companies. Cloud-native is an innovative technology necessary for realizing companies digital transformation, Zhang et al. (2022) combined with evolutionary game theory to construct the game relationship between cloud providers and companies in cloud-native selection, which provides a reference for various stakeholders to promote the landing of cloud-native and companies digital transformation. Gao et al. (2022) constructed a value co-creation synergistic mechanism among core manufacturing companies, service companies and customers based on a tripartite evolutionary game model to provide a universal synergistic path for the digital transformation of service-oriented manufacturing. Evolutionary game theory has been widely applied to various other fields. For example, in the field of social governance, Encarnação et al. (2016) constructed a tripartite game model involving the civil sector, state sector, and business sector, providing a new research approach for promoting societal paradigm shifts. In the field of medical investment, Alalawi and Zeng (2020) developed a tripartite game model involving public healthcare providers, private healthcare providers and patients, offering new solutions to cooperation dilemmas in healthcare systems. In the field of safety technology regulation, scholars have used multi-agent evolutionary game theory to explore various aspects of AI technology regulation, making significant contributions to the research on the normative development of AI technology (Alalawi et al., 2024; Bova et al., 2024). Additionally, evolutionary game theory has been used to study the relationship between compliance with agreements and cooperation. This type of research focuses on how commitments influence cooperation between agents. As an external manifestation of trust, commitments are an important tool for maintaining social interactions and can promote the evolution of cooperation (Sasaki et al., 2015). Participating in bilateral commitments and adhering to them can enhance the coordination of cooperation between participants, serving as a key factor in the transition from guided cooperation to spontaneous cooperation among participants (Barrett, 2016; Han, 2022; Han et al., 2022; Ogbo et al., 2022).

As typical co-operative companies, some studies have established a tripartite evolutionary game model of information sharing among agricultural supply chain subjects dominated by farmers' cooperatives to explore the interaction law of information sharing behaviors of decision-making subjects in the agricultural supply chain (Wang et al., 2022), however, the existing studies pay less attention to the digital transformation of farmers' cooperatives. In reality, farmers' cooperatives, as an innovative form of farmers' self-organization system, have realized the upgrading of small farmers' market subject status, and are the basic support unit of the rural economy and the organic carrier for the development of digital economy (Luo et al., 2017; Xie et al., 2021). By the end of 2022, there were 2.225 million farmers' cooperatives legally registered in China,[7] covering nearly half of all farmers. The digital transformation of farmers' cooperatives is the only way for China to fundamentally achieve digital agricultural production. Moreover, in the context of digital rural development, digital transformation is also a driving force for the high quality development of cooperatives and an important trend for future development (Mendes et al., 2022). Therefore, there is a need for an in-depth discussion on the digital transformation of farmers' cooperatives.

Therefore, based on the evolutionary game theory, this paper includes the main stakeholders in the digital transformation of farmers' cooperatives—the government, digital technology companies and farmers' cooperatives—into the same analysis system, constructs a three-party evolutionary game model, and carries out a simulation analysis of the digital transformation of farmers' cooperatives from the perspective of the government's policy to answer the following main questions: (1) How do government subsidies and government regulations affect the digital transformation of farmers' cooperatives? (2) Under what conditions do governments reduce or even withdraw from intervention policies for the digital transformation of farmers' cooperatives? By answering the above questions, we propose a new framework for synergistic development, and based on a dynamic evolutionary perspective, we predict the future development trend of the digital transformation of farmers' cooperatives under the influence of government policies, and accordingly propose policies and paths to promote the development of digital transformation of agricultural production.

The remaining part of the paper is structured as follows: Section 2 demonstrates the applicability of the evolutionary game approach to this research problem and constructs an evolutionary game model for the three subjects. In Section 3, the simulation is conducted based on the case data of Zhejiang Province, and the simulation results are analyzed. In Section 4, the simulation results are discussed. Section 5 summarizes the main findings of the paper and makes relevant policy recommendations accordingly.

2 Materials and methods

2.1 Problem description

At present, China's agricultural development faces the challenge of tightening resource and environmental constraints. According to the 7th National Population Census, China's population aged 60 years and above is 264.02 million, accounting for 18.7% of the population, and the growth rate of the elderly population has accelerated significantly, and the proportion will reach about 25% by 2030 (Yin et al., 2021). It is foreseeable that the problem of scarcity of agricultural production labor will become more and more serious with the continuous outflow of rural labor and aging phenomenon. In addition, China's high-quality agricultural development faces challenges such as limited agricultural resources, large regional differences in factor endowments, and weak stability of endowment structure in the short term (Zhong, 2019). The digital transformation of agriculture has become a goal that aligns the interests of governments and agricultural operators. At the same time, the Chinese government's digital policy dividend in recent years has attracted a large number of agribusinesses to carry out research and development investment in digital agricultural technology, making it possible for new types of agricultural businesses to realize digital transformation. Government, digital technology companies and farmers' cooperatives are three important stakeholders in the process of agricultural digital transformation. The government, as a policy maker and implementer, hopes to break through the dilemma of agricultural development and empower high-quality agricultural development through the digital transformation of agriculture. As rational "economic man," digital technology companies and farmers' cooperatives are more concerned with their own economic interests, and there is a clear divergence of interests with government departments. Therefore, there are different scenarios of cooperation between the government, digital technology companies and farmers' cooperatives based on their respective interests in the process of digital transformation of agriculture.

Farmers' cooperatives, as an innovative form of farmers' self-organization system, have realized the upgrading of the status of small farmers as market subjects, but the vast majority of farmers' cooperatives are in the exploratory stage of digital transformation, lack of transformational thinking, and have a weak foundation for the application of digital technology (Mendes et al., 2022). Digital technology companies provide products, tools and services for the digital transformation of farmers' cooperatives, which can empower farmers' cooperatives to transform digitally and help them create digital benefits. Due to the greater risk and uncertainty of digital transformation of farmers' cooperatives, digital technology companies are more concerned about providing services for the digital transformation of large companies based on their own interests, which also makes digital technology companies less willing to provide high-quality services for the digital transformation of farmers' cooperatives. In response to the real problems faced by digital technology companies and farmers' cooperatives, the Ministry of Agriculture and Rural Development has put forward the transformation incentive idea of "farmers' cooperatives contribute a little, digital technology companies give a little, and the government makes up a little." As the policy maker and action guide for the digital transformation of agriculture, the government can guide digital technology companies and farmers' cooperatives to jointly promote digital transformation through policy instruments. Government strategies are policy intervention and no policy intervention; the strategies of digital technology companies are to provide high-quality services to farmer cooperatives or to provide low-quality services; and the strategies of farmers' cooperatives are to digitally transform and not to digitally transform.

When all three participants choose to work together, the government implements supportive policies that provide subsidies and incentives to farmers' cooperatives and digital technology companies involved in the digital transformation of agriculture, the digital technology companies provide high-quality digital transformation services to farmers' cooperatives with government incentives, and the farmers' cooperatives choose to undergo digital transformation. In this process, the government actively monitors the behavior of digital technology companies and implements incentives T_{g1} for farmers' cooperatives based on their satisfaction with digital technology services and subsidies αM for digitally transformed farmers' cooperatives. Digital technology companies can get

7 Data sources: http://www.moa.gov.cn/govpublic/NCJJTZ/202208/t20220810_6406722.htm.

government incentives for providing high quality services to farmers' cooperatives and create synergistic benefits μE_c with digitally transformed farmers' cooperatives, and farmers' cooperatives get synergistic benefits of $(1-\mu)E_c$. The cost for digital technology companies to develop agricultural digitization equipment is C_e, and the cost for a farmers' cooperative to purchase the equipment is C_f. This model can be represented by (1,1,1), also known as Case 1. Table 1 provides a brief overview of the eight different scenarios of cooperation that may arise.

2.2 Evolutionary game theory method

Distinguished from the classical game theory, Evolutionary Game Theory (EGT) is a multidisciplinary fusion of theories that do not regard human beings as super-rational parties to the game, and believe that human beings reach the equilibrium of the game through trial-and-error methods. Smith and Price (1973) and Smith (1982) for the first time proposed Evolutionary Stable Strategy, to free people's attention from the rationality trap of game theory, from another angle for the study of game theory to find a possible breakthrough, evolutionary game theory has been rapidly developed. Evolutionary game theory encompasses three key components: the payoff matrix, evolutionary stable strategies, and replicator dynamics equations.

The payoff matrix illustrates the array of rewards gained by diverse participants employing different strategies.

The Evolutionarily Stable Strategy (ESS) denotes a strategy within a collective wherein, if adopted by certain individuals, it can withstand the incursion of alternative strategies. Thus, an ESS is both stable and enduring, capable of proliferating throughout groups.

Replicator dynamics delineates the dispersion and alterations of various strategies within a collective. It portrays the group's evolutionary progression as a dynamic system, utilizing mathematical methodologies to scrutinize group behavior evolution and the establishment of enduring strategies.

In the 1980s, many economists introduced evolutionary game theory into the field of economics to analyze social system change, industrial evolution, and stock markets, among others (Samuelson, 1997; Weibull, 1997). The evolutionary games theory is based on two main aspects: Selection and Mutation. Selection refers to the fact that strategies that result in higher payments will be adopted by more participants in the future; mutation refers to the fact that some individuals choose, in a randomized manner, strategies that are different from those of the group (which may be strategies that result in higher payments or strategies that result in lower payments). Mutation is an actually choice, but only a good strategy will survive. Mutation is a process of trial and error, of learning and imitation, which is adaptive and constantly improving. There is an inconsistency of interests among the three key players involved in the process of digital transformation in agriculture, which implies that there is a gaming relationship between them. Moreover, neither the government, nor digital technology companies, nor farmers' cooperatives can be "all-knowing," and they are all constantly revising and improving their own behaviors, imitating successful strategies, and ultimately converging on a stable state of cooperation. Evolutionary game theory can be used to explain the behavior of the various players in this process. Therefore, based on the evolutionary game theory, this paper constructs a tripartite dynamic evolutionary game model of the government, digital technology companies and farmers' cooperatives, examines the evolutionary state of different participants in the process of agricultural digital transformation from the perspective of government policy, and carries out simulation using Matlab software.

2.3 Formulas for modeling

Under different cooperation scenarios, the cost–benefit of the same subject's participation in the digital transformation of agriculture may be different, so there are eight different benefit matrices for the eight scenarios. The tripartite payoff matrix for scenario 1 (1, 1, 1) is shown in Equation 1:

$$\begin{cases} a11 = Eg + W - Tg1 - \alpha M - pCg \\ a12 = -Ce + Tg1 + \mu Ec \\ a13 = -Cf + S + \alpha M + (1-\mu)Ec \end{cases} \tag{1}$$

a_{11}, a_{12} and a_{13} denote the benefit matrices for the government, digital technology companies and farmers' cooperatives in scenario 1, respectively. Where E_g denotes the base benefit of the government's support for the digital transformation of farmers' cooperatives; and W denotes the economic benefit to the government from the high-quality technical services provided by digital technology companies to digitally transformed farmers' cooperatives under the government's support policy; T_{g1} denotes the incentives received by digital technology companies for providing high-quality services to farmers' cooperatives under the government's support policy, $T_{g1} = d + \theta A_1 + (1-p)\delta^2$; where d is the government's fixed incentive

TABLE 1 The introductions of different partnership modes.

Case	Modes	Government	Digital technology companies	Farmers' cooperative
1	(1,1,1)	Cooperation	Cooperation	Cooperation
2	(1,0,1)	Cooperation	Non-cooperation	Cooperation
3	(1,1,0)	Cooperation	Cooperation	Non-cooperation
4	(1,0,0)	Cooperation	Non-cooperation	Non-cooperation
5	(0,1,1)	Non-cooperation	Cooperation	Cooperation
6	(0,0,1)	Non-cooperation	Non-cooperation	Cooperation
7	(0,1,0)	Non-cooperation	Cooperation	Non-cooperation
8	(0,0,0)	Non-cooperation	Non-cooperation	Non-cooperation

for digital technology companies, θA_1 denotes the government's performance incentive for digital technology companies, θ is the government's variable incentive base, which indicates the strength of incentives for digital technology companies, and A_1 denotes the farmers' cooperatives' satisfaction with the high-quality technical services provided by digital technology companies. $(1-p)\delta^2$ denotes the exogenous random variable, the larger δ^2 indicates that the greater the degree of information asymmetry between the government and the digital technology companies, the greater the impact of exogenous factors on the performance output of the digital technology companies (Feng et al., 2022), and p denotes the government's regulatory intensity, and when the government's regulatory intensity reaches its maximum value, the exogenous random variable's impact is zero. At this point, the performance of digital technology companies fully reflects the satisfaction of farmers' cooperatives with the technical services provided by digital technology companies, which can be regarded as a state of information symmetry between the government and digital technology companies; αM denotes the government's subsidy for the digital transformation of farmers' cooperatives, where α is the government's subsidy intensity; C_g denotes the government's regulatory cost.

C_e denotes the cost of technology research and development for digital technology companies choosing to provide high-quality services; E_c denotes the synergistic benefits created by digital technology companies and farmers' cooperatives, and μ is the synergistic benefit allocation coefficient.

C_f denotes the cost of digital transformation of farmers' cooperatives; S denotes the labor cost saved by digital transformation of farmers' cooperatives, $S = ms$, m is the number of labor saved, i.e., the amount of labor saved in agricultural production by a set of digital equipment (automatic film rolling, water and fertilizer integrated intelligent irrigation system), and s is the marginal labor cost.

The tripartite payoff matrix for Scenario 2 (1, 0, 1) is shown in Equation 2:

$$\begin{cases} a21 = Eg - Tg2 - \alpha M - pCg + pF \\ a22 = -nR1 + Tg2 - pF \\ a23 = -Cf + S + \alpha M - nR2 \end{cases} \tag{2}$$

a_{21}, a_{22}, and a_{23} denote the payoff matrices for the government, digital technology companies, and farmers' cooperatives, respectively, in Scenario 2. where T_{g2} denotes the incentives received by digital technology companies for providing low-quality services to farmers' cooperatives under the government's support policy, $T_{g2} = d + \theta A_2 + (1-p)\delta^2$, where A_2 denotes farmers' cooperatives' satisfaction with low-quality technical services provided by digital technology companies; and F denotes the government's penalty for low-quality services provided by digital technology companies; nR_1 denotes the cost of after-sales service that digital technology companies need to pay for providing low-quality services, where n is the demand for after-sales service by farmers' cooperatives, R_1 is the marginal cost of after-sales service provided by digital technology companies; and R_2 is the marginal cost of repairing digitized equipment in farmers' cooperatives.

The tripartite payoff matrix for scenario 3 (1, 1, 0) is shown in Equation 3:

$$\begin{cases} a31 = Eg - Tg1 - pCg \\ a32 = -Ce + Tg1 \\ a33 = -Cr - Cs \end{cases} \tag{3}$$

a_{31}, a_{32}, and a_{33} denote the payoff matrices for the government, digital technology companies, and farmers' cooperatives in Scenario 3, respectively. Where C_r denotes the regret cost of farmers' cooperatives not choosing digital transformation under the government intervention policies; and C_s denotes the losses incurred by farmers' cooperatives not choosing digital transformation, including the loss of agricultural production due to future labor barriers.

The tripartite payoff matrix for scenario 4 (1, 0, 0) is shown in Equation 4:

$$\begin{cases} a41 = Eg - Tg2 - pCg + pF \\ a42 = Tg2 - pF \\ a43 = -Cr - Cs \end{cases} \tag{4}$$

a_{41}, a_{42} and a_{43} denote the payoff matrices for the government, digital technology companies and farmers' cooperatives in scenario 4, respectively.

The tripartite payoff matrix for scenario 5 (0, 1, 1) is shown in Equation 5:

$$\begin{cases} a51 = \beta W \\ a52 = -Ce + \beta\mu Ec \\ a53 = -Cf + S + \beta(1-\mu)Ec \end{cases} \tag{5}$$

a_{51}, a_{52} and a_{53} denote the payoff matrices of the government, digital technology companies and farmers' cooperatives in scenario 5, respectively, where β denotes the trust coefficient between digital technology companies and farmers' cooperatives under the government support policy.

The tripartite payoff matrix for scenario 6 (0, 0, 1) is shown in Equation 6:

$$\begin{cases} a61 = 0 \\ a62 = -nR1 \\ a63 = -Cf + S - nR2 \end{cases} \tag{6}$$

a_{61}, a_{62} and a_{63} denote the benefit matrices for the government, digital technology companies and farmers' cooperatives in scenario 6, respectively.

The tripartite payoff matrix for scenario 7 (0, 1, 0) is shown in Equation 7:

$$\begin{cases} a71 = 0 \\ a72 = -Ce \\ a73 = -Cs \end{cases} \tag{7}$$

a_{71}, a_{72} and a_{73} denote the benefit matrices for the government, digital technology companies and farmers' cooperatives in scenario 7, respectively.

The tripartite payoff matrix for scenario 8 (0, 0, 0) is shown in Equation 8:

$$\begin{cases} a_{81} = 0 \\ a_{82} = 0 \\ a_{83} = -C_s \end{cases} \tag{8}$$

a_{81}, a_{82}, and a_{83} denote the payoff matrices for the government, digital technology companies, and farmers' cooperatives in Scenario 8, respectively.

Based on the above assumptions, we have drawn a diagram of the relationships between the model variables, as shown in Figure 1.

Based on the above eight sets of payoff matrices, the replication dynamic equations for the government, digital technology companies, and farmers' cooperatives are distributed as Equations 9, 10, 11:

$$F(x) = \frac{\mathrm{d}x}{dt} = x(1-x)[Eg - pCg - yTg_1 - Z\alpha M + yz(1-\beta)W + (1-y)(pF - Tg_2)] \tag{9}$$

$$F(y) = \frac{dy}{dt} = y(1-y)[-Ce + x(Tg_1 - Tg_2 + pF) + znR_1 + xz\mu Ec + (1-x)z\beta\mu Ec] \tag{10}$$

$$F(z) = \frac{dz}{dt} = z(1-z)[-C_f + S + C_s + x(\alpha M + C_r) - (1-y)nR_2 + xy(1-\mu)Ec + (1-x)y^2(1-\mu)Ec] \tag{11}$$

To obtain the local stationary points and ESS in a dynamic system for both players in the game, set Equations 9, 10, 11 to zero. This indicates that the strategies of both players no longer change over time, and the choices made by each participant are the optimal strategies at this point. An ESS must satisfy a pure strategy Nash equilibrium, whereas other forms of Nash equilibria are less likely to be stable strategies in the system (Hammerstein and Parker, 1982; Selten and Selten, 1988; Björnerstedt and Weibull, 1994). Therefore, this paper only discusses the following eight points: (1,1,1), (1,0,1), (1,1,0), (0,1,0), (0,0,1), (0,1,1), (1,0,0), and (0,0,0).

3 Results

3.1 Initial parameter settings

The data of this study comes from the research team's investigation of the agricultural digital transformation in Jiaxing City, Zhejiang Province, China. Zhejiang Province is located in the Yangtze River Delta region of China, which has been regarded as an economically developed region since ancient times, and Zhejiang Province has been listed as an early pilot region for the development of digital agriculture, while Jiaxing City is a model for the development of digital agriculture in Zhejiang Province. The specific initial parameters are shown in Table 2.

The data in this study were obtained from three main sources: First, the official government website. Policies and laws on agricultural digitization in Zhejiang Province and Jiaxing City. Second, field research. We researched the Bureau of Agriculture and Rural Affairs, three farmers' cooperatives, and a digital technology company in Nanhu District, Jiaxing City, in August 2022 to obtain first-hand information. The research covers the costs and benefits of digital technology companies in providing high-quality services, and the costs and benefits of digital transformation of farmers' cooperatives. We organized the case data of the research and supported the case data with data provided by the government, and finally came up with the initial values of the parameters of this paper. The third is the opinion of experts in the field of agricultural economics. The initial values of the social benefits obtained by the government and the regret cost of not undergoing digital transformation in farmers' cooperatives were obtained by expert estimation for both (1,1,1) and (0,1,1) scenarios. In order to reduce the influence of subjective factors and ensure the scientificity, accuracy and validity of parameter quantification, we invited 12 experts in the field of agricultural economics (3 professors, 4 associate professors and 5 PhD students) and randomly divided them into 6 groups, and the whole valuation process was divided into 6 steps. In the first step, the model construction and the meaning of each parameter are explained and discussed; in the second step, the trial valuation and optimization of the valuation criteria; in the third step, the estimated value and revision of the valuation criteria; in the fourth step, the first formal valuation; in the fifth step, the revision of the formal valuation results; and in the sixth step, the calculation of the final valuation using the averaging method. It is assumed that the intensity of government subsidies, the intensity of government regulation and the service quality of digital technology companies are all 0.5, which indicates the neutral attitudes of the government and digital technology companies towards policies and service quality in the initial state. Based on the information obtained from the above three channels, this paper simplifies the data, and the specific parameter settings are shown in Table 2.

3.2 Stability analysis of equilibrium strategy

Eight possible scenarios are presented in Section 2.3, but at this point we are not sure if these eight scenarios are asymptotically stable states (ESS), and ESS can only be achieved when both Nash equilibrium and pure strategy Nash equilibrium are satisfied. According to the Lyapunov discriminant, the eigenvalues of the Jacobi matrix obtained by taking the first-order partial derivatives of the replicated dynamic equations of the government, digital technology companies, and farmers' cooperatives with respect to x, y, and z, respectively, can be used to determine the asymptotic stability of the eight scenarios. If the 8 scenarios are evolutionary steady states, the condition that the eigenvalues of all 8 equilibrium points are less than 0 needs to be satisfied, which is analyzed as follows.

We simulate the evolutionary trajectories of the government, digital technology companies, and farmers' cooperatives under different scenarios using the formulas in Section 2.3 and the initial parameters provided in Table 2, as shown in Figures 2, 3, where "Probability" denotes the proportion of the participants'

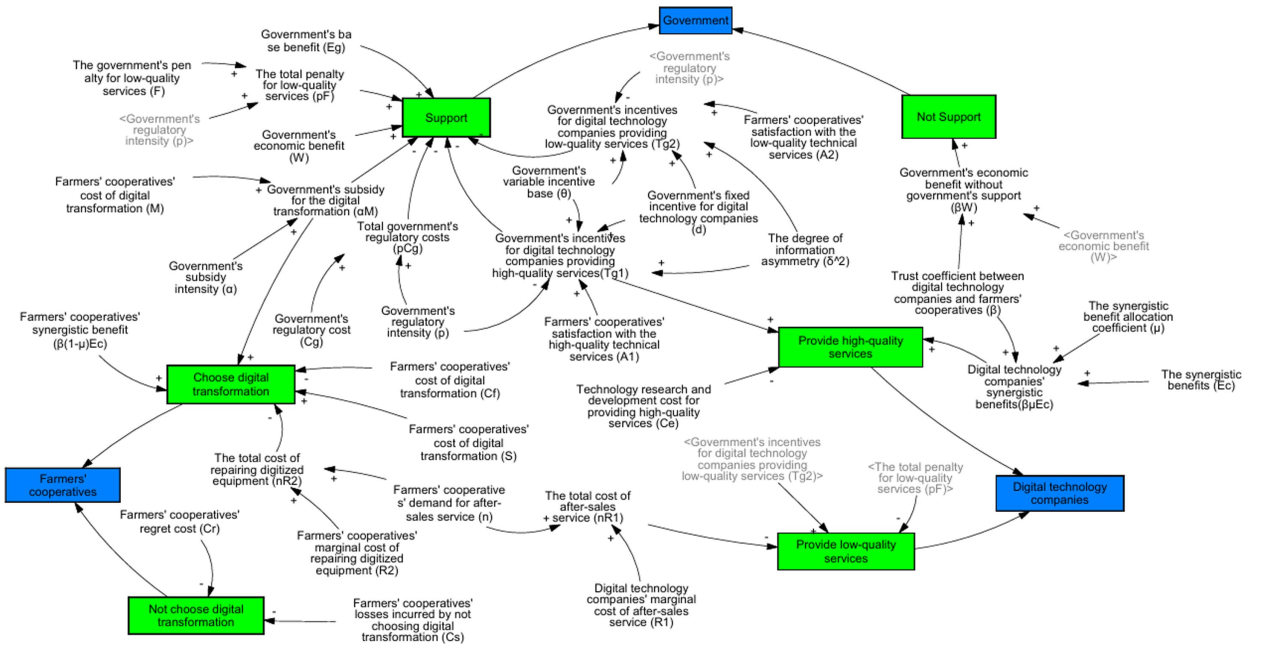

FIGURE 1
Relationship between model variables.

willingness to cooperate, i.e., the probability of wishing to cooperate. "Time" indicates the time evolution when a cooperative mode starts.

As shown in Figure 2A, in the (1,1,1) scenario, the final states of the government, the digital technology companies, and the farmers' cooperatives all stabilize. We substitute the point (1,1,1) into the Jacobi matrix to obtain three eigenvalues, which are $-E_g-(1-\beta)W+pC_g+T_{g1}+\alpha M$, $C_e+T_{g2}-T_{g1}-pF-nR_1-\mu E_c$ and $C_f-ms-C_s-\alpha M-C_r-(1-\mu)E_c$. When the condition that all the three eigenvalues are less than zero is fulfilled, (1,1,1) is an evolutionary steady state, and all the three participants are able to obtain the satisfactory benefits. The government has gained social benefits and political achievements by supporting digital technology companies and farmers' cooperatives to collaborate on digital transformation. Digital technology companies have received government incentives for providing high-quality services. The digital transformation of farmers' cooperatives saves on labor costs and is also subsidized by the government. In this evolutionary steady state, the government shows the strongest willingness to cooperate, followed by the orderly participation of farmers' cooperatives and digital technology companies.

(1,1,0) is an evolutionary steady state when $-E_g+pC_g+T_{g1}<0$, $C_e+T_{g2}-T_{g1}-pF<0$ and $-C_f+ms+C_s+\alpha M+C_r+(1-\mu)E_c<0$ are satisfied simultaneously. The willingness of the government, digital technology companies and farmers' cooperatives to participate is shown in Figure 2B. The digital transformation of farmers' cooperatives requires a large amount of investment in the early stage, and the labor cost savings and government subsidies after the transformation are not enough to compensate for the costs and risks of their transformation, so the willingness of farmers' cooperatives to digitally transform gradually decreases, and eventually reaches zero. The Government and the digital technology companies receive social benefits and incentives, respectively, and therefore chosen to continue their cooperation.

Figure 2C shows the strategy evolution of the three participants for the (1,0,1) scenario. The costs and benefits to the government in this cooperative scenario need to satisfy $-E_g-pF+pC_g+\alpha M+T_{g2}<0$, which suggests that the government receives social benefits that outweigh its regulatory and subsidy costs, and therefore the government chooses the strategy of policy interventions; The costs and benefits of digital technology companies satisfy $-C_e-T_{g2}+T_{g1}+pF+nR_1+\mu E_c<0$, which indicates that the synergistic benefits and government incentives gained from providing high-quality services are not enough to make up for the cost of technological research and development invested by digital technology companies, and therefore, digital technology companies choose the strategy of providing low-quality services. The costs and benefits of farmers' cooperatives need to satisfy $C_f-ms-C_s-\alpha M-C_r+nR_2<0$, which suggests that even though the low-quality services provided by digital technology companies for farmers' cooperatives make them increase the post-production equipment maintenance costs, the labor costs saved by the digital transformation for farmers' cooperatives and the government subsidies make up for the equipment maintenance costs, and thus the farmers' cooperatives still choose the digital transformation under the government policy interventions.

As shown in Figure 2D, the scenario of (1,0,0) is an evolutionary steady state when both $-E_g-pF+pC_g+T_{g2}<0$, $-C_e-T_{g2}+T_{g1}+pF<0$ and $-C_f+ms+C_s+\alpha M+C_r-nR_2<0$ are satisfied. The government intervenes in the digital transformation of agriculture to gain social benefits, while digital technology companies choose low-quality service strategies to avoid R&D risks, which increases the risk of equipment maintenance for farmers' cooperatives and leads them to withdraw from cooperation.

TABLE 2 Initial parameters for the EGT analysis.

Participants	Variables	Parameters	Values (yuan/year)
Government	E_g	Government's base benefit of the farmers' cooperatives' digital transformation	45×10^4
	C_g	Government's regulatory cost	10×10^4
	W	Government's economic benefit from the high-quality technical services provided by digital technology companies to digitally transformed farmers' cooperatives	50×10^4
	F	Government's penalty for low-quality services provided by digital technology companies	8×10^4
	θ	Government's variable incentive base	2×10^4
	p	Government's regulatory intensity	0.5
	α	Government's subsidy intensity	0.5
	β	The trust coefficient between digital technology companies and farmers' cooperatives under the government support policy	0.5
	d	Government's fixed incentive for digital technology companies	1×10^4
	δ^2	The degree of information asymmetry between the government and digital technology companies	1
Digital technology companies	C_e	Digital technology companies' technology research and development cost for providing high-quality services	12×10^4
	R_1	Digital technology companies' marginal cost of after-sales service	1×10^4
	E_c	The synergistic benefits created by digital technology companies and farmers' cooperatives	6×10^4
	μ	The synergistic benefit allocation coefficient	0.6
Farmers' cooperatives	C_f	Farmers' cooperatives' cost of digital transformation	100×10^4
	C_r	Farmers' cooperatives' regret cost who not choosing digital transformation	10×10^4
	C_s	Farmers' cooperatives' losses incurred by not choosing digital transformation	15×10^4
	R_2	Farmers' cooperatives' marginal cost of repairing digitized equipment	1×10^4
	s	Farmers' cooperatives' labor cost saved by digital transformation	8×10^4
	A_1	Farmers' cooperatives' satisfaction with the high-quality technical services provided by digital technology companies	1
	A_2	Farmers' cooperatives' satisfaction with the low-quality technical services provided by digital technology companies	-1
	m	The number of labors saved	5×10^4
	n	Farmers' cooperatives' demand for after-sales service	5×10^4

Figure 3A shows the strategy evolution of the three participants for the (0,1,1) scenario. The gradual withdrawal of government intervention policies and the realization of mutually beneficial cooperation between digital technology companies and farmers' cooperatives is our ideal stable state. If the scenario of (0,1,1) is asymptotically stable, it needs to simultaneously satisfy $E_g+(1-\beta)W-pC_g-T_{g1}-\alpha M<0$, $C_e-nR_1-\beta\mu E_c<0$ and $C_f-ms-C_s-\beta(1-\mu)E_c<0$ This suggests that the trust coefficient of cooperation between the digital technology companies and the farmers' cooperatives is higher, and that even in the absence of governmental regulation and subsidies they can also realize cooperation.

Figure 3B shows the strategy evolution of the three participants under the (0,1,0) scenario. Due to the high capital investment required for the digital transformation of agriculture, the willingness of farmers' cooperatives to digitally transform gradually decreases, and they eventually withdraw from the cooperation. The willingness of the government and digital technology companies to cooperate has always shown cyclical changes, which shows that without the support of the government and farmers' cooperatives, digital technology companies have insufficient motivation to provide high-quality digital services. The pattern of (0,1,0) is always unable to achieve stability.

Figure 3C shows the evolutionary trajectories of the three participants for the (0,0,1) scenario. According to the stability condition of the equilibrium point $C_f-ms-C_s+nR_1<0$, the willingness of farmers' cooperatives to digitally transform rapidly rises to 1. The reason is that digital transformation can save the labor cost of farmers' cooperatives and improve the level of their fine management of crops, so in the absence of the support of the government and the digital technology companies, farmers' cooperatives will still choose digital transformation based on their own interests.

As shown in Figure 3D, when all three participants choose not to cooperate, the government does not subsidize digital technology companies and farmers' cooperatives, and farmers' cooperatives' financial investment costs for digital transformation are higher than

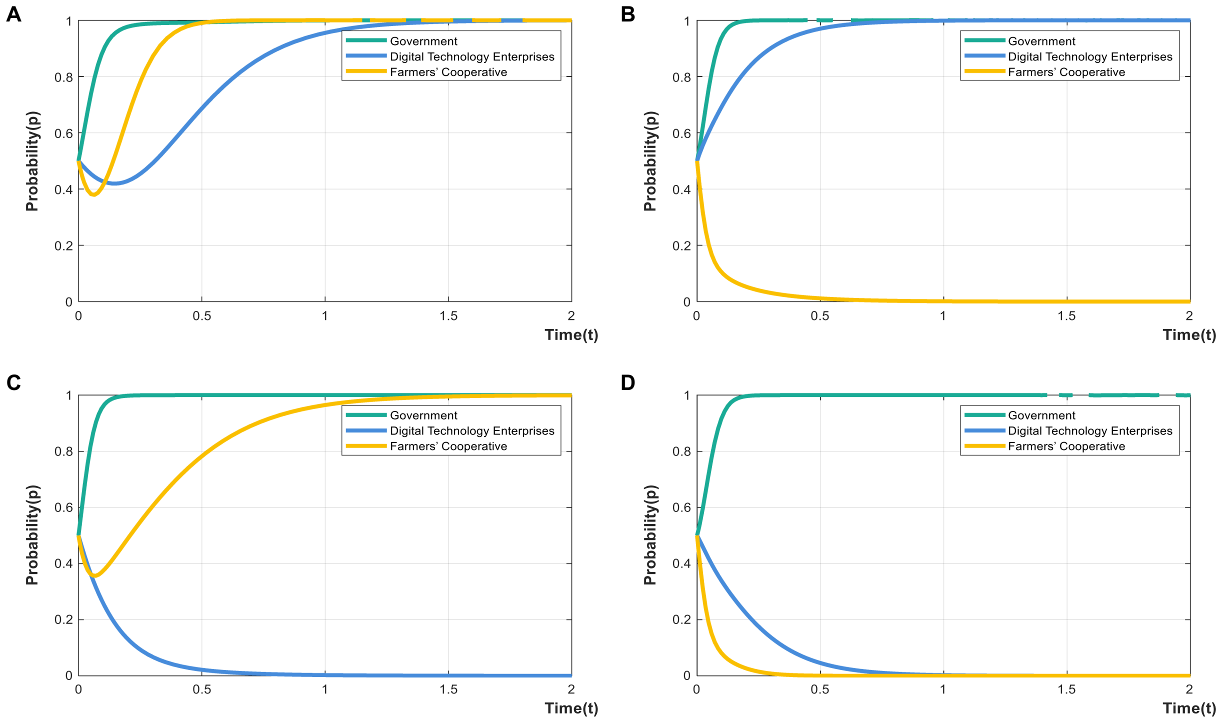

FIGURE 2
Evolutionary trajectories of the government, e-commerce team and agri-technology companies under different partnership modes: **(A)** (1,1,1), **(B)** (1,0,1), **(C)** (1,1,0), **(D)** (1,0,0).

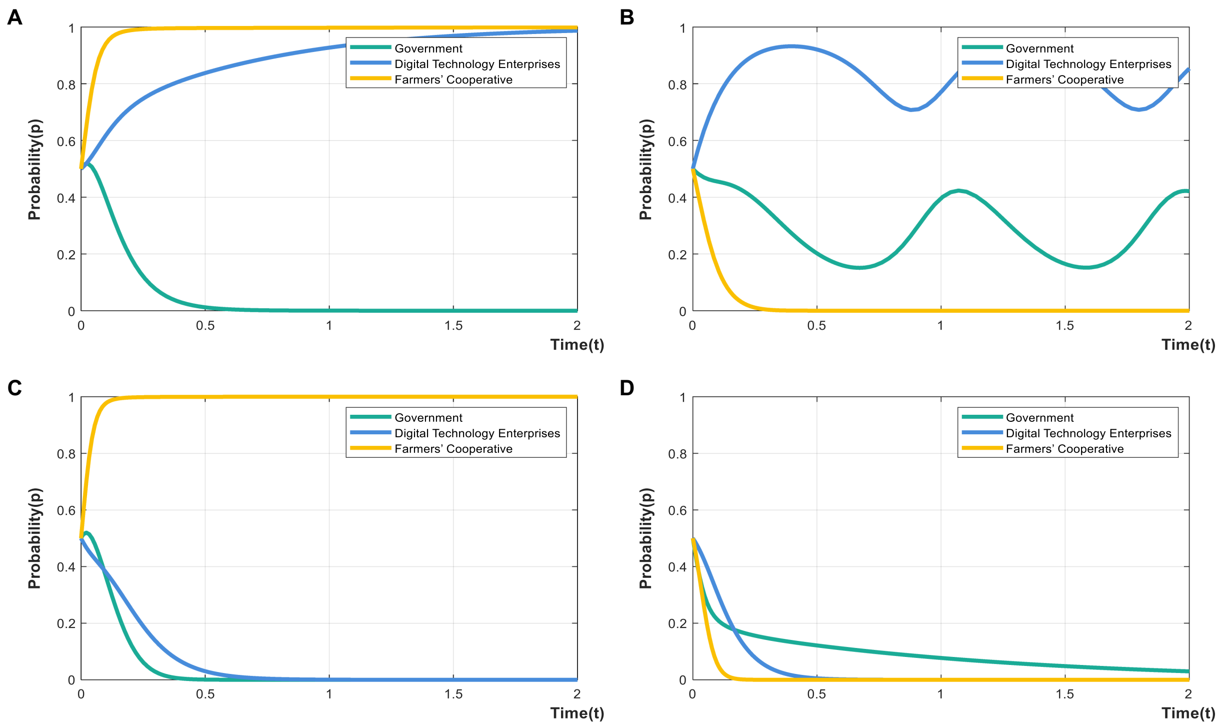

FIGURE 3
Evolutionary trajectories of the government, agri-technology companies and farmers' cooperative under different partnership modes: **(A)** (0,1,1), **(B)** (0,0,1), **(C)** (0,1,0), **(D)** (0,0,0).

the benefits they receive. In the absence of government subsidies and market demand, the incentive of digital technology companies to provide high-quality digitization services gradually decreases and eventually becomes zero.

Figures 3, 4 show the simulation results for all the evolutionary games. The participation of digital technology companies in the digital transformation of agriculture follows a political logic and an economic logic, when the government does not intervene in the digital transformation of agriculture and the farmers' cooperatives are not willing to digitally transform, the digital technology companies will not provide high-quality digitization services, and the (0,1,0) model will always fail to reach stability. (1,1,1) and (0,1,1) are the more desirable cooperation modes and both are stable under certain conditions. In the next section, we will focus on analyzing these two states.

3.3 Digital transformation of agricultural production side guided by government participation

Based on the simulation analysis of the three participants under different cooperation modes, we find that (1,1,1) is the ideal evolutionary stable state, i.e., digital technology companies and farmers' cooperatives achieve win-win cooperation under the government policy intervention. However, there is still a large gap between the real situation and the ideal state, so this section discusses the effects of government subsidy policy and regulatory policy on the strategies of the three participants based on the scenario of (1,1,1).

3.3.1 Government subsidies

The impact of government subsidies on government, digital technology companies and farmers' cooperatives is shown in Figures 4A–C. Government subsidies have a significant effect on government, digital technology companies and farmers' cooperatives, and the level of government subsidies is negatively correlated with the willingness to intervene in government policy and positively correlated with the strategies of digital technology companies and farmers' cooperatives, and digital technology companies are more sensitive to the level of government subsidies (Martens and Zscheischler, 2022). Figure 4A shows the strategy evolution trajectory of the three participants when the government implements a weak subsidy policy ($\alpha \le 0.3$), and the willingness to cooperate between digital technology companies and farmers' cooperatives gradually decreases and eventually becomes zero, which suggests that farmers' cooperatives' motivation to digitally transform themselves is weaker under the intensity of the weak subsidy, and this leads to the unwillingness of digital technology companies to research and develop high-quality digitization equipment. Figure 4B shows that digital technology companies and farmers' cooperatives reached cooperation under medium government subsidy ($0.4 \le \alpha \le 0.6$), which suggests that government subsidy between 0.4 and 0.6 can be effective in facilitating the digital transformation of agriculture. Figure 4C shows that the implementation of strong subsidy intensity ($\alpha \ge 0.7$) by the government is not conducive to the sustainability of the subsidy policy and the stability of the strategic choices of farmers' cooperatives and digital technology companies. Therefore, keeping the level of government subsidy between 0.4 and 0.6 can effectively promote the digital transformation of agriculture.

3.3.2 Government regulation

The impact of government regulation on government, digital technology companies and farmers' cooperatives is shown in Figures 5A–C. Government regulation has no significant effect on the strategy choices of government and farmers' cooperatives, but it has a significant effect on the strategies of digital technology companies. Figures 5A,B indicate that digital technology companies choose not to cooperate under both weak ($p \le 0.3$) and moderate ($0.4 \le p \le 0.6$) levels of government regulation, but the higher the level of government regulation, the longer the hesitation of digital technology companies to choose not to cooperate. Figure 5C shows that the implementation of strong regulation by the government ($p \ge 0.7$) facilitates digital technology companies to actively provide high-quality services to agricultural operators. The main reason is that while digital technology companies save on technology R&D costs for agricultural digitization equipment by choosing a low-quality service strategy, strong government regulation has strengthened the penalties for digital technology companies and increased their costs of providing low-quality services.

3.4 Digital transformation of agricultural production side without government participation

The government can make digital technology companies and farmers' cooperatives evolve from a state of non-cooperation to a state of win-win cooperation by increasing the strength of subsidies and regulation, but the strong subsidy policy and the strong regulatory policy bring a heavy financial burden to the government and disturb the market order, and in the long run, the government intervention policy needs to be gradually withdrawn (Martens and Zscheischler, 2022). In this section, which explores under what scenarios the government withdraws from intervention policies, we simulate the scenarios of the three participants in (1,1,1) and (0,1,1) by moderating the coefficients of trust in the cooperation between the digital technology companies and the farmers' cooperatives and the amount of labor saved from the digital transformation of the agriculture, which are two non-policy factors.

3.4.1 Cooperation trust coefficient between agri-technology companies and farmers' cooperatives

The effect of the coefficient of trust in cooperation between digital technology companies and farmers' cooperatives on the three participants is shown in Figure 6. We took the values of the cooperative trust coefficient as 0.3, 0.5, and 0.7, indicating low, medium, and high trust levels, respectively. Figures 6A,B represent the evolution process under the scenarios (1,1,1) and (1,1,0), respectively. The simulation results found that the level of cooperative trust between digital technology companies and farmers' cooperatives has a significant effect on the choice of government strategies. In the (1,1,1) scenario, even with a medium or low level of trust, farmers' cooperatives and digital technology companies are able to achieve win-win cooperation, with the government, as the country's administrative body, playing a key coordinating role. However, when the level of cooperative trust between farmers' cooperatives and digital technology companies is high, the willingness of the government to intervene in policies gradually decreases, and the willingness of farmers' cooperatives to cooperate, as the less risk-resistant party, evolves in a cyclical manner. This suggests that the government tends to implement a

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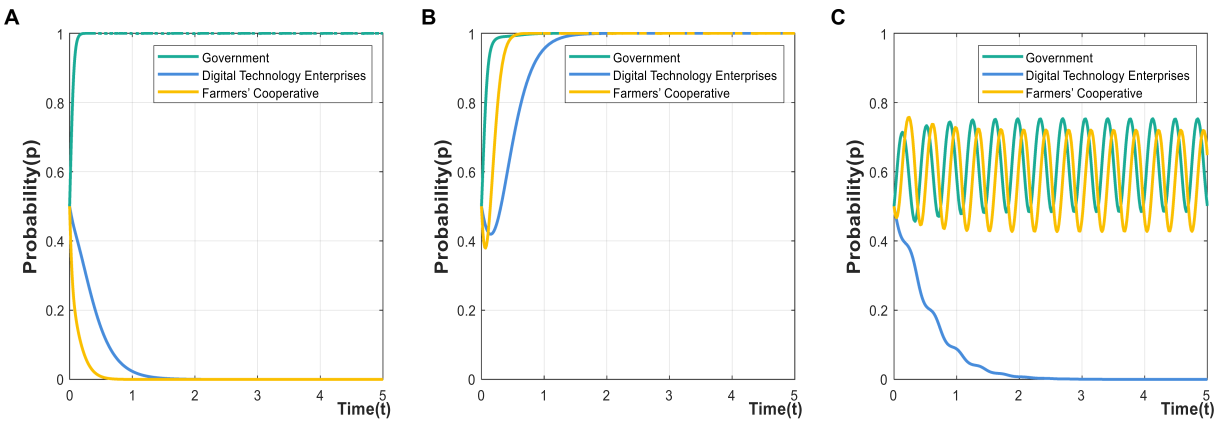

FIGURE 4
The effect of α on the evolution trajectory under government participation: **(A)** $\alpha \leq 0.3$, **(B)** $0.4 \leq \alpha \leq 0.6$, **(C)** $\alpha \geq 0.7$.

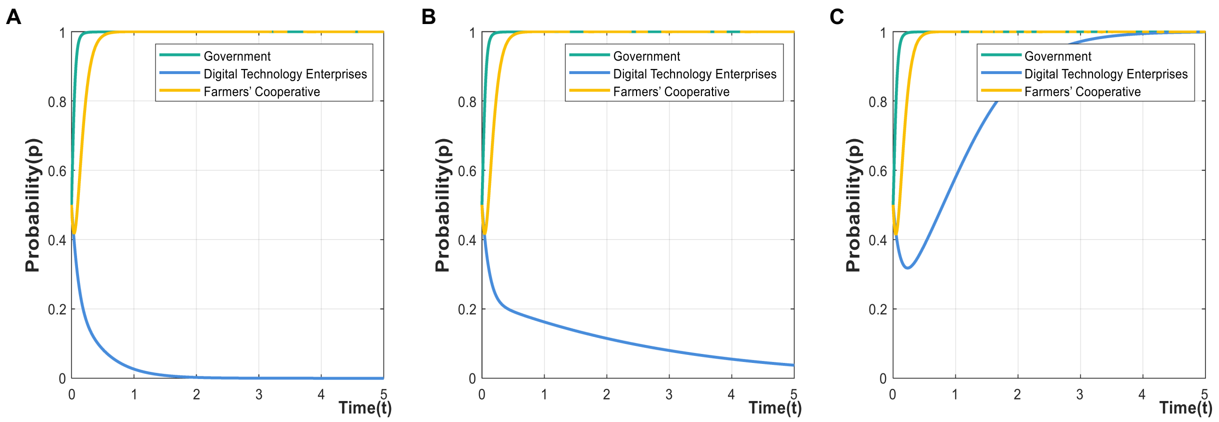

FIGURE 5
The effect of p on the evolution trajectory under government participation: **(A)** $p \leq 0.3$, **(B)** $0.4 \leq p \leq 0.6$, **(C)** $p \geq 0.7$.

non-intervention strategy at high levels of trust between digital technology companies and farmers' cooperatives, and that farmers' cooperatives are more sensitive to government policy interventions compared to digital technology companies. In the (0,1,1) scenario, the government chooses to implement policy interventions when farmers' cooperatives and digital technology companies have only low cooperative trust ($\beta = 0.3$) and withdraws from policy interventions when there is medium or high cooperative trust. In conclusion, the level of cooperative trust between digital technology companies and farmers' cooperatives can be used as a reference for the government's policy intervention. In the early stage of cooperation between digital technology companies and farmers' cooperatives, the government should give certain guidance and support policies, and the government can consider withdrawing from the intervention policy when a high degree of tacit understanding of cooperation has been formed between digital technology companies and farmers' cooperatives.

3.4.2 Quantity of labor saved by digitization

Figure 6 shows the impact of the amount of labor saved by digital transformation on the strategies of the government, digital technology companies and farmers' cooperatives under two scenarios (1,1,1) and (1,1,0). We set the number of labor saved by digital transformation to 5, 10, and 15, which represents the number of laborers that can be saved by digital transformation of farmers' cooperatives to 5, 10, and 15, respectively. The simulation results show that the amount of labor saved by digital transformation has a significant impact on government, digital technology companies, and farmers' cooperatives. In the (1,1,1) scenario, the higher the amount of labor that can be saved by digital transformation, the more the government tends to refrain from policy interventions and the more digital technology companies tend to provide low-quality services. When the number of laborers saved by digital transformation reaches 12, farmers' cooperatives maintain a strong willingness to digitally transform, even if governments and digital technology companies choose not to cooperate; When the number of laborers saved by digital transformation is between 4 and 11, the digital transformation of farmers' cooperatives needs to be achieved with the support of the government and digital technology companies; When the number of labor saved by digital transformation is less than three, farmers' cooperatives will not undergo digital transformation even if government policies intervene. In the (0,1,1) scenario, when the number of laborers saved

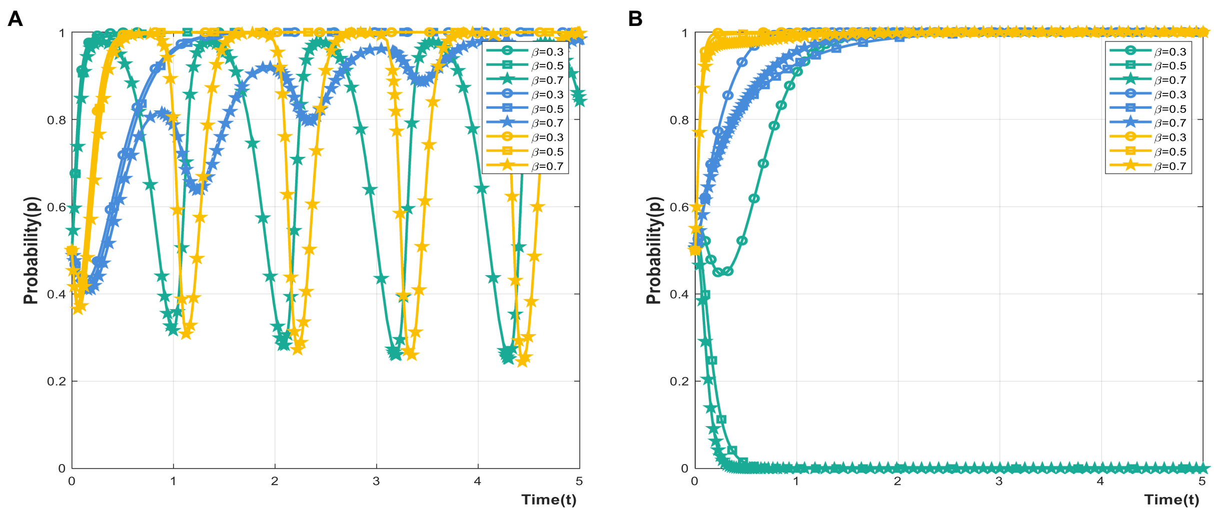

FIGURE 6
The effect of β on the evolution trajectory: **(A)** (1, 1, 1) and **(B)** (0,1,1).

by the digital transformation reaches 12, farmers' cooperatives and digital technology companies can achieve mutual benefits even without government policy intervention; When the number of laborers saved by digital transformation is between 4 and 11, the willingness of farmers' cooperatives to digitally transform decreases, and the government implements policy interventions to ensure that digital technology companies continue to provide high-quality services; When the number of laborers saved by digital transformation is less than three, the willingness of farmers' cooperatives to cooperate rapidly decreases to 0. Digital technology companies lose synergistic gains with farmers' cooperatives and have to rely on policy subsidies to sustain their continued provision of high-quality services for the digital transformation of agriculture, and at this point the willingness of the government to implement policy interventions rapidly increases to 1. In conclusion, whether farmers' cooperatives digitally transform is based on their own cost–benefit considerations, the government should increase support for digital technology companies in the early stage of the development of agricultural digital technology, so that they will continue to research and development of agricultural digital equipment, and to increase the amount of labor saved by the digital equipment; after the maturity of the agricultural digital technology, the government should withdraw from the policy intervention in a timely manner (Martens and Zscheischler, 2022) (see Figure 7).

4 Discussion

This paper examines the impact of government subsidies and government regulation on the digital transformation of farmers' cooperatives. Considering that continued government involvement in the digital transformation of agriculture may impose a heavy financial burden on the government, we further simulate the impact of two non-policy factors on government policy exit, namely, the coefficient of trust in cooperation between digital technology companies and farmers' cooperatives and the impact of the amount of labor saved by the digital transformation on government policy exit.

In recent years, the Chinese Government has attached great importance to the application of digital technology in agriculture, and has formulated subsidy policies for the research and development and acquisition of intelligent agricultural equipment. The Guidance on the Implementation of Agricultural Machinery Purchase Subsidy Policy for 2021–2023[8] issued by the Ministry of Agriculture and Rural Affairs clearly states that provinces can focus on the promotion and application of intelligent agricultural machinery products, increase the ratio of subsidy measurement for some products to 35%, and promote the establishment of research and development specialties for cutting-edge fields such as agricultural robots.

In the early stages of agricultural digital transformation, that is, when farmers' cooperatives recognize the need to change their production methods to promote agricultural production, government subsidies are key factors in encouraging and guiding farmers' cooperatives and digital technology companies to participate in the digital transformation of agriculture. For example, the manager of the ChuDaJie Melon Planting Cooperative (hereinafter referred to as CDJ Cooperative) in Jiaxing, Zhejiang, perceived a growing shortage of agricultural labor and recognized the importance of digital transformation early on. They believed that digitalization could not only address labor shortages but also improve future market returns. However, considering the significant investment required for digital equipment, they initially refused digital transformation. In 2020, the CDJ Cooperative received government subsidies, prompting them to change their decision and choose digital transformation. Due to the initially less subsidy amounts, the CDJ Cooperative initially chose to implement digitalization on only 0.27 hectares as a trial base. As the subsidy amounts increased, the CDJ Cooperative continuously expanded the scale of digitalization. Prospect theory suggests that individuals tend to be more risk-averse when faced with potential

8 *The Guidance on the Implementation of Agricultural Machinery Purchase Subsidy Policy for 2021–2023* can be found at https://www.gov.cn/zhengce/zhengceku/2021-04/07/content_5598134.htm.

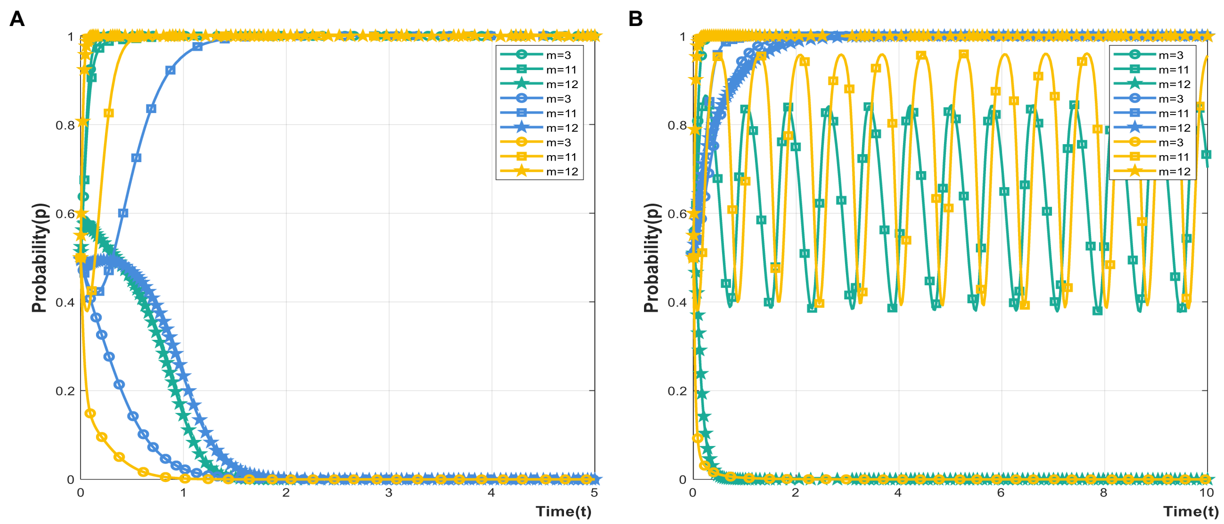

FIGURE 7
The effect of m on the evolution trajectory: **(A)** (1, 1, 1) and **(B)** (0,1,1).

losses than when presented with gains. Moreover, the extent of this aversion to risk is closely tied to decision-makers' sensitivity towards gains and losses. Farmers' cooperatives, as independent business entities, typically exhibit weaker resistance to risk and are highly attuned to potential losses. Therefore, during the initial stages of digital transformation, government subsidies targeted towards digital initiatives can serve to mitigate farmers' cooperatives' reluctance towards making initial capital investments. Consequently, such subsidies can effectively enhance their inclination to embrace digital transformation initiatives. Digital technology companies are actively involved in the research and development of agricultural digitization technologies based on political and economic logic in order to capture the digital agriculture policy dividend. As mentioned by the managers of digital technology companies during the interviews, as agricultural economic organizations, farmers' cooperatives have disadvantages in resource endowments and limited profitability. Compared to other types of companies, they are not considered high-quality customer groups. Without government guidance, it would be difficult to establish cooperative relationships with farmers' cooperatives.

However, excessive subsidies can put financial pressure on governments and hinder the digital transformation of farmers' cooperatives (Khanna et al., 2022). Some studies have found that more government subsidies aren't always better (Hong et al., 2024). The government should always set the optimal investment and usage subsidy to satisfy the binding budget constraint (Chen et al., 2023). As shown in the simulation results in this paper, the implementation of strong subsidy policy by the government ($\alpha \geq 0.7$) is not conducive to the sustainability of the policy and the stability of the cooperation between farmers' cooperatives and digital technology companies, and the digital transformation of agriculture can be effectively promoted when the government subsidy is between 0.4 and 0.6. Therefore, at the early stage of the development of agricultural digitization, the government improves the digitization capacity of farmers' cooperatives by means of publicity and training, increases the possibility of creating more synergistic benefits between farmers' cooperatives and digital technology companies, and improves the probability that digital technology companies will provide high-quality services for the digitization transformation of farmers' cooperatives. It is noteworthy that research shows government subsidies cannot avoid negative behaviors such as "fraudulent claims," which weaken the efficiency of subsidy programs (Meriggi et al., 2021). In this paper, while government subsidy policies incentivize digital technology companies to participate in the research and development of agricultural digital technologies, they may also result in the low-end aggregation of digital technology companies. The possible reason is that many digital technology companies are eager to enter the market to enjoy the policy dividend, but have no willingness to develop sustainably after entering, leading to a double mismatch and waste of policy and economic resources. Based on a study of three farmers' cooperatives in Jiaxing City, Zhejiang Province, we found that many farmers' cooperatives had a strong willingness to undergo digital transformation at the initial stage under the government's publicity and subsidy policies, but after purchasing and using the digital equipment, problems such as equipment failures and untimely repairs often arose, which thwarted the farmers' cooperatives' motivation to sustain the digital transformation. Government regulatory policies are conducive for digital technology companies to improve their agricultural digitization services while enjoying policy dividends. According to the simulation results, the implementation of a strong regulatory policy by the government ($p \geq 0.7$) facilitates digital technology companies to actively provide high-quality services to farmers' cooperatives. The provision of low-quality services by digital technology companies saves technology R&D costs, but strong government regulatory policies that reinforce penalties for digital technology companies increase the costs of providing low-quality services by digital technology companies (Gaál et al., 2021).

Excessive incentives and regulatory intensity will put pressure on government finances, and government intervention should be gradually reduced or withdrawn after playing a guiding role, so as to ultimately achieve win-win collaboration and sustainable development for digital technology companies and farmers' cooperatives. Farmers' cooperatives and digital technology companies are both market players, and agricultural digitization policies are market-driven for investment and production, but are not a single factor influencing their final decisions. As the aging problem of agriculture in China continues to intensify, the labor employment problem of new types of agricultural businesses continues to stand out, and agricultural digital technology provides a feasible path to solve this problem (Song et al., 2022). According to the simulation results, when the number of laborers saved by digital transformation reaches 12, farmers' cooperatives maintain a strong willingness to transform digitally even if the government and digital technology companies choose not to cooperate. When digital transformation can sufficiently alleviate the labor problem of farmers' cooperative production, based on risk–benefit considerations, farmers' cooperatives will actively choose digital transformation. The trust relationship between farmers' cooperatives and digital technology companies is also a key element influencing the digital transformation of farmers' cooperatives. According to the simulation results, when farmers' cooperatives and digital technology companies are in a state of medium-low cooperative trust, government intervention is needed to realize mutual cooperation, and when farmers' cooperatives and digital technology companies have a high level of cooperative trust, the government does not need to guide them to realize their mutual benefit and win-win situation. On the one hand, data elements embedded can promote agricultural operators to be more transparent in the supply and demand of resources and factors, enhance the efficiency of the flow of traditional factors of production, and bring about a greater resource aggregation effect for the development of the agricultural economy. On the other hand, in the digital transformation of agriculture, farmers' cooperatives and digital technology companies are communities of interest, and increased trust in cooperation can help increase the synergistic benefits of the digital transformation of agriculture.

5 Conclusions and policy implications

5.1 Conclusion

China is moving from traditional to modern agriculture, and needs to use digital technology to help transform and upgrade agriculture. Based on the case of digital transformation of farmers' cooperatives in Jiaxing City, Zhejiang Province, this paper classifies the cooperation modes of stakeholder governments, digital technology companies and farmers' cooperatives in the digital transformation of farmers' cooperatives into eight types, and simulates and analyzes two typical cooperation modes based on evolutionary game theory. The results of the study show that:

First, the involvement of digital technology companies in the digital transformation of agriculture mainly follows political and economic logic. When the government does not implement policy interventions and farmers' cooperatives are not willing to undergo digital transformation, digital technology companies will not provide high-quality services for digital transformation, and the (0,1,0) model will always fail to reach stability. (1,1,1) and (0,1,1) are more desirable modes of cooperation.

Second, government subsidies have a significant impact on government, digital technology companies and farmers' cooperatives. Government subsidies are negatively correlated with government policy intervention willingness and positively correlated with the strategies of digital technology companies and farmers' cooperatives, and digital technology companies are more sensitive to government subsidies. The government's strong subsidy policy will create a financial burden for the government, and the digital transformation of farmers' cooperatives can be effectively promoted when the government's subsidy is between 0.4 and 0.6.

Third, government regulation does not have a significant effect on the strategy choices of government and farmers' cooperatives, but it does have a significant effect on the strategies of digital technology companies. Strong government regulatory policies ($p \geq 0.7$) are conducive to digital technology companies actively providing high-quality services to agricultural operators. The provision of low-quality services by digital technology companies saves technology research and development costs, but strong government regulation reinforces penalties for digital technology companies' services and increases the costs of providing low-quality services by digital technology companies.

Fourth, the government implements intervention policies at low cooperative trust ($\beta = 0.3$) between farmers' cooperatives and digital technology companies, and withdraws from intervention policies at medium and high cooperative trust. At the initial stage of cooperation between digital technology companies and farmers' cooperatives, the government should give certain guidance and support policies, and when a high degree of tacit understanding of cooperation has been formed, the government may consider withdrawing from intervention policies.

Fifth, when the number of laborers saved by digital transformation reaches 12, farmers' cooperatives maintain a strong willingness to digitally transform, even if the government and digital technology companies choose not to cooperate; When the number of laborers saved by digital transformation is between 4 and 11, the digital transformation of farmers' cooperatives needs to be achieved with the support of the government and digital technology companies; When the number of laborers saved by digital transformation is less than three, farmers' cooperatives will not opt for digital transformation even if government policies intervene.

5.2 Policy implications

Based on the above research, this paper derives the following managerial insights:

First, excessive subsidies and incentives will put pressure on government finances, while smaller reductions in subsidies and incentives will not affect system stability. The Government can provide subsidies and incentives to farmers' cooperatives and digital technology companies through gradual investment and batch subsidies, and then gradually reduce the subsidies or withdraw from them after playing a guiding role. Ultimately, this will lead to a win-win collaboration between farmers' cooperatives and digital technology companies and a "blood-forming" and self-generating digital transformation of agriculture.

Second, the government's active guidance and construction of cooperation and trust mechanisms between farmers' cooperatives and digital technology companies can increase the probability of digital technology companies providing high-quality digital services to farmers' cooperatives. The government should take rural infrastructure construction as a focus point to make up for the shortcomings in the infrastructure for the digital transformation of agriculture and lay the foundation for the digital economy to drive the modernization of agriculture. The government should strengthen the publicity of agricultural digitization, set up learning examples and benchmarks for agricultural business entities, mobilize the enthusiasm of agricultural business entities to carry out agricultural digitization, and motivate them to make efforts to learn and master digital technology.

Finally, to a certain extent, the government has improved the regulation of digital technology companies, which has a facilitating role in guiding them to provide high-quality services for the digital transformation of farmers' cooperatives. Currently, the evaluation of the ranking of digital technology companies in China mainly focuses on the four levels of companies, technology, product and market, and lacks the evaluation of social responsibility. The provision of high-quality services for the digital transformation of agriculture could be added to the evaluation system of the social responsibility aspect of digital technology companies, indirectly increasing the pressure of social responsibility of digital technology companies.

5.3 Limitations

We recognize and acknowledge that there are some important limitations due to the underlying model assumptions, which may provide avenues for future research. First, this paper only considers the game relationship among the government, digital technology companies and farmers' cooperatives in the development of agricultural digital transformation, and does not consider other stakeholders such as banks and social organizations. In the future, the scope of the study can be further expanded to consider the impact of multiple stakeholders on the digital transformation of farmers' cooperatives. Second, this study only examines the impact of digital transformation of farmers' cooperatives on the revenue of the government and digital technology companies under limited rationality, and does not consider the issue of digital transformation maturity, i.e., the maturity of digital transformation of farmers' cooperatives has a difference in the impact of costs and revenues of each subject. Future research could introduce a maturity level for digital transformation of farmers' cooperatives to further refine the system's profit and loss matrix. Finally, the game model in this study only considers the simple binary relationship of "participation-non-participation" of each participant's strategy. Future research could look at the participant's strategy as a continuous variable ranging from 0 to 1, an assumption that is more in line with what happens in reality.

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

YZ: Writing – review & editing, Writing – original draft, Software, Methodology, Data curation. LM: Writing – review & editing, Writing – original draft, Supervision, Investigation, Formal analysis, Conceptualization. WC: Writing – review & editing, Visualization, Validation, Resources, Project administration, Funding acquisition, Formal analysis.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work was supported by the National Social Science Foundation of China (21CJY049).

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.

Publisher's note

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