Research on Agricultural Data-Sharing Strategies from the Perspective of Rural Revitalization

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Abstract. Rural revitalization is important for solving three rural issues, and strengthening the construction of digital informatization equipment and facilities in rural areas and promoting the integration and sharing of agricultural data are important measures and inevitable choices for promoting rural revitalization strategies, realizing agricultural modernization and comprehensively developing rural areas. This study selects rural cooperatives, agricultural product processing enterprises, and local governments as observation objects; combines the background of rural revitalization; and, through the construction of the differential game model, considers the optimal level of digital informatization platform and other facility construction and data-sharing efforts and their respective and overall optimal benefits. Four cases, such as the independent and cooperative decision-making of rural cooperatives and agricultural product processing enterprises under the mechanism of cost sharing and government rewards and penalties, are considered, as are the optimal benefits for each participant and for the whole. The study reveals that (1) the synergistic cooperation model under the government reward and punishment mechanism can increase the overall benefits of agricultural cooperatives and rural enterprises as well as the optimal level of the local government, realizing the Pareto-optimal state; (2) the level of digital infrastructure construction is well improved under government participation and can effectively promote the flow of information, improve production efficiency, and increase the benefits of rural enterprises and agricultural cooperatives, thus realizing the sustainable development of the rural economy. This study provides a theoretical basis and practical support for the construction of digital facilities and agricultural data sharing in rural areas.

Keywords: Rural Revitalization; Differential Gaming; Data Sharing; Digital Facilities.

1. Introduction

The report of the 19th National Congress put forth, for the first time, the strategy of rural revitalization, stressing that "the issue of agriculture, rural areas and farmers is a fundamental issue related to the country's economy and people's livelihood, and it is necessary to take the solution of the three rural issues as the top priority of the work of the whole party". A rural revitalization strategy is an important “magic weapon” with which to solve the "three rural issues" in China. In 2024, Central Document No. 1 "Opinions of the State Council of the Central Committee of the Communist Party of China on Learning and Applying the Experience of the ‘Thousand Villages Demonstration and Ten Thousand Villages Improvement’ Project to Powerfully and Effectively Promote the Comprehensive Revitalization of the Rural Areas" put forward a roadmap for the comprehensive revitalization of rural areas. Since then, the issue of rural revitalization has been deepening and has gradually become a hot topic in academia. Promoting the comprehensive revitalization of the countryside is the overall focus of the work of the "three rural areas" in the new era, and the implementation of a rural revitalization strategy is the most arduous task involved in building a modern socialist country in the new era. The abovementioned document emphasizes the need to promote the development of rural industries, strengthen support for employment in rural industries, promote the optimization and upgrading of the agricultural products processing industry, push forward the construction of rural infrastructure, insist on the implementation of digital rural development actions, give full play to the advantages of the digital economy, empower the development of the rural economy, narrow the "digital divide" between urban and rural areas, encourage the construction of regional big data platforms, and strengthen the interoperability of agricultural-related data. Although policy support and the digital economy have empowered rural development, which has resulted in certain developments of the rural economy, some remote areas still face many difficulties, such as unbalanced industrial development, weak digital infrastructure, untimely data sharing, and high dependence on traditional factor inputs. As a result, access to information in rural areas is limited, affecting the full release of policy dividends and leading to inefficient resource allocation, thus making it difficult to realize the synergistic development of urban and rural areas. Based on the above problems, this paper explores in depth how to effectively address the problems of asymmetric information, poor communication, and untimely data sharing in rural economic development by strengthening the construction of digital infrastructure and promoting agricultural data sharing to promote the digital development of rural industries, enhance the level of digital economic development in rural areas, and comprehensively promote the implementation of a rural revitalization strategy.

1.1 Rural Revitalization

Rural revitalization refers to the national strategy of focusing on the "three rural issues", promoting the comprehensive and coordinated development of the rural economy, culture, ecology, and society; gradually narrowing the gap between urban and rural areas; and realizing common prosperity (Han, J. 2020; Mingjiao.et al., 2020; Dongsheng Zhang,et al., 2020) In recent years, with the rapid development of the digital economy, countries worldwide have made great progress in urban and rural construction. However, the rapid development of the economy has also affected the urban–rural development divide, highlighting numerous development problems, for example, the siphoning phenomenon of cities to rural areas, with many people flowing into cities (Guo, B., 2022; Muhtar, E. A.,et al., 2023); urban expansion, such as soil erosion and the decline of biodiversity, bringing about an increase in environmental pressures in rural areas; and the agglomeration of public and basic resources in urban areas, leading to a continuous widening of the gap between urban and rural areas (Jiang, Q.et al., 2022; Abdul-Wakeel Karakara, A., & Dasmani, I. 2019). The development of the countryside has much room for improvement and has gradually been deepening, from the Urban and Rural Planning Law in 2008, to the construction of a beautiful countryside in 15 years, and finally to the rural revitalization strategy of the 19th National Congress.

Many documents have also pointed out that rural economic development should be promoted through industrial prosperity and rural revitalization through industrial revitalization and that industrial development is an important force in promoting rural revitalization in a comprehensive way (Hong Yinxing, et al., 2018). (Dai, M. L., et al.,2023) used remote sensing images, semistructured interviews, and observations to explore how to promote rural revitalization through rural tourism development and found that the development of tourism promotes the role of the rural economy. (Shen, J., & Chou, R. J., 2022) explored how to revitalize an ancient village with the help of tea culture tourism through field experiments and in-depth interviews. (Wu, K., Kong, D., & Yang, X., 2023) explored the significance of the impact of industrial development on rural revitalization and found that an increase in the degree of rural industrialization and commercialization is conducive to the accumulation of farmers' livelihood capital, improves farmers' livelihood, and thus promotes the development of the rural economy. (Wu. J et al., 2021) analyzed and discussed the impact of industrial clusters on rural poverty alleviation based on spatial econometric modeling, the results of which showed that the number of industrial clusters is negatively correlated with the level of poverty and has positive and spillover effects on the income of rural residents. Moreover, with the development of the digital economy, the widespread popularization of e-commerce has led to the growth of the rural economy and promoted the increased income of rural residents (Chao, P., & Zhang, C., 2021). Taobao village has seized the opportunity to achieve rural economic agglomeration and industrial upgrading with the help of the rapidly developing e-commerce industry and promoted the rural economy for goods (Lin, J.,et al., 2022). Moreover, (Liu, Q., Gong, D., & Gong, Y., 2022) constructed an evaluation index of rural revitalization and development potential and identified the main factors influencing rural revitalization. (Li, H., et al., 2020) dynamically assessed the sustainability of rural households' livelihoods based on the composite index method, the entropy method, and the coupled coordination model, the results of which showed that the development of rural tourism significantly contributed to the sustainability of livelihoods and that rural tourism may be an important stimulus for promoting the rural revitalization strategy. However, (Wu, W., Li, Y., & Liu, Y., 2022) found, through a case study, that a single industrial structure and backward infrastructure construction were the main constraints on the development of poor villages in the "three mountains and one beach" of Henan Province. In addition, rural areas are remote and face logistical challenges and tend to be less politically and economically integrated, and public services are often characterized by insufficient information about the needs of service providers and users (Kosec, K., & Wantchekon, L., 2020).

1.2 Data Sharing and Rural Revitalization

Data sharing refers mainly to the transfer of data between two or more organizations and individuals (Vancauwenberghe, G.,et al., 2014). In the era of the digital economy, data act as a key production factor (Li Haijian,& Zhao Li. 2021), and data sharing has become an important method of information data utilization that can realize the reuse of data resources; reduce the cost of data collection (Ghoshal, A., et al., 2020[21]; improve the efficiency of companies; and increase companies' income, consumer surplus and social welfare (Hulsen, T., 2020; Jorzik, N., et al., 2023). (Jorzik, N., et al., 2023) explored the incentives and welfare attributes of industrial data sharing and found that the positive impact of data sharing on the value and readiness of firms' data motivates them to share data. (Duan, Y.,et al.,2024) focused on the impact of multilevel knowledge sharing on the level of risk control of rural inclusive finance and argued that building diverse knowledge-sharing platforms and utilizing multilevel knowledge sharing can promote the risk control of rural inclusive finance in the post-COVID-19 era. Furthermore, (Han, J., 2020) systematically analyzed the difficulties faced in the implementation of rural revitalization strategies from the perspective of people, land, and capital and emphasized the importance of establishing a credit information-sharing platform for farmers and promoting data sharing to motivate the development of digital inclusive finance and realize rural revitalization strategies.

Digital agriculture supported by big data technology is considered a solution to the challenge of how to increase production and reduce the degree of environmental impact. The use of big data technologies, however, depends on the willingness of farmers to pool their agricultural production data. (Zhang, A., et al., 2021) studied farmers' willingness to provide agricultural data for analysis and how this willingness is affected by other factors. (Van der Burg, S., Wiseman, L., & Krkeljas, J., 2021) argued that when farmers are willing to share their data with agribusinesses that develop digital technologies, they can help farmers make scientific decisions, improve production efficiency, and reduce the impact of agricultural production on the environment. Although data sharing has many benefits, the design process of each independent subsystem fails to carry out the unification of data formats and standards, the unification of communication protocols, etc., leading to the emergence of information silos, information chimneys, subsystems, etc., making it difficult to realize data sharing and intelligent linkages between systems (Wang Guofa, et al., 2019). Serious information asymmetry still exists in the rural supply chain in many places (Bhatia, M. S.,et al., 2023), and data sharing and driving are still weak links in China's digital village construction for the purpose of the achievement of rural revitalization (Liu, Z., Gao, P., & Li, W., 2022).

1.3 Digital Facilities, Data Sharing, and Rural Revitalization

Digital facilities are not only the most important types of facilities in the digital economy (Schade, P., & Schuhmacher, M. C., 2022) but also an important strategic resource for enterprise development in the digital economy era, helping enterprises realize data generation, data sharing, and information acquisition across time and space (Rodon Modol, J., & Eaton, B., 2021). The construction of digital information facilities can realize data dissemination across spatial distances and accelerate the progress of enterprise knowledge acquisition. Digital facilities also facilitate technological exchange and learning between firms, help form knowledge alliances between firms and, to some extent, make it easier for disadvantaged firms to gain technological knowledge and application skills (Paunov, C., & Rollo, V., 2016). At the same time, digital informatization facilities directly increase the scope of enterprises' knowledge acquisition and strengthen their innovation capability. With the continuous construction of and improvement in digital informatization facilities, the level of information processing capacity of enterprises also increases, facilitating interenterprise dialog and experience sharing (Osmundsen, K., & Bygstad, B., 2022).

(Wu, W., et al., 2023) empirically showed that digital infrastructure is an external driver of digital transformation and entrepreneurial orientation. The rapid development of digital infrastructure has decreased the imitation cost of enterprises. (Yang, Y., & Gu, R., 2023) empirically investigated the impact mechanism of digital infrastructure and regional collaborative innovation on industrial eco-efficiency based on the measurement model of ultraefficient relaxation, revealing that digital infrastructure significantly improves industrial eco-efficiency. Digital facilities are important for rural economic development and revitalization, as they promote the rapid flow of information, enable rural areas to access key information such as agricultural science and technology and market information more quickly, improve productivity, and open up new economic growth and employment opportunities in rural areas. However, (Salemink, K., & Bosworth, G., 2017) found that there is still a persistent and growing disparity between rural and urban areas in terms of the quality of digital infrastructure and that technology diffusion in rural areas is constrained. (Fahmi, F. Z., & Mendrofa, M. J. S., 2023) found that digital infrastructure such as information and communications technology (ICT) plays an important role in economic development worldwide. However, the degrees of digital connectivity and usage are uneven, and poor individuals in rural areas usually do not have access to information that is critical to their livelihoods. The physical availability of services and digital amenities may contribute to rural economic growth, while with reduced access to public services, weak physical and digital amenities may lead to population and economic decline in rural areas (Castillo, C. P.,et al., 2024).

The literature has proven the important role of digital technology and data sharing in promoting economic development, and many studies have focused on the impact of data sharing and the construction of digital facilities on the supply chain (Yang, H., & Wang, Y., 2021; Baihaqi, I., & Sohal, A. S., 2013), enterprise innovation (Yu, H., Gao, Y., & Lu, Y., 2023), and digital transformation of enterprises (Wu, W.,et al.,2023) to explore the impact of digital technology and information sharing on the ability of enterprises to address asymmetric information to enhance the efficiency of business operations. Rural revitalization is an important strategic direction of national development. Few studies have focused on the digital divide brought about by weak rural digital infrastructure and differences in the level of urban development; the rapid development of digital technology; the existence of information silos, information asymmetry, and many other problems; and how to empower rural revitalization through digital technology, promote rural data integration and the sharing of information silos, and promote the development of the countryside. This situation is a real problem that urgently needs to be solved. In the process of promoting the integration and sharing of data, each participating body maximizes its interests as the starting point, and the decisions of each body affect other bodies; this situation requires the government's guidance and supervision, but how to effectively promote the integration and sharing of data among all parties remains a difficult task (Hu Chunjiao., et al., 2023; Chen Xiaolan, et al., 2023). Therefore, this paper combines differential game theory, introduces government guidance and supervision, constructs a game model between agricultural product processing enterprises and agricultural cooperatives based on digital infrastructure and data integration and sharing at two levels, and considers the game process of the participating subjects under the decentralized and cooperative decision-making of agricultural cooperatives and agricultural product processing enterprises under the government's system of acceptance of rewards and punishments. We seek the equilibrium point of the long-term interests of each participant and the influencing factors affecting data integration and sharing to explore the coordination mechanism and optimal strategy of the government, agricultural cooperatives, and agricultural product processing enterprises under a dynamic framework and to provide the basis for promoting data integration and sharing in the countryside.

The contributions of the article are reflected mainly in the following aspects: (1) considering the cooperative relationship between agricultural cooperatives and agricultural product processing enterprises, comprehensively studying the game mechanism between processing enterprises, cooperatives, and the government in the process of rural data integration and sharing; (2) comprehensively considering the impact of government subsidies, as well as rewards and punishments, on the process of rural data integration and sharing; and (3) considering the impact mechanism of digital infrastructure and data integration and sharing at dual levels on rural revitalization.

2. Model Assumptions and Construction

Hypothesis 1: This paper considers two groups—agricultural cooperatives (R) and agricultural product processing enterprises (A). Agricultural cooperatives and agricultural product processing enterprises have a greatly increased the demand for data storage and processing when they openly share data and build data ecosystems. At the same time, they also have to face the issues of data security and privacy protection, data interoperability and integration, and real-time data analysis needs when sharing data, all of which need to be supported by strong digital infrastructure (Chen Jiemei, & Lin Zeng., 2024). Therefore, agricultural cooperatives and agricultural product processing enterprises need to increase their levels of investment in digital infrastructure construction when building data-sharing platforms to strengthen their digital support capabilities. In addition, data security, reliability, and quality are also critical aspects of data sharing, and agricultural cooperatives and agroprocessing enterprises need to review data for compliance, security, and quality. Considering that the cost investment is positively related to the efforts of agricultural cooperatives and agricultural product processing enterprises and the convexity of the effort cost (Cao Bingbing, et al., 2019), the cost function of agricultural cooperatives and agricultural product processing enterprises in the construction of digital facilities and other information technology platforms and equipment and data open sharing is shown in Eq. (1):

$$\begin{cases} C_{DR} = \frac{1}{2}\mu_R D_R^2; C_{DA} = \frac{1}{2}\mu_A D_A^2 \\ C_{ER} = \frac{1}{2}\vartheta_R E_R^2; C_{EA} = \frac{1}{2}\vartheta_A E_A^2 \end{cases} \tag{1}$$

where $\mu_R > 0$ and $\mu_M > 0$ denote the effort cost coefficients of the digital infrastructure construction of agricultural cooperatives and agricultural product processing enterprises, respectively. $\vartheta_R > 0$ and $\vartheta_A > 0$ denote the effort cost coefficients of data cleansing and reviewing for the open sharing of data by agricultural cooperatives and agricultural product processing enterprises, respectively. $D_R(t)$, $D_A(t)$, $E_R(t)$, $E_A(t)$ indicate the effort level of digital infrastructure construction and open data sharing of retailers and manufacturers at moment t, respectively, and indicate the effort level of their willingness to invest in the labor force, capital, and equipment to build a data ecosystem and enhance the level of data openness. Moreover, $D_R(t) \geq 0$, $D_A(t) \geq 0$, $E_R(t) \geq 0$, and $E_R(t) \geq 0$.

Hypothesis 2: The level of data openness efforts of rural cooperatives and agroprocessing enterprises affects the level of data openness in the supply chain ecosystem, and the level of their digital infrastructure development efforts also affects changes in the level of digital infrastructure in the region. With changes in time and space, due to data obsolescence, the mobilization of technical personnel loss, digital infrastructure aging, and other factors cause the data of rural cooperatives and agricultural processing enterprises to reach the open level of storage and the level of digital infrastructure to decrease. The level of digital infrastructure storage and the level of openness of the data to changes in the differential equations are as follows (2), (3):

$$\dot{K}(t)=\gamma_R D_R(t)+\gamma_A D_A(t)-\delta K(t) \tag{2}$$

$$\dot{L}(t)=\alpha_R E_R(t)+\alpha_A E_A(t)-\varphi L(t) \tag{3}$$

where $L(t)$ denotes the data openness level of agricultural cooperatives and agroprocessing enterprises at moment t, which is jointly determined by the data open-sharing effort level of rural cooperatives and agroprocessing enterprises. The initial data open-sharing level is $L(0)=L_0\geq 0$. α_R and α_M denote the influence coefficients of the data openness activities of agricultural cooperatives and agricultural product processing enterprises on the supply chain data open-sharing level, respectively. δ *and* φ denote the natural decay levels of the digital infrastructure storage level and the data openness level, respectively.

Hypothesis 3: According to learning-by-doing theory, the accumulation of experience leads to a decrease in cost inputs (Pan, X., & Li, S., 2016), which indirectly increases cost benefits. The growth rate of knowledge accumulation in agricultural cooperatives and agroprocessing firms is ω. Therefore, the increased cost benefit is $\omega(L(t)-L_0)$.

Hypothesis 4: High-quality agricultural data sharing and the deepening of rural digital infrastructure bring about significant benefits to agricultural cooperatives and agroprocessing enterprises, including increased production efficiency, optimized supply chain management, improved product traceability, enhanced decision support, improved innovation and sustainability, and increased market opportunities (Gao, D., et al., 2020). Such data sharing and the deepening of rural digital infrastructure not only improve crop yield and quality and reduce production costs but also enhance market competitiveness and provide a solid foundation on which to achieve more efficient, transparent, and sustainable agricultural operations. It is assumed that the total supply chain benefit function resulting from the open sharing of data between agricultural cooperatives and agroprocessing enterprises is as shown in Eq. (4):

$$Q(t)=Q_0+\varepsilon K(t)+\tau L(t)+\omega(L(t)-L_0) \tag{4}$$

where $Q_0>0$ characterizes the initial state of supply chain revenue, ε denotes the influence coefficient of the level of digital infrastructure construction on the total revenue of the supply chain data ecosystem, τ denotes the influence coefficient of the degree of open sharing of data on the total revenue of the supply chain data ecosystem, and ω denotes the impact of the learning efficiency of agricultural cooperatives and agricultural product processors on the degree of reduction in costs.

Hypothesis 5: To support the promotion of rural revitalization and development to achieve common prosperity, the government provides cost sharing for the digital infrastructure inputs of agricultural cooperatives and agricultural product processing enterprises (Fan, Z., Zhou, Z., & Zhang, W., 2024). in terms of the proportion of $\theta_R(t)$ and $\theta_A(t)$ to realize high-quality economic development driven by industrial development in rural areas in China.

Hypothesis 6: The total benefits of the open-sharing data of agricultural cooperatives and agricultural product processing enterprises are distributed between the two, and the distribution ratios are β and $1-\beta$, respectively, where $(0<\beta<1)$. In the infinite time region, agricultural cooperatives and agricultural product processing enterprises have the same discount rate ρ, and both objectives are to seek the optimal data opening strategy that maximizes their returns in the infinite time region.

2.1 Independent Decision-Making Model (N)

In the noncooperative context, agricultural cooperatives and agricultural product processing enterprises independently choose the degrees of their respective efforts to open and share data to maximize their profits. In this case, the objective functions and constraints of agricultural cooperatives and agricultural product processing enterprises are as follows:

$$J_R=\int_0^{\infty}e^{-\rho}\left\{\begin{aligned}&\beta[Q_0+\varepsilon K(t)+\tau L(t)+\omega(L(t)-L_0)]\\&-\frac{1}{2}\mu_R(1-\theta_R)D_R^2-\frac{1}{2}\vartheta_R E_R^2\end{aligned}\right\}dt \tag{5}$$

$$J_A=\int_0^{\infty}e^{-\rho}\left\{\begin{matrix}(1-\beta)[Q_0+\varepsilon K(t)+\tau L(t)+\omega(L(t)\\ -L_0)]-\frac{1}{2}\mu_A(1-\theta_A)D_A^2-\frac{1}{2}\vartheta_A E_A^2\end{matrix}\right\}dt \tag{6}$$

Proposition 1: The equilibrium strategies of agricultural cooperatives and agricultural product processing firms under the independent decision-making game model are as follows:

(1) The degree of the optimal level of shared data effort of each of the two parties, the agricultural cooperative and the agricultural product processing enterprise, is given by Eqs. (7 and (8), respectively:

$$(D_R,E_R)=\left(\frac{\gamma_R\beta\varepsilon}{\mu_R(1-\theta_R)(\rho+\delta)},\frac{\alpha_R\beta(\tau+\omega)}{\vartheta_R(\rho+\varphi)}\right) \tag{7}$$

$$(D_A,E_A)=\left(\frac{\gamma_A\beta(1-\varepsilon)}{\mu_A(1-\theta_A)(\rho+\delta)},\frac{\alpha_A(1-\beta)(\tau+\omega)}{\vartheta_A(\rho+\varphi)}\right) \tag{8}$$

(2) The optimal level of digital infrastructure construction and optimal data-sharing-level trajectory dimensions are shown in Eqs. (9) and (10), respectively:

$$K^{N*}=\frac{\prod U^{N*}}{\delta}+(K_0-\frac{\prod U^{N*}}{\delta})\mathrm{e}^{-\delta t} \tag{9}$$

$$L^{N*}=\frac{\prod H^{N*}}{\varphi}+(L_0-\frac{\prod H^{N*}}{\varphi})\mathrm{e}^{-\varphi t} \tag{10}$$

where $\prod U^{N*}=\gamma_R D_R^{\ *}+\gamma_A D_A^{\ *}$ and $\prod H^{N*}=\alpha_R E_R^{\ *}+\alpha_A E_A^{\ *}$.

(3) The independent decision-making mode of agricultural cooperatives and agricultural product processing enterprises in their respective optimal revenue functions are, respectively, as follows:

$$V_R^N(K,L)=\left[\begin{matrix}\frac{\beta(Q_0-\omega L_0)}{\rho}+\frac{\beta\varepsilon K}{\delta+\rho}+\frac{\beta L(\varepsilon+\omega)}{\rho+\varphi}+\frac{[\alpha_A(\tau+\omega-\beta\tau-\beta\omega)]^2}{\vartheta_A(\rho+\varphi)^2}\\ +\frac{[\alpha_R\beta(\varepsilon+\omega)]^2}{2\vartheta_R(\rho+\varphi)^2}+\frac{[\gamma_A\varepsilon(1-\beta)]^2}{\mu_A(1-\theta_A)(\rho+\delta)^2}+\frac{(\gamma_R\varepsilon\beta)^2}{2\mu_R(1-\theta_R)(\rho+\delta)^2}\end{matrix}\right] \tag{11}$$

$$V_A^N(K,L)=\left[\begin{matrix}\frac{(1-\beta)(Q_0-\omega L_0)}{\rho}+\frac{\beta(1-\varepsilon)K}{\delta+\rho}+\frac{(\tau+\omega-\beta\tau-\beta\omega)L}{\rho+\varphi}+\frac{[\alpha_R\beta(\tau+\omega)]^2}{\vartheta_R(\rho+\varphi)^2}\\ +\frac{[\alpha_A(\tau+\omega-\beta\tau-\beta\omega)]^2}{2\vartheta_A(\rho+\varphi)^2}+\frac{[\gamma_A\varepsilon(1-\beta)]^2}{2\mu_A(1-\theta_A)(\rho+\delta)^2}+\frac{(\gamma_R\varepsilon\beta)^2}{\mu_R(1-\theta_R)(\rho+\delta)^2}\end{matrix}\right] \tag{12}$$

2.2 Synergistic Cooperative Model (C)

In a collaborative cooperation scenario, the agricultural cooperative and agroprocessing enterprise form a close partnership with the support of government subsidies. Both parties make joint decisions to determine the optimal levels of effort for building digital infrastructure and sharing data, aiming to maximize the total long-term benefits for both sides. Within this framework, the two parties jointly determine their optimal effort strategies to achieve a win–win solution:

$$J_A=\int_0^{\infty}\mathrm{e}^{-\rho}\left\{\begin{matrix}Q_0+\varepsilon K(t)+\tau L(t)+\omega(L(t)-L_0)-\frac{1}{2}\vartheta_A E_A^2\\ -\frac{1}{2}\mu_A(1-\theta_A)D_A^2-\frac{1}{2}\vartheta_R E_R^2-\frac{1}{2}\mu_R(1-\theta_R)D_R^2\end{matrix}\right\}\mathrm{dt} \tag{13}$$

Proposition 2: The equilibrium strategies of agricultural cooperatives and agricultural product processing firms under the collaborative cooperative decision-making model are as follows:

(1) The degree of the optimal level of shared data effort for each agricultural cooperative and agricultural product processing enterprise is calculated via Eqs. (14) and (15), respectively:

$$(D_R,E_R)=\left(\frac{\gamma_R\varepsilon}{\mu_R(1-\theta_R)(\rho+\delta)},\frac{\alpha_R(\tau+\omega)}{\vartheta_R(\rho+\varphi)}\right) \tag{14}$$

$$(D_A, E_A) = \left(\frac{\gamma_A(1-\varepsilon)}{\mu_A(1-\theta_A)(\rho+\delta)}, \frac{\alpha_A(\tau+\omega)}{\vartheta_A(\rho+\varphi)} \right) \tag{15}$$

(2) The optimal levels of digital infrastructure construction and the optimal data-sharing trajectory dimensions are shown in Eqs. (16) and (17), respectively:

$$K^{C*} = \frac{\prod U^{C*}}{\delta} + (K_0 - \frac{\prod U^{C*}}{\delta})\mathrm{e}^{-\delta t} \tag{16}$$

$$L^{C*} = \frac{\prod H^{C*}}{\varphi} + (L_0 - \frac{\prod H^{C*}}{\varphi})\mathrm{e}^{-\varphi t} \tag{17}$$

where $\prod U^{C*} = \gamma_R D_R^* + \gamma_A D_A^*$ and $\prod H^{C*} = \alpha_R E_R^* + \alpha_A E_A^*$.

(3) The overall optimal benefit function of agricultural cooperatives and agricultural product processing enterprises under the collaborative cooperative decision-making model is shown in Eq. (18):

$$V^C(K,L) = \begin{bmatrix} \frac{Q_0 - \omega L_0}{\rho} + \frac{\varepsilon K}{\delta+\rho} + \frac{(\varepsilon+\omega)L}{\rho+\varphi} + \frac{(\gamma_A \varepsilon)^2}{2\mu_A(1-\theta_A)(\rho+\delta)^2} \\ + \frac{[\alpha_A(\tau+\omega)]^2}{2\vartheta_A(\rho+\varphi)^2} + \frac{[\alpha_R \beta(\tau+\omega)]^2}{2\vartheta_R(\rho+\varphi)^2} + \frac{(\gamma_R \varepsilon)^2}{2\mu_R(1-\theta_R)(\rho+\delta)^2} \end{bmatrix} \tag{18}$$

2.3 Independent Decision-making Model under the Government Reward and Punishment Mechanism (GN)

The government accepts the digital infrastructure construction level $\mathrm{T}(\mathrm{K}-\mathrm{K}_0)$ of agricultural cooperatives and agricultural product processing enterprises to ensure the realization of the government's supervision of the use of infrastructure construction subsidy funds, to avoid fraudulent subsidies for agricultural cooperatives and agricultural product processing enterprises, to prevent adverse impacts and, at the same time, to subsidize and reward the enterprises that meet the standards for the purpose of encouraging the active cooperation of cooperatives and agricultural product processing enterprises in rural areas and of opening up and sharing data. The phenomenon of information asymmetry in rural areas should be improved, the development of the rural digital economy should be enhanced, and rural revitalization should be promoted.

Cooperatives and agricultural product processing enterprises in the supply chain jointly build digital infrastructure, promote data interoperability, build a good and complete rural digital supply chain system, and promote the development of a rural digital economy, assuming that the rural cooperatives bear governmental rewards and penalties at the acceptance stage $\mathrm{wT}(\mathrm{K}-\mathrm{K}_\mathrm{g})$ and that the manufacturer bears the rewards and penalties $(1-\mathrm{w})\mathrm{T}(\mathrm{K}-\mathrm{K}_\mathrm{g})$, and (0<W<1). The objective benefit functions of cooperatives and agricultural product processing enterprises are as follows:

$$J_R = \int_0^{\infty} \mathrm{e}^{-\rho} \left\{ \begin{matrix} \beta[Q_0 + \varepsilon K(t) + \tau L(t) + \omega(L(t) - L_0)] \\ -\frac{1}{2}\mu_R(1-\theta_R)D_R^2 - \frac{1}{2}\vartheta_R E_R^2 + \mathrm{w}T(K-K_g) \end{matrix} \right\} \mathrm{dt} \tag{19}$$

$$J_A = \int_0^{\infty} \mathrm{e}^{-\rho} \left\{ \begin{matrix} (1-\beta)[Q_0 + \varepsilon K(t) + \tau L(t) + \omega(L(t) - L_0)] \\ -\frac{1}{2}\mu_A(1-\theta_A)D_A^2 - \frac{1}{2}\vartheta_A E_A^2 + \mathrm{w}T(K-K_g) \end{matrix} \right\} \mathrm{dt} \tag{20}$$

Proposition 3: In the independent decision-making game model of agricultural cooperatives and agricultural product processing enterprises under the introduction of the governmental reward and punishment mechanism, the respective equilibrium strategies are as follows:

(1) Agricultural cooperatives and agricultural product processing enterprises have their optimal levels of shared data effort according to Eqs. (21) and (22), respectively:

$$(D_R, E_R) = \left(\frac{\gamma_R(\beta\varepsilon + \mathrm{w}T)}{\mu_R(1-\theta_R)(\rho+\delta)}, \frac{\alpha_R \beta(\tau+\omega)}{\vartheta_R(\rho+\varphi)} \right) \tag{21}$$

$$(D_A, E_A) = \left(\frac{\gamma_A[\beta(1-\varepsilon)+T-wT)]}{\mu_A(1-\theta_A)(\rho+\delta)}, \frac{\alpha_A(1-\beta)(\tau+\omega)}{\vartheta_A(\rho+\varphi)} \right) \tag{22}$$

(2) The optimal level of digital infrastructure construction and optimal data-sharing-level trajectory dimensions are shown in Eqs. (23) and (24), respectively:

$$K^{GN*} = \frac{\prod U^{GN*}}{\delta} + (K_0 - \frac{\prod U^{GN*}}{\delta})\mathrm{e}^{-\delta t} \tag{23}$$

$$L^{GN*} = \frac{\prod H^{GN*}}{\varphi} + (L_0 - \frac{\prod H^{GN*}}{\varphi})\mathrm{e}^{-\varphi t} \tag{24}$$

where $\prod U^{GN*} = \gamma_R D_R^* + \gamma_A D_A^*$ and $\prod H^{GN*} = \alpha_R E_R^* + \alpha_A E_A^*$.

(3) The independent decision-making game model of agricultural cooperatives and agricultural product processing enterprises under the government reward and punishment mechanism and their respective optimal benefit functions are as follows:

$$V_R^{GN}(K,L) = \begin{bmatrix} \frac{\beta(Q_0 - \omega L_0) + wTK_g}{\rho} + \frac{(\beta\varepsilon + \mathrm{w}T)K}{\delta+\rho} + \frac{(\tau+\omega)\beta L}{\rho+\varphi} + \frac{[\alpha_R\beta(\varepsilon+\omega)]^2}{2\vartheta_R(\rho+\varphi)^2} \\ + \frac{[\alpha_A(\tau+\omega-\beta\tau-\beta\omega)]^2}{\vartheta_A(\rho+\varphi)^2} + \frac{[\gamma_A\varepsilon(1-\beta)]^2}{\mu_A(1-\theta_A)(\rho+\delta)^2} + \frac{(\gamma_R\varepsilon\beta)^2}{2\mu_R(1-\theta_R)(\rho+\delta)^2} \end{bmatrix} \tag{25}$$

$$V_A^{GN}(K,L) = \begin{bmatrix} \frac{(1-\beta)(Q_0 - \omega L_0) + (1-w)TK_g}{\rho} + \frac{(\varepsilon + T - \beta\varepsilon - w\mathrm{T})K}{\delta+\rho} \\ + \frac{(\tau+\omega-\beta\tau-\beta\omega)L}{\rho+\varphi} + \frac{[\alpha_R\beta(\tau+\omega)]^2}{\vartheta_R(\rho+\varphi)^2} + \frac{[\gamma_A\varepsilon(1-\beta)]^2}{2\mu_A(1-\theta_A)(\rho+\delta)^2} \\ + \frac{[\alpha_A(\tau+\omega-\beta\tau-\beta\omega)]^2}{2\vartheta_A(\rho+\varphi)^2} + \frac{(\gamma_R\varepsilon\beta)^2}{\mu_R(1-\theta_R)(\rho+\delta)^2} \end{bmatrix} \tag{26}$$

2.4 Synergistic Cooperation Model under the Government Reward and Punishment Mechanism (GC)_

The government subsidizes the costs of agricultural cooperatives and agroprocessing enterprises to support their digital facility construction. To avoid subsidy-seeking behavior, strategic transformation, and other problems in processing enterprises and cooperatives, this study establishes a reward and punishment mechanism for government acceptance results. The government accepts the level of digital infrastructure construction of agricultural cooperatives and agricultural product processing enterprises. At this time, agricultural cooperatives and agroprocessing enterprises, as a whole, in the case of government acceptance, work closely with one another to determine the level of digital infrastructure construction and data-sharing efforts needed to achieve a specific target. The decision-making goal is to maximize the sum of the long-term interests of both parties and jointly determine their optimal effort strategies. At this point, the objective function of the collaborative cooperation situation under the government reward and punishment mechanism is as follows:

$$J_A = \int_0^\infty \mathrm{e}^{-\rho} \begin{Bmatrix} Q_0 + \varepsilon K(t) + \tau L(t) + \omega(L(t) - L_0) - \frac{1}{2}\vartheta_A E_A^2 - \frac{1}{2}\vartheta_R E_R^2 \\ -\frac{1}{2}\mu_A(1-\theta_A)D_A^2 - \frac{1}{2}\mu_R(1-\theta_R)D_R^2 + wT(K - K_g) \end{Bmatrix} \mathrm{d}t \tag{27}$$

Proposition 4: In the introduction of the government reward and punishment mechanism under the collaborative decision-making model of agricultural cooperatives and agricultural product processing enterprises, the respective equilibrium strategies are as follows:

(1) Agricultural cooperatives and agricultural product processing enterprises' optimal levels of shared data effort are given by Eqs. (28) and (29), respectively:

$$(D_R, E_R) = \left(\frac{\gamma_R(\varepsilon+T)}{\mu_R(1-\theta_R)(\rho+\delta)}, \frac{\alpha_R(\tau+\omega)}{\vartheta_R(\rho+\varphi)} \right) \tag{28}$$

$$(D_A, E_A) = \left(\frac{\gamma_A(T+\varepsilon)}{\mu_A(1-\theta_A)(\rho+\delta)}, \frac{\alpha_A(\tau+\omega)}{\vartheta_A(\rho+\varphi)} \right) \tag{29}$$

(2) The optimal level of digital infrastructure construction and optimal data-sharing-level trajectory dimensions are shown in Eq. (30) and Eq. (31), respectively:

$$K^{GC*} = \frac{\prod U^{GC*}}{\delta} + (K_0 - \frac{\prod U^{GC*}}{\delta})e^{-\delta t} \tag{30}$$

$$L^{GC*} = \frac{\prod H^{GC*}}{\varphi} + (L_0 - \frac{\prod H^{GC*}}{\varphi})e^{-\varphi t} \tag{31}$$

Among them, $\prod U^{GC*} = \gamma_R D_R^* + \gamma_A D_A^*$ and $\prod H^{GC*} = \alpha_R E_R^* + \alpha_A E_A^*$.

(3) For the government reward and punishment mechanism under the collaborative decision-making game model of agricultural cooperatives and agricultural product processing enterprises, the overall optimal benefit function is as follows:

$$V^C(K,L) = \begin{bmatrix} \frac{Q_0 - \omega L_0 - TK_g}{\rho} + \frac{(\varepsilon + T)K}{\delta + \rho} + \frac{(\tau + \omega)L}{\rho + \varphi} + \frac{[\alpha_A(\tau + \omega)]^2}{2\vartheta_A(\rho + \varphi)^2} \\ + \frac{[\alpha_R(\tau + \omega)]^2}{2\vartheta_R(\rho + \varphi)^2} + \frac{(\gamma_R \varepsilon)^2}{2\mu_R(1-\theta_R)(\rho + \delta)^2} + \frac{(\gamma_A \varepsilon)^2}{2\mu_A(1-\theta_A)(\rho + \delta)^2} \end{bmatrix} \tag{32}$$

3. Model Comparative Analysis

3.1 Comparative Analysis

The optimal level of effort for each of the cooperatives and processing companies in the four scenarios, as well as the optimal returns for both parties under the four strategies, and the optimal returns for the supply chain as a whole are presented below.

Corollary 1: A comparison and analysis of the optimal level of effort of agricultural cooperatives and agricultural product processing enterprises in the four cases can be obtained as follows: $E_{R4} = E_{R2} > E_{R1} = E_{R3}$ and $E_{A4} = E_{A2} > E_{A1} = E_{A3}$. When $\varepsilon > \frac{wT}{1-\beta}$, $D_R^{GC} > D_R^C > D_R^{GN} > D_R^N$; when $\frac{wT}{1-\beta} > \varepsilon > 0$, $D_R^{GC} > D_R^C > D_R^{GN} > D_R^N$.

processing enterprises, respectively. $D_R(t)$, $D_A(t)$, $E_R(t)$, $E_A(t) \frac{wT}{1-\beta} > \varepsilon > 0$ indicate the effort level of

From Corollary 1, it can be seen that the levels of effort taken by agricultural cooperatives and agricultural product processing enterprises in data sharing are the same in the Model N and GN scenarios, while the levels of effort made by both parties in data sharing are the same in the Model C and GC scenarios; however, the levels of effort of the latter are significantly greater than those of the former. When $\frac{wT}{1-\beta} > \varepsilon > 0$, the level of effort of digital infrastructure construction of agricultural cooperatives and agricultural product processing enterprises in Model GN is greater than that in Models N and C. When $\varepsilon > \frac{wT}{1-\beta}$, the level of effort of digital infrastructure construction under Model C is greater than that under Models N and GN; however, the level of effort of both parties' digital infrastructure construction in Model GC is greater than that in the other three models in both scenarios.

Corollary 2: Comparative analysis of the three game situations reveals that the level of data openness and sharing is $L^{GC*} = L^{C*}(K,L) > L^{N*} = L^{GN*}$. When $\frac{wT}{1-\beta} > \varepsilon > 0$, $K^{GC*} > K^{GN*} > K^{C*} > K^{N*}$; when $\varepsilon > \frac{wT}{1-\beta}$, $K^{GC*} > K^{C*} > K^{GN*} > K^{N*}$.

Proof:

$$L^{C*} - L^{N*} = \frac{\prod H^{C*} - \prod H^{N*}}{\varphi}(1 - e^{-\varphi t}) > 0 \tag{33}$$

$$K^{GC*} - K^{C*} = \frac{\prod U^{GC*} - \prod U^{C*}}{\delta}(1 - e^{-\delta t}) > 0 \tag{34}$$

Corollary 2 shows that the data-sharing levels of both Models C and GC are better than those of Models N and GN, the level of digital infrastructure construction in Model GN is significantly higher than that of Model N, and the optimal level of digital infrastructure construction by agricultural product processing enterprises and agricultural cooperatives is realized in Model GC and is strictly better than that in the other three scenarios.

Corollary 3: The overall optimal returns of agricultural cooperatives and agroprocessing enterprises in the four scenarios after the introduction of government incentives and penalties are compared.

When $\frac{K\rho}{\rho+\delta} < K_g$, $\varepsilon > \frac{wT}{1-\beta}$; $V^{GC}(K,L) > V^{C}(K,L) > V^{N}(K,L) > V^{GN}(K,L)$;

when $\frac{K\rho}{\rho+\delta} > K_g > 0$, $\frac{wT}{1-\beta} > \varepsilon > 0$ $V^{GC}(K,L) > V^{C}(K,L) > V^{GN}(K,L) > V^{N}(K,L)$.

Corollary 3 shows that when $\frac{K\rho}{\rho+\delta} < K_g, \varepsilon > \frac{wT}{1-\beta}$, and therefore, $0 < K^{GC*} < K_g < K^{C*}$; at this point, the actual digital infrastructure construction level under Model GC is smaller than the target construction level, agricultural processing enterprises and agricultural cooperatives are penalized, and the overall revenue is reduced compared to that under Model C. The degree of loss is determined by the gap between the digital infrastructure construction level and the strength of the government's penalty. When $\frac{K\rho}{\rho+\delta} > K_g > 0, 0 < K^{GC*} < K_g < K^{C*}$; at this time, the government's established digital infrastructure construction level goal is reached in Model GC, and the overall benefits of both parties are maximized, and thus, the results under this scenario are strictly better than those of the other three scenarios.

3.2 Example Analysis

Based on Corollaries 1-3 and the proof, the optimal level of data sharing, the optimal level of digital infrastructure, the optimal level of effort to realize data sharing, the optimal benefit of each side, and the optimal level of the system as a whole for each of the four different decision-making contexts of agroprocessing enterprises and agricultural cooperatives are identified. Moreover, according to the literature, the benchmark parameters of the model are: $\mu_R = \mu_R = 1, \vartheta_R = \vartheta_A = 1, Q_0 = 5, \varepsilon = 2, \tau = 3, \alpha_A = \alpha_R = 0.6, \gamma_R = \gamma_A = 0.6, \delta = \varphi = 0.1$, $L_0 = 5$, $K_0 = 5$, $\omega = \beta = 0.4$, $\rho = 0.9$, $w = 0.6$, $T = 0.6$, $K_g = 10$, and $\theta_A = \theta_R = 0.4$. MATLAB2023 is used for the numerical simulation.

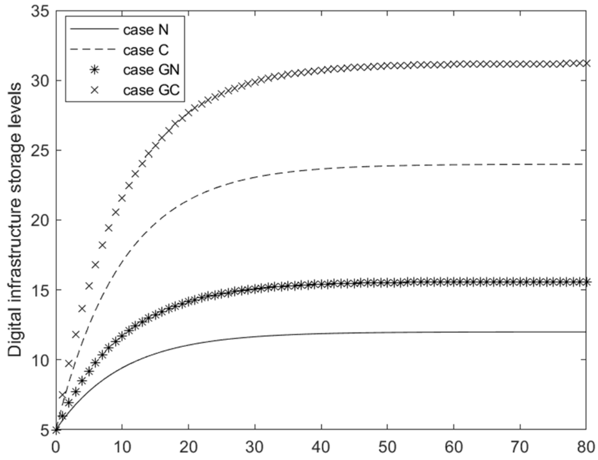


Fig 1. Trends in digital infrastructure storage level changes under the four modes

The trend of changes in the level of digital infrastructure construction of agricultural cooperatives and enterprises is shown in Figure 1. Under the four-game decision-making models, the level of data sharing increases over time, and the level of digital infrastructure of both parties is the lowest under Model C. The level of digital infrastructure of agricultural cooperatives and enterprises is the lowest under Model GN. After the introduction of the government reward and punishment mechanism, the level of digital infrastructure under Model GN is significantly improved. In Model GC, the government assesses the level of digital infrastructure construction of enterprises and cooperatives, and the government's assessment motivates enterprises and cooperatives to increase their level of investment in the construction of digital infrastructure. At the same time, enterprises and cooperatives are incentivized by the government to achieve a win–win situation, and thus, the level of digital infrastructure in the Model GC scenario is higher than that in the other three model scenarios. Therefore, the digital infrastructure level in the Model GC scenario realizes Pareto improvement and achieves the optimal digital infrastructure level compared with the other three model scenarios.

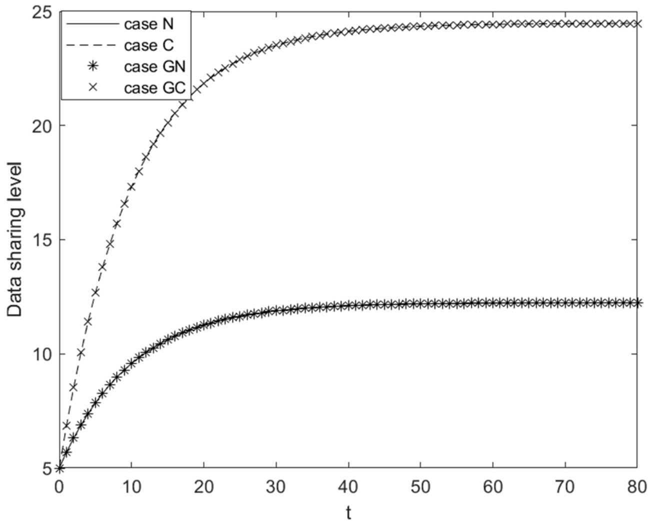
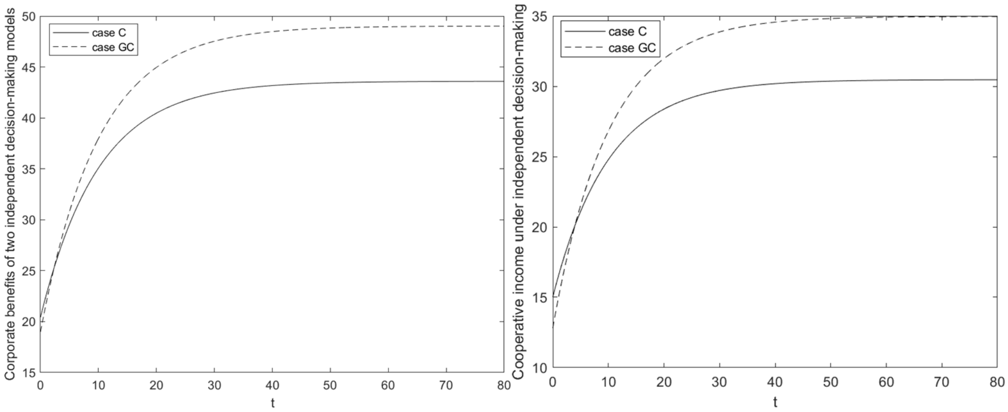


Fig 2. Trends in data-sharing levels under the four modes

Figure 2 shows the trend change in the level of data sharing between cooperatives and enterprises. The level of data sharing in Model C is better than that in Model N. However, there is no change in the government participation model, the level of data sharing remains unchanged, the government's main assessment of the construction of digital infrastructure for enterprises and cooperatives and the level of data sharing are not easy to quantitatively assess, and the advancement of digital infrastructure can be used to enhance the operation of digital technology and to improve operational efficiency for the purpose of strengthening arithmetic support. In scenarios where manufacturing enterprises make cost-sharing decisions with retail enterprises, there is a noticeable improvement in the level of data sharing, achieving Pareto improvement. Under the game decision model of collaborative cooperation, the level of data sharing reaches an optimal state, thus validating Proposition 1.

From Figures 3(a) and (b), it can be observed that in Model N, without government participation in the early stage, the respective gains of cooperatives and enterprises are better than those in the scenario where the government participates in the game because in the early stage, enterprises and cooperatives do not reach the level of digital infrastructure construction set by the government and are therefore penalized by the government. At the later stage, when the agricultural processing enterprises and agricultural cooperatives strive to improve the level of digital infrastructure construction to achieve the target set by the government, both parties are rewarded by the government for overbuilding their digital infrastructure, and the total benefit increases compared to that under the scenario without government participation.



(a) (b)

Fig 3. Trend chart of the incomes of enterprises and cooperatives under independent decision-making

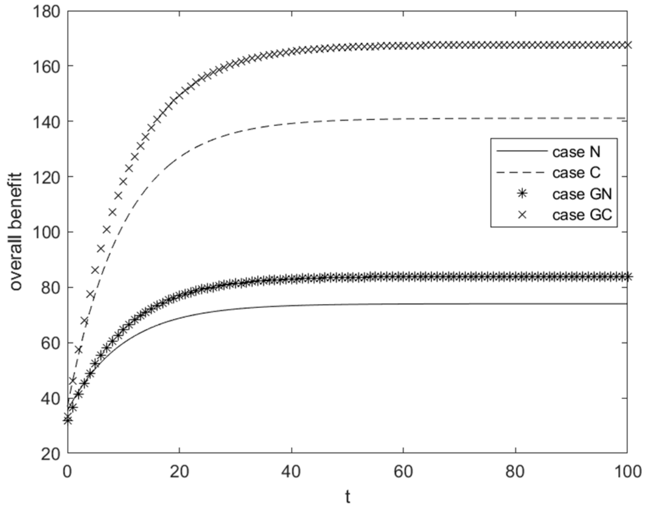


Fig 4. Overall income of the system in the four modes

Fig 4 clearly demonstrates that the overall profits of cooperatives and enterprises are optimized under the collaborative cooperation model with government participation. In the independent decision-making model with government participation, the overall profit for both enterprises and cooperatives is improved compared to that of the independent decision model without government participation. This improvement is determined by the intensity of government incentives and the level of digital infrastructure.

4. Conclusion

This work studies the dynamic coordination problem of agricultural data sharing with the help of differential games, taking into account the efforts taken by agricultural cooperatives and rural enterprises toward digital infrastructure construction and data sharing, as well as the introduction of the government participation game and the time factor. A differential game model is constructed and solved jointly under four different situations, and the impacts of government subsidies, rewards and punishments in the process of agricultural data sharing are analyzed through the use of examples. The below conclusions are obtained.

(1) The data-sharing level, digital infrastructure construction level, and total profit of agricultural cooperatives and rural enterprises in the centralized decision-making state under the government reward and punishment mechanism are greater than those in the independent decision-making game model, which indicates that the collaborative cooperation model under the government reward and

punishment mechanism can help the overall profit system composed of agricultural cooperatives, rural enterprises, and the local government reach the optimal level and realize the Pareto-optimal state.

(2) With government subsidies and the introduction of government rewards and penalties, when a certain state is reached, the two models under the government reward and penalty mechanism significantly improve the level of digital infrastructure construction, the respective returns of agricultural cooperatives and rural enterprises, and the overall returns of both parties compared with the two models without government rewards and penalties. Moreover, the Pareto improvement in the profits of all the participating members is realized. Thus, the introduction of the government reward and penalty mechanism is also considered a more practical and managerial value, and the government guides the two sides in building digital infrastructure, sharing data, and promoting the stable and good development of the rural economy.

(3) The degree of investment in digital infrastructure construction, the level of data-sharing efforts, and the coefficient of government subsidies are time independent for rural enterprises and cooperatives under the four decisions. This finding exhibits the stability of the respective strategies.

(4) The level of digital infrastructure construction is improved under government participation, which can effectively promote the flow of information, make it easier for rural enterprises to access market demand and industry dynamics, improve their competitiveness, reduce transaction costs, improve productivity, and increase the respective benefits of rural enterprises and agricultural cooperatives, thus leading to the realization of the sustainable development of the rural economy.

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