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RESEARCH ON INFORMATION COLLABORATION STRATEGY OF FRESH AGRICULTURAL PRODUCTS SUPPLY CHAIN UNDER CARBON CAP-AND-TRADE

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Abstract. The information coordination of fresh agricultural products supply chain is conducive to improving the overall efficiency and competitiveness of the supply chain, and reducing carbon emissions. Under the carbon cap-and-trade policy, this paper constructed an evolutionary game model of supply chain information collaboration involving a fresh agricultural products supplier, a cold chain logistics service provider and a fresh agricultural products retailer, explored the selection of information collaboration strategies of each subject, and simulated it with system dynamics. The results show that: The stability strategy of the game system is related to the initial willingness of each subject. When any two parties participate in information collaboration, the other party will also choose to participate in collaboration. In addition, the choice of information collaboration strategy of the subject is also related to the collaborative planning ability, collaborative strategy formulation ability, consumers' preference, the initial cost of each subject, revenue sharing and cost sharing mechanism, government subsidies, government regulation and carbon cap-and-trade policy. It is worth noting that the collaborative planning capability is more conducive to promoting the subject to choose information collaborative strategy than the collaborative strategy formulation capability; the carbon trading price has a greater impact on the subject's participation in collaboration, while the total amount of carbon quota has no impact on the choice of the subject's information collaboration strategy. Furthermore, based on the research results, the corresponding management suggestions are put forward from the two aspects of the government and the participants.

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1. Introduction

A study by the University of Michigan shows that the two industries with the largest greenhouse gas (GHG) emissions are electricity and transportation, and in terms of electricity, refrigeration technology ranks second in carbon emissions [4]. In the process of production and sales of fresh agricultural products, on the one hand, energy is required for logistics transportation, and on the other hand, electricity and refrigerant are consumed

Keywords. Carbon cap-and-trade policy, fresh agricultural products supply chain, information collaboration, tripartite evolutionary game, system dynamics.

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in the process of processing, storage and transportation to maintain the freshness of products. Therefore, the carbon emissions generated by the operation of fresh agricultural products supply chain are much higher than those of ordinary agricultural products supply chain. In recent years, consumers pay more attention to the freshness and quality of fresh agricultural products [14,26,27], and enterprises use refrigeration technology more frequently in the circulation process to maintain the freshness of fresh agricultural products, which brings more carbon emissions. At the same time, the implementation and promotion of carbon cap-and-trade policy has brought more challenges to the supply chain operation of fresh agricultural products. How to reduce energy consumption and carbon emissions while ensuring the freshness and quality of products has become a major problem in the supply chain operation of fresh agricultural products.

Supply chain information collaboration refers to the deep processing of information by supply chain members using collaborative thinking, which emphasizes that members build and share all kinds of information resources, and form synergy through interaction and coordination [21]. The members of the fresh agricultural product supply chain can make close connections between production, inventory, logistics, sales and other supply chain links through collaborative utilization of information such as production, logistics, market demand and other information, avoiding unnecessary production waste, chain breakage, inventory backlog, and ineffective transportation [5,7,13], ensuring the whole cold chain of products and reducing energy consumption and carbon emissions [25]. For example, the "Fresh Day by Day" program of "Hema" is well received by the market. "Hema" sends the next day's sales plan to Chongming Cooperative Farm Base, and the farmers pick and package the products according to the plan, and then send them to stores by cold chain for unified packaging and pricing. This operation mode not only improves product quality but also avoids the transportation cost of 30 yuan per order for other fresh food stores, and reduces losses by 20%–30% compared to traditional modes. It can improve supply chain operation efficiency while reducing energy consumption and carbon emissions brought by ineffective transportation. For another example, the intelligent warehousing and transportation system jointly built by "Yili" Group and JingDong (JD) Cold Chain. Based on information collaboration, it can smoothly connect all links from Jindian ecological circulation farm, to JD's unmanned warehouse and alternative fuel vehicle transportation, to the intelligent distribution of unmanned vehicles, and create an integrated low-carbon milk supply chain.

It can be seen that through information collaboration, the integration degree of fresh agricultural products supply chain can be effectively improved, the chain break can be reduced, the efficiency can be improved, and the carbon emissions can be reduced, which is an effective way to deal with the upgrading of market consumption and the development of low-carbon economy.

So, what is the operational mode of information collaboration in the fresh agricultural product supply chain, and how does information collaboration affect the carbon emissions of the fresh agricultural product supply chain? Under the carbon cap-and-trade policy, what are the influencing factors of the main body's choice of information collaboration strategy in the supply chain of fresh agricultural products, and how do these factors affect the main body's decision-making of information collaboration behavior? These are the main research questions of this article.

The remainder of this paper is organized as follows. Section 2 reviews the related literature. Section 3 constructs an information collaboration operation mode for the fresh agricultural product supply chain. Section 4 constructs an evolutionary game model with the participation of three parties. Section 5 conducts numerical simulation experiments using system dynamics and analyzes the experimental results. Section 6 summarizes the research conclusions, and presents main management insights, as well as research prospects.

2. Literature review

Literature review focuses on three parts: fresh agricultural products supply chain information sharing, supply chain information collaboration and fresh agricultural products supply chain operation under carbon cap-and-trade policy.

Information sharing is the foundation of information collaboration, and many scholars have conducted in-depth research on the information sharing of fresh agricultural products supply chain. In fresh product supply chain, Shukla and Jharkharia [24] suggested that insufficient information shared could lead to mismatch between demand and supply, contributing to unfulfilled demand and wastes. Extant literature in the context of perishable product supply chain suggests that under certain conditions, information sharing could positively affect supply chain performance [20, 40]. Afterwards, scholars studied the information sharing decision-making behavior of members in the fresh agricultural product supply chain. Yang *et al.* [33] believed that the asymmetry of freshness information in fresh agricultural product supply chain would exacerbate losses, and thus designed a repurchase contract to ensure the sharing of freshness information in the supply chain. Li *et al.* [15] constructed an evolutionary game model for information sharing in the fresh agricultural product supply chain, and found that the greater the difference between the income obtained from information sharing and the cost of information system construction, the greater the likelihood of enterprises participating in information sharing. Dan *et al.* [6] showed that it is best for sellers to share information only with 3PL, but because of the information transmission between 3PL and suppliers, when the freshness elasticity is high, the equilibrium strategy of information sharing is complete information sharing. Wang *et al.* [28] found that companies sharing information with farmers can always improve farmers' profits. Liu *et al.* [17] found that information sharing is always profitable for manufacturers.

In terms of supply chain information collaboration, Ma *et al.* [21] proposed that unlike information sharing, in addition to sharing information, information collaboration also requires supply chain members to make collaborative decisions. Panahifar *et al.* [23] found that information sharing centered collaboration has a positive and significant impact on supply chain performance. Kyongjun and Jongho [12] proposed a method of using open source as a collaborative support tool, which can maintain the continuity of information transmission during collaborative decision-making processes. Xu *et al.* [30] believed that manufacturers must provide appropriate incentives to ensure that retailers share real demand information in information collaboration. Zhang *et al.* [39] constructed a high-end equipment supply chain collaboration model based on information sharing. In terms of information collaboration decision-making, Du and Qu [8] constructed a tripartite evolutionary game model for information collaboration between cross-border e-commerce platforms, domestic logistics enterprises, and foreign logistics enterprises, and conducted dynamic simulation analysis on the tripartite information collaboration strategy. It was found that the willingness to collaborate information is influenced by the degree of information standardization, information collaboration risks, and allocation mechanisms. Focusing on the fresh agricultural product supply chain, Li *et al.* [16] proposed the mechanism and path for achieving cross functional collaborative innovation in the fresh supply chain based on information sharing.

Carbon cap-and-trade means that the government decomposes the total amount of carbon emission rights into a certain unit of carbon emission rights, and then allocates the emission rights to carbon dioxide emission source enterprises in a specific way and allows them to buy and sell carbon emission rights in the market. With the implementation of carbon limit trading policies, scholars have begun to study the operation of fresh agricultural product supply chains under carbon cap-and-trade policy. In terms of coordination in the fresh agricultural product supply chain, Bai *et al.* [3] studied the coordination and optimization of the secondary supply chain of fresh agricultural products under the carbon cap-and-trade policy when the deterioration rate of fresh products is fixed and the market demand depends on price, promotion efforts and carbon reduction and drainage; Ma *et al.* [22] studied the decision-making and coordination of a three-level supply chain under carbon cap-and-trade, assuming that the demand for fresh products is a multiplier form of freshness, price, and random influencing factors; Yang and Yao [32] hypothesized that consumers have dual preferences for freshness and low-carbon, and studied the decision-making and coordination contracts of fresh agricultural supply chain under carbon cap-and-trade. In terms of inventory management in the supply chain of fresh agricultural products, Yang *et al.* [34] used a game model to study the ordering strategy of fresh agricultural products supply chain under carbon cap-and-trade; Accorsi *et al.* [1] established a linear programming ordering model of fresh agricultural products under carbon constraints to study the deterioration rate and ordering strategy of fresh agricultural products.

Table 1. The authors' contributions.

Author	Contributions
Yang Yang	Writing – original draft preparation, visualization, methodology
Guanxin Yao	Conceptualization, writing – review – editing, supervision

Overall, there has been a lot of research on the information sharing of fresh agricultural products supply chain, the information collaboration of supply chain and the operation of supply chain under carbon cap-and-trade, but there are still some shortcomings. Firstly, scholars generally agree that information sharing has a positive impact on the fresh agricultural product supply chains, but the essence of promoting supply chain performance through information sharing lies in the utilization of information, rather than information sharing itself. At present, the development scales of fresh agricultural products suppliers, cold chain logistics service providers and fresh agricultural products sellers in China are different, especially the phenomenon of "small, scattered and chaotic" exists in fresh agricultural products suppliers and cold chain logistics service providers [19]. In the context of inconsistent information utilization capabilities of subjects, how to effectively utilize shared information becomes a key issue that needs to be addressed to improve the operational efficiency of the fresh agricultural product supply chain. Therefore, different from the existing research, we consider the influence of information collaborative utilization ability on decision-making, rather than information utilization ability. Secondly, scholars have recognized the positive impact of information collaboration on supply chain performance and innovation, but there is still a lack of research on information collaboration focused on fresh agricultural product supply chains. We put forward the operation mode of information collaboration in the supply chain of fresh agricultural products, which can supplement the existing research. Thirdly, existing research has noticed the impact of carbon cap-and-trade policy on fresh agricultural products supply chain decision-making, but there is little literature on the relationship between information collaboration and carbon emissions in the fresh agricultural product supply chain. In fact, information collaboration has a certain impact on supply chain carbon emissions [18,35,36]. We revealed the rules of information collaborative decision-making among fresh agricultural product supply chain entities under carbon cap-and-trade policy, which can make up for the shortcomings of existing research.

The authors' contributions are shown in Table 1.

3. The operational mode of information collaboration in the supply chain of fresh agricultural products

Participants in information collaboration include a fresh agricultural products supplier, a cold chain logistics service provider and a fresh agricultural products seller. By integrating information technologies such as blockchain, the Internet of Things, and Big data, all subjects build an information collaborative decision-making system to share market demand information, product information, inventory information, logistics information, sales information, capital information, and so on in real time. Each subject makes collaborative decisions based on shared information, including strategic level collaborative decisions, management level collaborative decisions, and operational level collaborative decisions. Specifically, the strategic level collaborative decision-making is made by the leadership of each subject through coordination and communication based on all the information shared, including collaborative formulation of market competition strategy, product innovation strategy, product pricing strategy, etc. Management level collaborative decision-making refers to the collaborative planning of product production, transportation, warehousing and sales following the strategic decisions. Firstly, the seller makes a sales plan according to the market demand, secondly, the supplier makes a production plan and a delivery plan based on the sales demand information and inventory information, and finally, the cold chain logistics service provider forms a logistics transportation plan according to the transportation demand. Moreover, through

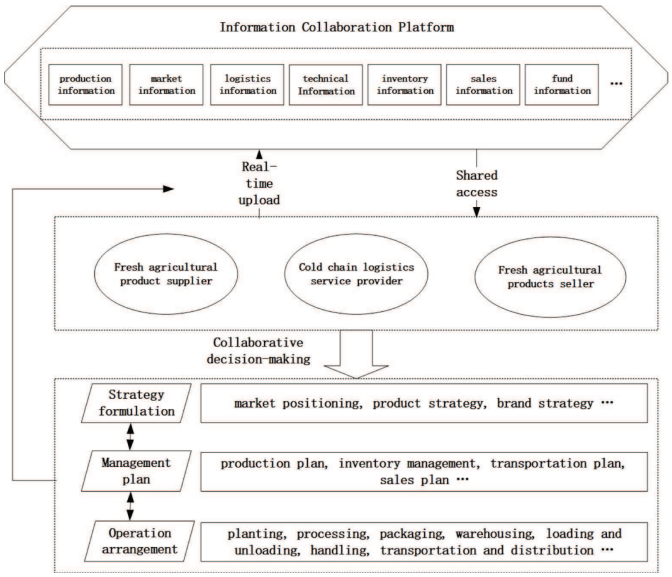

FIGURE 1. Operation mode of information collaboration in fresh agricultural products supply chain.

the real-time feedback of information, subjects can synchronously and timely optimize management plans and strategic decisions. Operational level collaborative decision-making refers to the actual operations of each subject in areas such as warehousing, loading and unloading, transportation and distribution, and product shelving based on collaborative decisions at the management level. And, each subject should provide real-time feedback on operational information, on the one hand, to maintain consistency of operations and ensure product safety and traceability; on the other hand, it provides support for management level collaborative decision-making. The specific operation process of fresh agricultural products supply chain information collaboration is shown in Figure 1.

4. Evolutionary game model construction

4.1. Model assumptions and symbolic description

It is assumed that the fresh agricultural products supplier A, the cold chain logistics service provider C and the fresh agricultural products sales E all have two strategic choices: information collaboration and information non-collaboration. The strategy set is (collaboration, non-collaboration), and the probability is $(x, 1-x)$, $(y, 1-y)$ and $(z, 1-z)$ respectively.

Other assumptions are as follows:

(1) It is assumed that the subject is bounded rationality and can constantly learn and change its own strategies.
(2) Assuming that under the sales volume Q_1, the basic benefits of fresh agricultural products supplier A, fresh agricultural products seller E and cold chain logistics service provider C are π_A, π_E and π_C, respectively. The initial inventory and transportation costs of them are C_A, C_E and C_C respectively.
(3) Under the information collaboration operation mode of fresh agricultural products supply chain, the fresh agricultural products supplier, the cold chain logistics service provider and the fresh agricultural products sales need to construct an information collaborative decision-making system, which requires paying construction costs including material costs, technical development costs, personnel operation training costs, and so on. It is assumed that the total cost of information collaboration in fresh agricultural products sup-

ply chain is C_{zI}, which is divided among fresh agricultural products supplier A, fresh agricultural products seller E and cold chain logistics service provider C at the ratio of ϵ_1, ϵ_2 and ϵ_3.

(4) By collaborating to develop management plans and operational arrangements, subjects can improve the operational efficiency of the fresh agricultural product supply chain and bring direct benefits. Specifically, supply chain collaborative planning can improve inventory management efficiency, reduce inventory backlog, and thus reduce inventory costs for various subjects [11]; by coordinating transportation and distribution arrangements, transportation and distribution efficiency can be improved, ineffective transportation and duplicate distribution can be reduced, and transportation costs can be reduced [2]. Therefore, when the three parties collaborate on information, the degree of improvement in supply chain efficiency is expressed as $\alpha\rho_z\theta_z(\theta_z = \theta_A + \theta_E + \theta_C)$. α is the operational efficiency improvement coefficient under unit information amount and unit planning ability, ρ_z represents the collaborative planning ability of the three parties (according to [11], the key to improving efficiency lies in the ability to utilize information), and θ_i represents the information amount shared by each subject [22]. Therefore, the cost reduced by efficiency improvement can be characterized as $C_A\alpha\rho_z\theta_z$, $C_E\alpha\rho_z\theta_z$ and $C_C\alpha\rho_z\theta_z$. It means that the higher the efficiency improvement, the greater the cost reduction.

(5) Supply chain collaborative planning can improve overall efficiency, reduce chain disruptions, enhance the freshness of fresh agricultural products [29], and thus bring external market benefits, expressed as $Q_1\mu_1\alpha\rho_z\theta_z$, μ_1 represents consumers' preference for freshness.

At the same time, through the collaborative formulation of market strategies such as brand promotion, product innovation and quality improvement, the quality and added value of fresh agricultural products can be improved, the needs of some high-quality consumers can be met, and external market benefits can be brought. For example, the "Yuanxiaoji" egg brand jointly developed and launched by "Yonghui" fresh supply chain members through sharing and collaborative use of market demand information for eggs, production information of free-range eggs in mountains and selenium-enriched five-black eggs, and logistics information is well received by the market. The external benefits brought by collaborative strategy-making ability are described as $\mu_2\phi_z\theta_z$, which means that the benefits are directly proportional to consumers' high-quality consumption preference μ_2, the amount of shared information θ_z and the collaborative strategy-making ability ϕ_z of the three parties (related to the leadership ability of each subject). Specifically, the more data is shared [10], and the higher the ability of collaborative strategy formulation, the more effective information can be identified and utilized by the leaders of enterprises, and the more reasonable market strategies such as brand promotion, product innovation and quality improvement are formulated, and the higher the product quality and added value are. When consumers tend to consume high-quality fresh food, the more external benefits the supply chain members can get.

All the external profits are shared among the three parties in the proportion of γ_1, γ_2 and $\gamma_3(\gamma_1+\gamma_1+\gamma_3 = 1)$.

(6) When only two parties choose information collaboration, due to the lack of information, no synergy effect can be generated, and the participants in the collaboration can only use the shared information, optimize the planning, improve their own operational efficiency, and thus obtain direct benefits. Specifically, when A and E cooperate at the same time, the benefits that A and E can obtain are $\alpha w_A(\theta_A + \theta_E)C_A$ and $\alpha w_E(\theta_A + \theta_E)C_E$ respectively; When A and C cooperate at the same time, the benefits that A and C can obtain are $\alpha w_A(\theta_C + \theta_A)C_A$ and $\alpha w_C(\theta_C + \theta_A)C_C$ respectively; When E and C cooperate at the same time, the benefits that E and C can obtain are $\alpha w_E(\theta_C + \theta_E)C_E$ and $\alpha w_C(\theta_C + \theta_E)C_C$ respectively.

At the same time, the subjects that do not participate in the collaboration will use the information shared by the collaboration parties and their own original information to obtain free riding benefits [38], which are expressed as $\alpha w_A\theta_z C_A$, $\alpha w_E\theta_z C_E$ and $\alpha w_C\theta_z C_C$, w_i refers to the planning capacity of each subject under the unit information volume.

(7) Similarly, when only A participates in the collaboration, E and C will use their own information and the information shared by A to obtain free rider benefits $\alpha w_E(\theta_A + \theta_E)C_E$ and $\alpha w_C(\theta_C + \theta_A)C_C$ respectively; When only E participates in the collaboration, A and C will use their own information and the information shared by E to obtain free riding benefits $\alpha w_A(\theta_A + \theta_E)C_A$ and $\alpha w_C(\theta_C + \theta_E)C_C$ respectively; When only

C participates in the collaboration, E and A will use their own information and the information shared by C to obtain free riding benefits $\alpha w_E(\theta_C + \theta_E)C_E$ and $\alpha w_A(\theta_C + \theta_A)C_A$ respectively.

(8) The government provides information construction cost subsidies to the subjects participating in information collaboration with a proportion of v, and punishes the non-cooperative subjects who use the shared information to obtain free riding benefits (uT), u represents the degree of supervision and T represents the fine. In order to control carbon emissions, we assume that the government implements the carbon cap-and-trade policy for fresh agricultural product suppliers, cold chain logistics service providers and fresh agricultural product sellers. Because in the pilot of carbon trading in China, fresh agricultural products suppliers and sales enterprises such as Bright Dairy Co., Ltd., Duoyu Food (Shenzhen) Co., Ltd. and Beijing Xinfadi Agricultural and Sideline Products Wholesale Market Center have been included, and the logistics industry is also a key industry to be included in the future. The carbon caps given to the fresh agricultural products supplier A, the fresh agricultural products seller E and the cold chain logistics service provider C are E_A, E_E and E_C, the carbon trading price is τ, and the initial carbon emissions of the game players are E_{0A}, E_{0E} and E_{0C}, respectively.

(9) The reduction in inventory costs means a reduction in the use of cold storage, which will reduce electricity and refrigerant consumption, thereby reducing carbon emissions. At the same time, the reduction in transportation costs will also reduce energy consumption, thereby reducing carbon emissions. For the convenience of research, we assume that the carbon emission reduction caused by unit cost reduction is e (we do not distinguish between inventory cost and transportation cost here). Then, when the three parties cooperate, the carbon emission reduction brought by information cooperation to each subject is expressed as $e\alpha\rho_z\theta_z C_A$, $e\alpha\rho_z\theta_z C_E$ and $e\alpha\rho_z\theta_z C_C$; When A and E cooperate, their carbon emission reductions are respectively expressed as $e\alpha w_A(\theta_A + \theta_E)C_A$ and $e\alpha w_E(\theta_A + \theta_E)C_E$, the carbon emission reduction of hitchhiking agent C is $e\alpha w_C\theta_z C_C$; When A and C cooperate, their carbon emission reductions are respectively expressed as $e\alpha w_A(\theta_A + \theta_C)C_A$ and $e\alpha w_C(\theta_A + \theta_C)C_C$, the carbon emission reduction of hitchhiking agent E is $e\alpha w_E\theta_z C_E$; When C and E cooperate, their carbon emission reductions are respectively expressed as $e\alpha w_C(\theta_C + \theta_E)C_C$ and $e\alpha w_E(\theta_C + \theta_E)C_E$, the carbon emission reduction of hitchhiking agent A is $e\alpha w_A\theta_z C_A$; When only A participates in synergy, the carbon emission reductions of E and C are $e\alpha w_E(\theta_A + \theta_E)C_E$ and $e\alpha w_C(\theta_A + \theta_C)C_C$; When only E participates in synergy, the carbon emission reductions of A and C are $e\alpha w_A(\theta_A + \theta_E)C_A$ and $e\alpha w_C(\theta_C + \theta_E)C_C$; When only C participates in synergy, the carbon emission reductions of E and A are $e\alpha w_E(\theta_C + \theta_E)C_E$ and $e\alpha w_A(\theta_A + \theta_C)C_A$.

The symbols and explanations involved in the above assumptions are shown in Table 2.

4.2. Model construction

When all three parties choose to participate in collaboration, the benefit function of A is composed of the basic benefits plus the cost reduction brought about by information collaboration, plus the shared external benefits minus the cost of information collaboration, plus government cost subsidies minus the cost of carbon emission trading, which is expressed as $\pi_A + \alpha\rho_z\theta_z C_A + \gamma_1(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) - \epsilon_1(1-v)C_{zI} - \tau(E_{0A} - e\alpha\rho_z\theta_z C_A - E_A)$. Similarly, the return functions of E and C are represented as $\pi_E + \alpha\rho_z\theta_z C_E + \gamma_2(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) - \epsilon_2(1-v)C_{zI} - \tau(E_{0E} - e\alpha\rho_z\theta_z C_E - E_E)$ and $\pi_C + \alpha\rho_z\theta_z C_C + \gamma_3(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) - \epsilon_3(1-v)C_{zI} - \tau(E_{0C} - e\alpha\rho_z\theta_z C_C - E_C)$.

When A and E participate in collaboration and C does not, A's income function is composed of the basic income plus the cost reduction caused by using the shared information of A and E minus the cost of information collaboration plus cost subsidies minus the cost of carbon emission trading, which is expressed as $\pi_A + \alpha w_A(\theta_A + \theta_E)C_A - \epsilon_1(1-v)C_{zI} - \tau(E_{0A} - e\alpha w_A(\theta_A + \theta_E)C_A - E_A)$; similarly, E's income function is expressed as $\pi_E + \alpha w_E(\theta_A + \theta_E)C_E - \epsilon_2(1-v)C_{zI} - \tau(E_{0E} - e\alpha w_E(\theta_A + \theta_E)C_E - E_E)$; at this time, the return function of C is composed of the basic return plus the free rider return minus the carbon emission trading cost and penalty cost, which is expressed as $\pi_C + \alpha w_C\theta_z C_C - \tau(E_{0C} - \alpha w_C\theta_z C_C - E_C) - uT$.

TABLE 2. Symbols involved in the text and their descriptions.

Variable	Description	Variable	Description
π_A	Basic income of A	ρ_z	Collaborative planning capability
E_{0A}	Initial carbon emissions of A	π_E	Basic income of E
w_A	Planning capability of A	E_{0E}	Initial carbon emissions of E
C_A	Initial cost of A	C_E	Initial cost of E
C_C	Initial cost of C	π_C	Basic income of C
w_E	Planning capability of E	E_{0C}	Initial carbon emissions of C
ϕ_z	Collaborative strategy formulation capability	w_C	Planning capability of C
E_A	Total carbon limit of A	γ_1	Collaborative benefit sharing coefficient of A
τ	Carbon trading price	E_E	Total carbon limit of E
γ_2	Collaborative benefit sharing coefficient of E	C_{zI}	Total cost of information collaboration
E_C	Total carbon limit of C	γ_3	Collaborative benefit sharing coefficient of C
e	Carbon emission reduction due to unit cost reduction	v	Proportion of informatization cost subsidy
θ_A	Information amount shared by A	u	The supervision of the government
μ_1	Consumer's freshness preference	θ_E	Information amount shared by E
T	Government punishment	μ_2	Consumers' high-quality preference
θ_C	Information amount shared by C	ϵ_2	Cost sharing coefficient of E
ϵ_3	Cost sharing coefficient of C	ϵ_1	Cost sharing coefficient of A
α	Coefficient of operational efficiency improvement	Q_1	Sales volumes

When A and C participate in collaboration and E does not, A's income function is composed of the basic income plus the cost reduction caused by using the shared information of A and C minus the cost of information collaboration plus cost subsidies minus the cost of carbon emission trading, which is expressed as $\pi_A+\alpha w_A(\theta_A+\theta_C)C_A-\epsilon_1(1-v)C_{zI}-\tau(E_{0A}-e\alpha w_A(\theta_A+\theta_C)C_A-E_A)$; similarly, C's income function is expressed as $\pi_C+\alpha w_C(\theta_A+\theta_C)C_C-\epsilon_3(1-v)C_{zI}-\tau(E_{0C}-e\alpha w_C(\theta_A+\theta_C)C_C-E_C)$; at this time, the return function of E is composed of the basic return plus the free rider return minus the carbon emission trading cost and penalty cost, which is expressed as $\pi_E+\alpha w_E\theta_z C_E-\tau(E_{0E}-\alpha w_E\theta_z C_E-E_E)-uT$.

When E and C participate in collaboration and A does not, E's income function is composed of the basic income plus the cost reduction caused by using the shared information of E and C minus the cost of information collaboration plus cost subsidies minus the cost of carbon emission trading, which is expressed as $\pi_E+\alpha w_E(\theta_E+\theta_C)C_E-\epsilon_2(1-v)C_{zI}-\tau(E_{0E}-e\alpha w_E(\theta_E+\theta_C)C_E-E_E)$; similarly, C's income function is expressed as $\pi_C+\alpha w_C(\theta_E+\theta_C)C_C-\epsilon_3(1-v)C_{zI}-\tau(E_{0C}-e\alpha w_C(\theta_E+\theta_C)C_C-E_C)$; at this time, the return function of A is composed of the basic return plus the free rider return minus the carbon emission trading cost and penalty cost, which is expressed as $\pi_A+\alpha w_A\theta_z C_A-\tau(E_{0A}-\alpha w_A\theta_z C_A-E_A)-uT$.

When A participates in collaboration and neither E nor C participates in collaboration, A's revenue function is composed of basic revenue minus information collaboration cost minus carbon emission trading cost, which is expressed as $\pi_A-\epsilon_1(1-v)C_{zI}-\tau(E_{0A}-E_A)$; E's revenue function is composed of basic revenue plus cost reduction obtained by using information shared by A and E's own information minus carbon emission trading cost minus penalty cost, which is expressed as $\pi_E+\alpha w_E(\theta_A+\theta_E)C_E-\tau(E_{0E}-e\alpha w_E(\theta_A+\theta_E)C_E-E_E)-uT$; similar to E, C's revenue function can be expressed as $\pi_C+w_C\alpha(\theta_C+\theta_A)C_C-\tau(E_{0C}-ew_C\alpha(\theta_C+\theta_A)C_C-E_C)-uT$.

When E participates in collaboration and neither A nor C participates in collaboration, E's revenue function is composed of basic revenue minus information collaboration cost minus carbon emission trading cost, which is expressed as $\pi_E - \epsilon_2(1-v)C_{zI} - \tau(E_{0E} - E_E)$; A's revenue function is composed of basic revenue plus cost reduction obtained by using information shared by E and A's own information minus carbon emission trading cost minus penalty cost, which is expressed as $\pi_A + \alpha w_A(\theta_A + \theta_E)C_A - \tau(E_{0A} - e\alpha w_A(\theta_A + \theta_E)C_A - E_A) - uT$; similar to A, C's revenue function can be expressed as $\pi_C + \alpha w_C(\theta_C + \theta_E)C_C - \tau(E_{0C} - \alpha w_C(\theta_C + \theta_E)C_C - E_C) - uT$.

When C participates in collaboration and neither A nor E participates in collaboration, C's revenue function is composed of basic revenue minus information collaboration cost minus carbon emission trading cost, which is expressed as $\pi_C - \epsilon_3(1-v)C_{zI} - \tau(E_{0C} - E_C)$; A's revenue function is composed of basic revenue plus cost reduction obtained by using information shared by C and A's own information minus carbon emission trading cost minus penalty cost, which is expressed as $\pi_A + \alpha w_A(\theta_C + \theta_A)C_A - \tau(E_{0A} - \alpha w_A(\theta_C + \theta_A)C_A - E_A) - uT$; similar to A, E's revenue function can be expressed as $\pi_E + \alpha w_E(\theta_C + \theta_E)C_E - \tau(E_{0E} - \alpha w_E(\theta_C + \theta_E)C_E - E_E) - uT$.

When none of the three parties choose to participate in the collaboration, the revenue function of each subject is composed of basic revenue minus carbon emission trading costs, which are respectively expressed as $\pi_A - \tau(E_{0A} - E_A)$, $\pi_E - \tau(E_{0E} - E_E)$, $\pi_C - \tau(E_{0C} - E_C)$.

The expected return U_1 of fresh agricultural products supplier A participating in information collaboration, the expected return U_2 of fresh agricultural products supplier A not participating in information collaboration, and the average return $\overline{U_A}$ can be obtained respectively.

$$\begin{aligned}
U_1 &= \pi_A + yz(\alpha\rho_z\theta_z C_A(1+\tau e) + \gamma_1(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z)) - \epsilon_1(1-v)C_{zI} \\
&\quad - \tau(E_{0A} - E_A) + y(1-z)(1+\tau e)\alpha w_A(\theta_A + \theta_E)C_A + z(1-y)(1+\tau e)\alpha_A(\theta_C + \theta_A)C_A \\
U_2 &= \pi_A + yz(1+\tau e)\alpha w_A\theta_z C_A + y(1-z)(1+\tau e)\alpha w_A(\theta_A + \theta_E)C_A \\
&\quad - (y + z - yz)uT + z(1-y)(1+\tau e)\alpha w_A(\theta_C + \theta_A)C_A - \tau(E_{0A} - E_A) \\
\overline{U_A} &= xU_1 + (1-x)U_2.
\end{aligned}$$

The replication dynamic equation of the information collaboration strategy selected by fresh agricultural product supplier A is:

$$\begin{aligned}
F(x) = \mathrm{d}x/\mathrm{d}t = x(1-x)[&yz(\alpha\rho_z\theta_z C_A(1+\tau e) + \gamma_1(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) \\
&- (1+\tau e)\alpha w_A\theta_z C_A) + (y + z - yz)uT - \epsilon_1(1-v)C_{zI}].
\end{aligned}$$

The expected return U_3 of fresh agricultural products seller E participating in information collaboration, the expected return U_4 of fresh agricultural products seller E not participating in information collaboration, and the average return $\overline{U_E}$ can be obtained respectively.

$$\begin{aligned}
U_3 &= \pi_E + xz(\alpha\rho_z\theta_z C_E(1+\tau e) + \gamma_2(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z)) - \epsilon_2(1-v)C_{zI} \\
&\quad - \tau(E_{0E} - E_E) + x(1-z)(1+\tau e)\alpha w_E(\theta_A + \theta_E)C_E + z(1-x)(1+\tau e)\alpha w_E(\theta_C + \theta_E)C_E \\
U_4 &= \pi_E + xz(1+\tau e)\alpha w_E\theta_z C_E + x(1-z)(1+\tau e)\alpha w_E(\theta_A + \theta_E)C_E \\
&\quad - (x + z - xz)uT + z(1-x)(1+\tau e)\alpha w_E(\theta_C + \theta_E)C_E - \tau(E_{0E} - E_E) \\
\overline{U_E} &= yU_3 + (1-y)U_4.
\end{aligned}$$

The replication dynamic equation of the information collaboration strategy selected by fresh agricultural products seller E is:

$$\begin{aligned}
F(y) = \mathrm{d}y/\mathrm{d}t = y(1-y)[&xz(\alpha\rho_z\theta_z C_E(1+\tau e) + \gamma_2(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) \\
&- (1+\tau e)\alpha w_E\theta_z C_E) + (x + z - xz)uT - \epsilon_2(1-v)C_{zI}].
\end{aligned}$$

The expected return U_5 of cold chain logistics service provider C participating in information collaboration, the expected return U_6 of cold chain logistics service provider C not participating in information collaboration, and the average return $\overline{U_C}$ can be obtained respectively.

$$\begin{aligned}
U_5 &= \pi_C + xy(\alpha\rho_z\theta_z C_C(1+\tau e) + \gamma_3(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z)) - \epsilon_3(1-v)C_{zI} \\
&\quad - \tau(E_{0C} - E_C) + y(1-x)(1+\tau e)\alpha w_C(\theta_C+\theta_E)C_C + x(1-y)(1+\tau e)\alpha w_C(\theta_C+\theta_A)C_C \\
U_6 &= \pi_C + xy(1+\tau e)\alpha w_C\theta_z C_C + y(1-x)(1+\tau e)\alpha w_C(\theta_C+\theta_E)C_C \\
&\quad - (x+y-xy)uT + x(1-y)(1+\tau e)\alpha w_C(\theta_C+\theta_A)C_C - \tau(E_{0C}-E_C) \\
\overline{U_C} &= zU_5 + (1-z)U_6.
\end{aligned}$$

The replication dynamic equation of the information collaboration strategy selected by cold chain logistics service provider C is:

$$\begin{aligned}
F(z) = \mathrm{d}z/\mathrm{d}t = z(1-z)[&xy(\alpha\rho_z\theta_z C_C(1+\tau e) + \gamma_3(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) \\
&- (1+\tau e)\alpha w_C\theta_z C_C) - \epsilon_3(1-v)C_{zI} + (x+y-xy)uT].
\end{aligned}$$

4.3. Model solution and stability analysis of equilibrium point

Through comparison, it can be found that when the benefits obtained by the subject participating in information collaboration, the shared information collaboration costs, the free riding benefits, the government cost subsidies, the government's supervision and penalties, and the carbon emission reduction benefits meet different size relationships, the stable points of the three-dimensional evolutionary game dynamic system are different. Specifically:

Condition (1): when $\alpha\theta_z C_A(1+\tau e)(\rho_z - w_A) + \gamma_1(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) + uT - \epsilon_1(1-v)C_{zI} > 0$, $\alpha\theta_z C_E(1+\tau e)(\rho_z - w_E) + \gamma_2(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) + uT - \epsilon_2(1-v)C_{zI} > 0$, $\alpha\theta_z C_C(1+\tau e)(\rho_z - w_C) + \gamma_3(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) + uT - \epsilon_3(1-v)C_{zI} > 0$, $E_1(0,0,0)$ and $E_8(1,1,1)$ are the stable points of the system;

Condition (2): when $\alpha\theta_z C_A(1+\tau e)(\rho_z - w_A) + \gamma_1(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) + uT - \epsilon_1(1-v)C_{zI} < 0$, $uT - \epsilon_2(1-v)C_{zI} > 0$, $uT - \epsilon_3(1-v)C_{zI} > 0$, $E_1(0,0,0)$ and $E_4(0,1,1)$ are the stable points of the system;

Condition (3): when $\alpha\theta_z C_E(1+\tau e)(\rho_z - w_E) + \gamma_2(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) + uT - \epsilon_2(1-v)C_{zI} < 0$, $uT - \epsilon_1(1-v)C_{zI} > 0$, $uT - \epsilon_3(1-v)C_{zI} > 0$, $E_1(0,0,0)$ and $E_7(1,0,1)$ are the stable points of the system;

Condition (4): when $\alpha\theta_z C_C(1+\tau e)(\rho_z - w_C) + \gamma_3(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) + uT - \epsilon_3(1-v)C_{zI} < 0$, $uT - \epsilon_1(1-v)C_{zI} > 0$, $uT - \epsilon_2(1-v)C_{zI} > 0$, $E_1(0,0,0)$ and $E_6(1,1,0)$ are the stable points of the system;

Condition (5): when $\alpha\theta_z C_A(1+\tau e)(\rho_z - w_A) + \gamma_1(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) + uT - \epsilon_1(1-v)C_{zI} < 0$, $\alpha\theta_z C_E(1+\tau e)(\rho_z - w_E) + \gamma_2(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) + uT - \epsilon_2(1-v)C_{zI} < 0$, $\alpha\theta_z C_C(1+\tau e)(\rho_z - w_C) + \gamma_3(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) + uT - \epsilon_3(1-v)C_{zI} < 0$, $uT - \epsilon_1(1-v)C_{zI} < 0$, $uT - \epsilon_2(1-v)C_{zI} < 0$, $uT - \epsilon_3(1-v)C_{zI} < 0$, $E_1(0,0,0)$ is the only stable point of the system.

5. Simulation analysis of evolutionary game based on system dynamics

In this section, we will use Vensim PLE software to build an SD model of the evolutionary game of information collaboration in the fresh agricultural product supply chain with the method of system dynamics, and carry out simulation analysis to study the impact of parameters on the system stability strategy, and then reveal the system evolution path.

5.1. SD model construction of information collaboration of fresh agricultural product supply chain

The SD model of information collaboration of fresh agricultural product supply chain is shown in Figure 2. x, y and z are system stocks, which are obtained by integrating the information collaborative change rate of fresh agricultural product suppliers, fresh agricultural product sellers and cold chain logistics service providers with

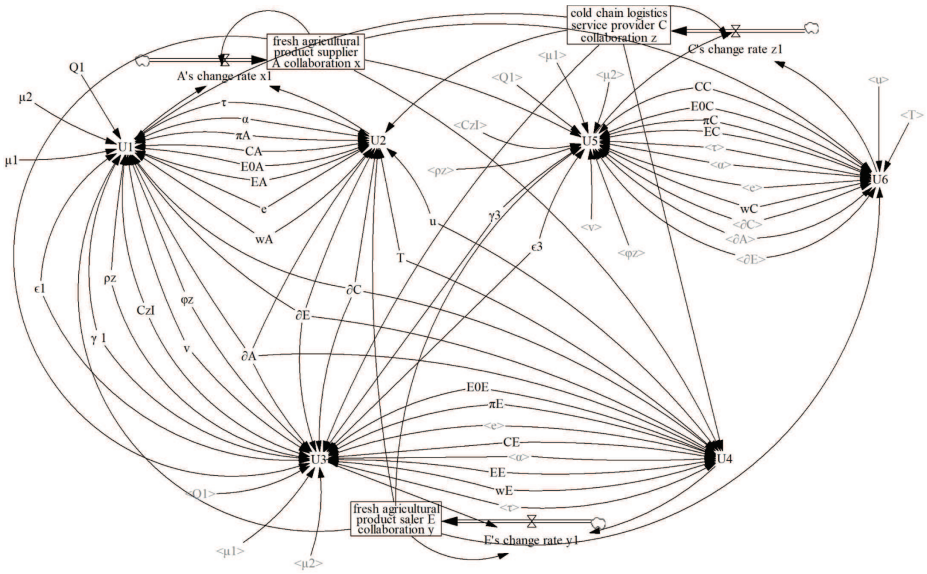

FIGURE 2. SD model of information collaboration of fresh agricultural product supply chain.

TABLE 3. Initial values of external variables in the model.

Variable	Initial value	Variable	Initial value	Variable	Initial value
π_A	10	ρ_z	1.5	E_{0A}	15
π_E	13	w_A	0.3	E_{0E}	8
C_A	6	C_E	4	C_C	8
π_C	12	w_E	0.5	E_{0C}	25
ϕ_z	0.8	w_C	0.4	E_A	10
γ_1	0.3	τ	0.5	E_E	3
γ_2	0.4	C_{zI}	25	E_C	15
γ_3	0.3	e	1.5	v	0.1
θ_A	3	u	0.8	μ_1	0.8
θ_E	4	T	5	μ_2	0.5
θ_C	3	ϵ_2	0.4	ϵ_3	0.3
ϵ_1	0.3	α	0.05	Q_1	5

time, U_1, U_2, U_3, U_4, U_5 and U_6 are intermediate variables, and the rest are exogenous variables. The functional relationship of each variable can be obtained by replicated dynamic equations.

5.2. Numerical simulation and analysis

Due to the fact that system dynamics mainly studies feedback loops, data accuracy has little impact on the results, and the main factor affecting the results is the structure of the model [9, 37]. Reference [15, 22, 31], we use numerical examples to conduct simulation experiments. The initial values of variables are shown in Table 3, and the simulation period is set to 10 Year, and the simulation step size is 0.03125.

5.2.1. The influence of initial intention on the evolution path of the system

We observe and analyze the evolution of the game system by changing the initial intentions of the fresh agricultural products supplier, the fresh agricultural products seller and the cold chain logistics service provider. Set

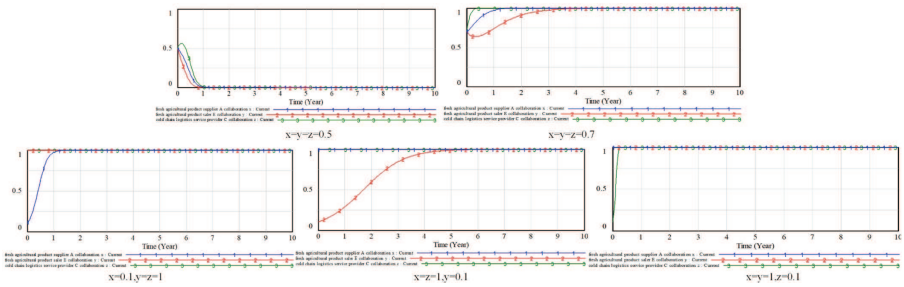

FIGURE 3. Evolution path of game system under different initial intentions.

the initial information collaboration willingness of the fresh agricultural product supplier, the fresh agricultural product seller and the cold chain logistics service provider as $(0.5, 0.5, 0.5)$, $(0.7, 0.7, 0.7)$, $(0.1, 1, 1)$, $(1, 0.1, 1)$, $(1, 1, 0.1)$, and the evolution path of the system is shown in Figure 3. When the initial intentions of the three parties are low (0.5), the system evolves towards (0,0,0); When the initial intentions of the three parties are all raised to 0.7, the system evolves in the direction of $(1, 1, 1)$; When the initial intention of any two parties is high (both are 1) and the initial intention of the other party is low (0.1), the evolution direction of the system is $(1, 1, 1)$.

We can draw some conclusions from this: First, the initial intentions of fresh agricultural product suppliers, fresh agricultural product sellers and cold chain logistics service providers affect the stability strategy of the information collaboration game system. When the initial intentions of the three parties are low, the final stability strategy of the game system is (non-collaboration, non-collaboration, non-collaboration); When the initial willingness of the three parties to collaborate is high, the final stability strategy of the game system becomes (collaboration, collaboration, collaboration). Secondly, the strategies among the three-party game players affect each other. As long as two parties choose information collaboration strategies, even if the other party's initial willingness to collaborate is low, they will eventually choose collaboration strategies to reach a stable state (collaboration, collaboration, collaboration).

5.2.2. Impact of key parameters on strategy selection

We set the initial cooperation willingness of the three-party game players to $(0.5, 0.5, 0.5)$, observe the evolution path of the system by regulating the key parameters, and then analyze the influence of the key parameters on the game players' strategy choice.

(1) Collaborative planning ability and collaborative strategy formulation ability.
With other parameters unchanged, we take different combinations of abilities: $\rho_z = 1.5, \phi_z = 0.8$, $\rho_z = 2, \phi_z = 0.8$, $\rho_z = 2.5, \phi_z = 0.8$, $\rho_z = 1.5, \phi_z = 3$, $\rho_z = 2, \phi_z = 3$, $\rho_z = 2.5, \phi_z = 3$, and the evolution path of the game system is shown in Figure 4. When we keep the collaborative strategy making ability unchanged and improve the collaborative planning ability from 1.5 to 2, we find that the game system still evolves in the direction of $(0, 0, 0)$, but the evolution speed becomes slower. We continued to increase the collaborative planning capability from 2 to 2.5, and the system evolved in the direction of $(1, 1, 1)$. When the collaborative planning capability is 1.5, the collaborative strategy formulation capability is improved from 0.8 to 3, and the system still evolves towards $(0, 0, 0)$. When the collaborative planning capability is 2, the collaborative strategy formulation capability is improved from 0.8 to 3, and the system evolves from $(0, 0, 0)$ to $(1, 1, 1)$. When the collaborative planning capability is 2.5, the collaborative strategy formulation capability is improved from 0.8 to 3, and the evolution speed of the system in the direction of $(1, 1, 1)$ is accelerated.
The improvement of collaborative planning capability can improve the operation efficiency of the supply chain, reduce the costs of all players, increase the carbon emission reduction benefits, improve the freshness

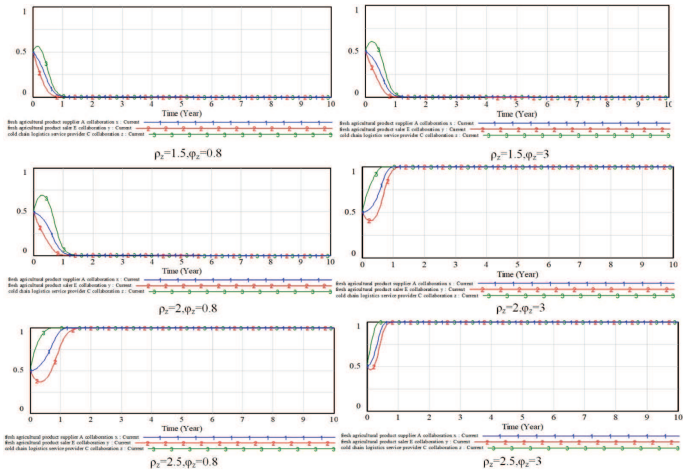

FIGURE 4. Evolution path of game system under different ability combinations.

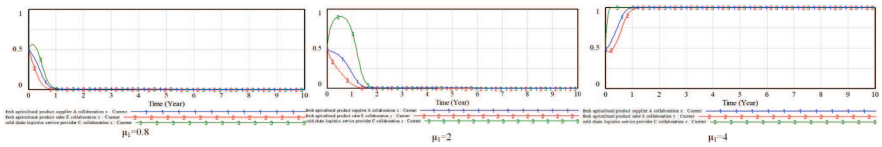

FIGURE 5. Evolution path of the system under different consumers' freshness preference.

of fresh agricultural products, and bring external benefits, which is conducive to encouraging game players to choose information collaboration strategies. When the collaborative planning capability is low, even if the three parties have a high collaborative strategy formulation capability, the subject will not choose the information collaboration strategy. However, properly increasing the ability of collaborative planning and then improving the ability of collaborative strategy formulation can effectively promote the subject's participation in information collaboration. That is to say, the ability of collaborative strategy formulation must be based on a certain ability of collaborative planning, so as to have an incentive effect on the subject information collaboration.

(2) Consumers' preference for freshness and high quality.
With other parameters unchanged, let $\mu_1 = 0.8$, $\mu_1 = 2$, $\mu_1 = 4$, and observe the evolution path of the game system (Fig. 5). It can be seen from the figure that when consumer freshness preference increases from 0.8 to 2, the game system still evolves in the direction of $(0, 0, 0)$, but the evolution speed becomes slower; When consumers' freshness preference increases from 2 to 4, the system evolves in the direction of $(1, 1, 1)$. With other parameters unchanged, let $\mu_2 = 0.5$, $\mu_2 = 2$, $\mu_2 = 4$, and observe the evolution path of the game system (Fig. 6). It can be seen from the figure that when the consumer's high quality preference increases from 0.5 to 2, the game system still evolves in the direction of $(0, 0, 0)$, but the evolution speed becomes slower; When consumers' high quality preference increases from 2 to 4, the system turns to $(1, 1, 1)$. The more consumers prefer fresh agricultural products with high freshness and good quality, the more external benefits can be obtained from information collaboration, and the more participants tend to choose information collaboration strategies.

(3) Initial cost.
With other parameters unchanged, let $C_A = 6, C_E = 4, C_C = 8$, $C_A = 16, C_E = 14, C_C = 18$, and observe the evolution path of the game system (as shown in Fig. 7). Under the given sales volume, by increasing

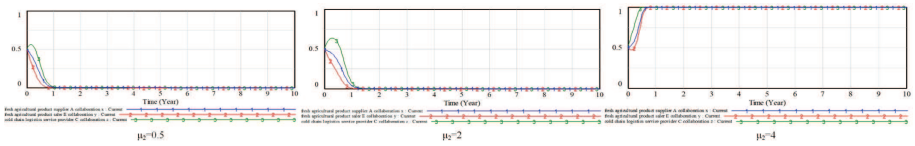

FIGURE 6. Evolution path of the system under different consumers' high-quality preference.

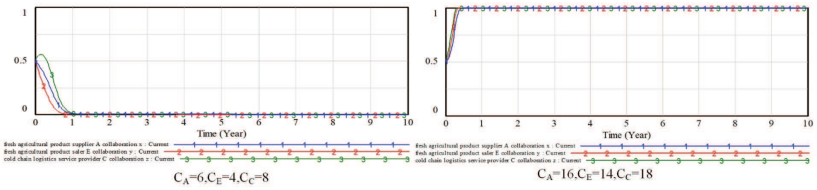

FIGURE 7. Evolution path of the system under different initial costs.

the initial cost of each subject by 10, it can be found that the system has evolved from $(0,0,0)$ to $(1,1,1)$. That is to say, under the given sales volume, the higher the initial cost of the fresh agricultural products supplier, the fresh agricultural products seller and the cold chain logistics service provider, the more inclined they are to choose information collaboration strategy. This is because their participation in information collaboration can improve operational efficiency, greatly reduce costs and increase profit margins.

(4) Profit sharing coefficient and cost sharing coefficient.

With other parameters unchanged, we make $\rho_z = 2.5$, and take different cooperative income distribution mechanisms to observe the evolution path of the game system. Specifically, keep the cost sharing coefficient unchanged, and take $\gamma_1 = 0.3, \gamma_2 = 0.4, \gamma_3 = 0.3$; $\gamma_1 = 0.1, \gamma_2 = 0.4, \gamma_3 = 0.5$ and $\gamma_1 = 0.1, \gamma_2 = 0.2, \gamma_3 = 0.7$; keep the revenue sharing coefficient unchanged, take $\epsilon_1 = 0.3, \epsilon_2 = 0.4, \epsilon_3 = 0.3$; $\epsilon_1 = 0.1, \epsilon_2 = 0.4, \epsilon_3 = 0.5$ and $\epsilon_1 = 0.1, \epsilon_2 = 0.2, \epsilon_3 = 0.7$. The evolution path of the game system in different situations is shown in Figure 8.

When the cost sharing coefficient is constant, the revenue sharing coefficients of A and C are decreased by 0.2 and increased by 0.2 respectively, and it is found that the system still evolves to $(1,1,1)$. Because C gets more external income, the evolution speed becomes faster, while A and E have no obvious change in the evolution speed to 1, although one income remains the same and the other income decreases. If E's revenue sharing coefficient is reduced by 0.2 and C's revenue sharing coefficient is increased by 0.2, it can be found that C evolves to 1 faster, but A and E evolve to 1 slower. This is due to the mismatch between the external income distribution and the cost borne by the main body. When the revenue sharing coefficient is constant, we reduce the cost sharing coefficient of A by 0.2 and increase the cost sharing coefficient of C by 0.2. At this time, the information collaboration cost borne by C increases, and its evolution to 1 slows down, but the evolution speed of A and E to 1 is accelerated, and the evolution of the whole system to $(1,1,1)$ speeds up. We continue to reduce the cost-sharing coefficient of E by 0.2, and increase the cost-sharing coefficient of C by 0.2, and the whole system evolves to $(1,1,1)$ faster. This is because among the three participants, cold chain logistics service provider C has the highest initial cost and carbon emission cost, so the subject C can get the most direct benefits from participating in information collaboration. When the subject C bears more information collaboration costs, other subjects are more willing to participate in information collaboration.

To sum up, when the subjects involved in information collaboration distribute external income, they should consider the information collaboration cost borne by each subject, and the income distribution coefficient should be equal to the cost coefficient borne by each other. When sharing the cost, we should consider the

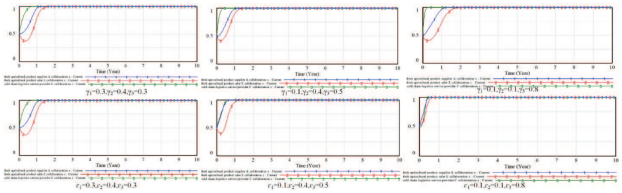

FIGURE 8. Evolution path of game system under different income and cost mechanisms.

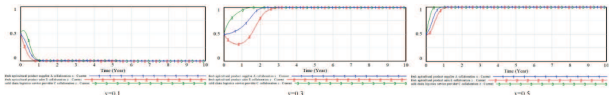

FIGURE 9. Evolution path of game system under different government cost subsidy proportions.

actual benefits of each subject's participation in information collaboration. The subject with the highest initial cost and carbon emission cost should share the cost more because it can get more efficiency gains. All in all, a reasonable and effective income distribution and cost sharing mechanism can effectively promote the evolution of the game system to (collaboration, collaboration, collaboration).

(5) Proportion of government cost subsidy.
With other parameters unchanged, let $v = 0.1$, $v = 0.3$ and $v = 0.5$, and observe the changes of the stability strategy of the system under different conditions. The evolution results of the three-party game system are shown in Figure 9. When the subsidy ratio of informatization cost provided by the government increases from 0.1 to 0.3, the stability strategy of the game system changes from $(0, 0, 0)$ to $(1, 1, 1)$. Continue to increase the proportion of government cost subsidy, and the system will evolve to $(1, 1, 1)$ faster. The more information cost subsidies given by the government, the less information collaboration costs each game player needs to pay, and the more game players tend to choose information collaboration strategies.

(6) Government supervision and government punishment.
With other parameters unchanged, we set different combinations of supervision and punishment, and observe the changes of the stability strategy of the system. Let $u = 0.8, T = 5$, $u = 1.5, T = 5$, $u = 0.8, T = 9$, $u = 1, T = 7$, $u = 1.5, T = 9$, and the evolution results of the three-party game system in different situations are shown in Figure 10. Keep the punishment unchanged, increase the supervision from 0.8 to 1.5, and the system will evolve from $(0, 0, 0)$ to $(1, 1, 1)$; keep the supervision unchanged, and increase the penalty from 5 to 9, and the system evolved from $(0, 0, 0)$ to $(1, 1, 1)$; when the supervision and punishment are improved at the same time, the system will evolve to $(1, 1, 1)$ faster. It can be concluded that the policy of "strict supervision and high punishment" is the most beneficial to promote the information coordination in the supply chain of fresh agricultural products. Of course, the policies of "moderate supervision and punishment", "low supervision and high punishment" and "high supervision and low punishment" are also effective.

(7) Carbon cap-and-trade policy.
With other parameters unchanged, we set different carbon trading policies: $\tau = 0.5, E_A = 10, E_E = 3, E_C = 15$; $\tau = 0.5, E_A = 0, E_E = 0, E_C = 0$; $\tau = 2, E_A = 10, E_E = 3, E_C = 15$, and the evolution result of the game system is shown in Figure 11. As can be seen from the figure, when the carbon trading price is constant, the carbon limit of each subject is reduced to 0, and the evolution direction of the system is the same as that under the initial carbon limit trading policy, all of which are $(0, 0, 0)$. When the carbon limit of the main body of the game is constant and the carbon transaction price rises to 2, the evolution direction of the game system changes from $(0, 0, 0)$ to $(1, 1, 1)$. That is to say, the carbon trading price has a greater

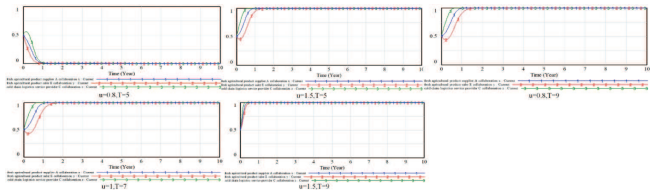

FIGURE 10. Evolution path of game system under different government supervision and punishment policies.

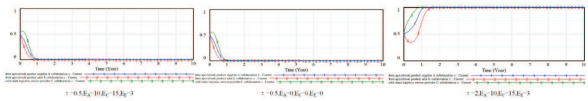

FIGURE 11. Evolution path of game system under different carbon cap-and-trade policies.

influence on the game players' information coordination strategy choice, while the total amount of carbon limit has no influence on the game players' coordination strategy choice.

6. Conclusion and outlook

6.1. Conclusion

On the premise of bounded rationality and under the background of the implementation of carbon cap-and-trade policy, this paper constructed an evolutionary game model of information collaboration in the fresh agricultural products supply chain, involving a fresh agricultural products supplier, a cold chain logistics service provider and a fresh agricultural products seller, and used system dynamics software to simulate and analyze the influence of initial intention and key parameters on the strategy selection of the three parties. Finally, we found some conclusions.

From the perspective of participants:

(1) When the initial willingness of the three participating parties exceeds a certain critical value, the system will evolve to the direction of collaboration, and when any two parties choose the information collaboration strategy, the other party will eventually choose the information collaboration strategy regardless of its initial willingness.

(2) When consumers have a high preference for freshness and the subject's collaborative planning ability is high, the more inclined the subject is to choose information collaboration strategies. When consumers do not have a preference for high quality, the collaborative strategy making ability cannot promote the participation of subjects in information collaboration. Only when consumers have a certain preference for high-quality consumption, that is, when they are willing to pay for fresh agricultural products with high quality and added value, can the formulation of collaborative strategies bring more external benefits and promote the selection of information collaborative strategies by the main body. In addition, it is worth noting that in the process of information collaboration of the fresh agricultural product supply chain, collaborative planning ability is a fundamental ability that subjects must possess.

(3) Under the established collaborative planning capability, the higher the initial cost of the subject, the more costs the subject reduces through information collaboration, and the higher its willingness to participate in information collaboration. Moreover, the subjects who get more direct benefits need to bear more information collaboration costs, and at the same time, they should share more information collaboration external

benefits. This mechanism of income distribution and cost sharing is reasonable and can promote the choice of information collaboration strategies of subjects.

From the perspective of government guidance:

(1) The cost subsidy given by the government, the government's policy of supervising and punishing the subject's hitchhiking will all affect the choice of the subject's coordination strategy. Specifically, cost subsidy can reduce the cost of information collaboration among subjects, which has a positive incentive for subjects to participate in information collaboration; effective supervision can reduce subjects' speculative free-riding behavior, protect the security of information sharing, and promote the choice of information collaboration strategies, and the combination of high supervision and high punishment is the most effective.
(2) The higher the price of carbon emission trading is, the more likely the subject is to choose the information coordination strategy, but the carbon quota has little impact on the subject's strategy choice. This is because the higher the price of carbon emission trading, the greater the marginal revenue of carbon emission reduction obtained by the subject when the carbon emission reduction brought by the subject's participation in information collaboration is fixed. Specifically, When the initial carbon emissions of the subject are higher than the carbon quota, the subject needs to purchase carbon emission quota in the carbon emission trading market. Information collaboration can reduce the carbon emissions of the subject, reduce the carbon emissions that the subject needs to purchase, save the carbon purchase cost, and even make the overall carbon emissions lower than the carbon limit, so that the subject can sell the carbon emissions to obtain carbon emission trading revenue. At this point, the higher the price of carbon emission trading, the more the cost saved or income obtained by the subject, and the more inclined the subject is to choose the information coordination strategy. When the initial carbon emissions of the subject are lower than the carbon limit, the subject can further reduce carbon emissions through information collaboration, and more surplus carbon emissions can be sold. The higher the carbon emission trading price, the higher the carbon emission trading income, the more inclined the subject is to choose information collaboration strategy.

Based on the above conclusions, in order to encourage fresh agricultural products supply chain subjects to participate in information collaboration, so as to reduce the carbon emissions of fresh agricultural products industry, ensure the quality of fresh agricultural products consumption and promote the industrialization development of fresh agricultural products, we can draw the following management enlightenment.

From the perspective of participants: On the one hand, it is necessary to strengthen the training of professionals and managers, first improve the ability of collaborative planning, and then expand their collaborative strategy making ability on the basis of having the ability of collaborative planning. On the other hand, for the subject with high initial cost and carbon transaction cost, information collaboration strategy should be selected. Because this type of subject can obtain higher direct benefits of information collaboration in the fresh agricultural product supply chain, it needs to bear more information collaboration costs, but it should also share more external benefits of information collaboration.

From the government's perspective: First, the government should encourage colleges and universities to cultivate fresh agricultural product supply chain professionals, and use government think tanks to provide professional knowledge training for participants in information collaboration. On the one hand, efforts should be made to improve the collaborative planning capability of the main body, including the collaborative management between the production of fresh agricultural products, cold chain logistics, and sales of fresh agricultural products; On the other hand, efforts should be made to improve the collaborative strategy formulation ability of the main body in the fresh agricultural product supply chain, including product strategy formulation ability, product innovation strategy formulation ability, quality improvement strategy formulation ability, brand promotion strategy formulation ability, etc. Second, create a benign market consumption atmosphere, strengthen consumers' requirements and preferences for freshness and high quality of fresh agricultural products, and create more external benefits for the supply chain information collaboration of fresh agricultural products. Third, the government should give appropriate information construction cost subsidies to the main body, strengthen the supervision and punishment of free riding, and accelerate the implementation of carbon limit trading policy

in the field of fresh agricultural product supply chain. In particular, we should focus on the macro-control of carbon emission trading prices.

6.2. Outlook

In addition to fresh agricultural product suppliers, fresh agricultural product sellers and cold chain logistics service providers, financial institutions also have a greater impact on the operation of the low-carbon supply chain. In the future, we will consider the role of green finance in carbon emission trading and carbon emissions of the fresh agricultural product supply chain, and conduct further research on the information collaboration of the fresh agricultural product supply chain.

Appendix A.

Proof of the stability of equilibrium points

According to the dynamic replication equation, a three-dimensional dynamic system can be obtained, and the Jacobi matrix of the system is:

$$J = \begin{pmatrix} \partial F(x)/\partial x & \partial F(x)/\partial y & \partial F(x)/\partial z \\ \partial F(y)/\partial x & \partial F(y)/\partial y & \partial F(y)/\partial z \\ \partial F(z)/\partial x & \partial F(z)/\partial y & \partial F(z)/\partial z \end{pmatrix} = \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{pmatrix}$$

$$\begin{aligned}
b_{11} &= (1-2x)(yz(\alpha\rho_z\theta_z C_A(1+\tau e) + \gamma_1(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) \\
&\quad - (1+\tau e)\alpha w_A\theta_z C_A) + (y+z-yz)uT - \epsilon_1(1-v)C_{zI}) \\
b_{12} &= x(1-x)(z(\alpha\rho_z\theta_z C_A(1+\tau e) + \gamma_1(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) \\
&\quad - (1+\tau e)\alpha w_A\theta_z C_A) + (1-z)uT) \\
b_{13} &= x(1-x)[y(\alpha\rho_z\theta_z C_A(1+\tau e) + \gamma_1(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) \\
&\quad - (1+\tau e)\alpha w_A\theta_z C_A) + (1-y)uT) \\
b_{21} &= y(1-y)(z(\alpha\rho_z\theta_z C_E(1+\tau e) + \gamma_2(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) \\
&\quad - (1+\tau e)\alpha w_E\theta_z C_E) + (1-z)uT) \\
b_{22} &= (1-2y)(xz(\alpha\rho_z\theta_z C_E(1+\tau e) + \gamma_2(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) \\
&\quad - (1+\tau e)\alpha w_E\theta_z C_E) + (x+z-xz)uT - \epsilon_2(1-v)C_{zI}) \\
b_{23} &= y(1-y)(x(\alpha\rho_z\theta_z C_E(1+\tau e) + \gamma_2(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) \\
&\quad - (1+\tau e)\alpha w_E\theta_z C_E) + (1-x)uT) \\
b_{31} &= z(1-z)(y(\alpha\rho_z\theta_z C_C(1+\tau e) + \gamma_3(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) \\
&\quad - (1+\tau e)\alpha w_C\theta_z C_C) + (1-y)uT) \\
b_{32} &= z(1-z)(x(\alpha\rho_z\theta_z C_C(1+\tau e) + \gamma_3(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) \\
&\quad - (1+\tau e)\alpha w_C\theta_z C_C) + (1-x)uT) \\
b_{33} &= (1-2z)(xy(\alpha\rho_z\theta_z C_C(1+\tau e) + \gamma_3(\mu_1\rho_z\theta_z\alpha Q_1 + \mu_2\phi_z\theta_z) \\
&\quad - (1+\tau e)\alpha w_C\theta_z C_C) - \epsilon_3(1-v)C_{zI} + (x+y-xy)uT).
\end{aligned}$$

According to Friedman's evolutionary game theory, the stable point must be strictly in the Nash equilibrium of pure strategy. Let $F(x)$, $F(y)$, and $F(z)$ be equal to zero, eight local equilibrium points can be obtained as $E_1(0,0,0)$, $E_2(0,0,1)$, $E_3(0,1,0)$, $E_4(0,1,1)$, $E_5(1,0,0)$, $E_6(1,1,0)$, $E_7(1,0,1)$, $E_8(1,1,1)$, respectively. Further, we judge the stability of the eight equilibrium points.

According to the above formula, eigenvalues of each local equilibrium point can be calculated, as shown in Table A.1.

TABLE A.1. Eigenvalues of local equilibrium points.

Equilibrium points	Eigenvalues		
	λ_1	λ_2	λ_3
$E_1(0,0,0)$	$-\epsilon_1(1-v)C_{zI}$	$-\epsilon_2(1-v)C_{zI}$	$-\epsilon_3(1-v)C_{zI}$
$E_2(0,0,1)$	$uT-\epsilon_1(1-v)C_{zI}$	$uT-\epsilon_2(1-v)C_{zI}$	$-\epsilon_3(1-v)C_{zI}$
$E_3(0,1,0)$	$uT-\epsilon_1(1-v)C_{zI}$	$\epsilon_2(1-v)C_{zI}$	$uT-\epsilon_3(1-v)C_{zI}$
$E_4(0,1,1)$	$\alpha\theta_z C_A(1+\tau e)(\rho_z-w_A)$ $+\gamma_1(\mu_1\rho_z\theta_z\alpha Q_1+\mu_2\phi_z\theta_z)$ $+uT-\epsilon_1(1-v)C_{zI}$	$\epsilon_2(1-v)C_{zI}-uT$	$\epsilon_3(1-v)C_{zI}-uT$
$E_5(1,0,0)$	$\epsilon_1(1-v)C_{zI}$	$uT-\epsilon_2(1-v)C_{zI}$	$uT-\epsilon_3(1-v)C_{zI}$
$E_6(1,1,0)$	$\epsilon_1(1-v)C_{zI}-uT$	$\epsilon_2(1-v)C_{zI}-uT$	$\alpha\theta_z C_C(1+\tau e)(\rho_z-w_C)$ $+\gamma_3(\mu_1\rho_z\theta_z\alpha Q_1+\mu_2\phi_z\theta_z)$ $+uT-\epsilon_3(1-v)C_{zI}$
$E_7(1,0,1)$	$\epsilon_1(1-v)C_{zI}-uT$	$\alpha\theta_z C_E(1+\tau e)(\rho_z-w_E)$ $+\gamma_2(\mu_1\rho_z\theta_z\alpha Q_1+\mu_2\phi_z\theta_z)$ $+uT-\epsilon_2(1-v)C_{zI}$	$\epsilon_3(1-v)C_{zI}-uT$
$E_8(1,1,1)$	$-(\alpha\theta_z C_A(1+\tau e)(\rho_z-w_A)$ $+\gamma_1(\mu_1\rho_z\theta_z\alpha Q_1+\mu_2\phi_z\theta_z)$ $+uT-\epsilon_1(1-v)C_{zI})$	$-(\alpha\theta_z C_E(1+\tau e)(\rho_z-w_E)$ $+\gamma_2(\mu_1\rho_z\theta_z\alpha Q_1+\mu_2\phi_z\theta_z)$ $+uT-\epsilon_2(1-v)C_{zI})$	$-(\alpha\theta_z C_C(1+\tau e)(\rho_z-w_C)$ $+\gamma_3(\mu_1\rho_z\theta_z\alpha Q_1+\mu_2\phi_z\theta_z)$ $+uT-\epsilon_3(1-v)C_{zI})$

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