sustainability

Article

The Collaboration Mechanism of Agricultural Product Supply Chain Dominated by Farmer Cooperatives

Yujia Huo [1], Jiali Wang [2], Xiangyu Guo [1,*] and Yang Xu [1]

[1] College of Economics and Management, Northeast Agricultural University, Harbin 150030, China; 18245115097@163.com (Y.H.); 13244616535@163.com (Y.X.)
[2] College of Engineering, Northeast Agricultural University, Harbin 150030, China; wjl-lily@163.com
* Correspondence: guoxy@neau.edu.cn; Tel.: +86-0451-8713-2132

Abstract: Problems such as the reduction of the added value of agricultural products and the interruption of the supply of agricultural products caused by the unstable collaborative relationship have seriously hindered the high-quality development of the agricultural product supply chain. Promoting the stable collaboration in the agricultural product supply chain is an urgent problem. Considering the characteristic demand of consumers for agricultural products, this paper takes the supply chain mainly operating characteristic agricultural products and dominated by farmer cooperatives as the research object and constructs a tripartite evolutionary game model of farmer cooperatives, manufacturers, and retailers. We study the supply chain collaboration mechanism from the main strategy choice and the specific factors affecting its strategy choice. The results show that farmer cooperatives implement a strict supervision strategy and increase the reward and punishment to promote the collaboration in the supply chain, but the increase in supervision cost is not conducive to the income of farmer cooperatives. In the case of loose supervision, the difference between the additional income and the collaboration input is higher than the "free-rider" income obtained when adopting a non-collaboration strategy, which is conducive to its evolution towards collaboration. In addition, increasing additional income, improving synergy coefficient, and reducing collaboration input and "free-rider" income will increase the probability of the system evolving to Pareto optimal, and accelerate the realization of comprehensive collaboration in the agricultural product supply chain dominated by farmer cooperatives. The research results provide a certain supplement to the related research on agricultural product supply chains in theory, and provide a reference for the comprehensive collaboration of the agricultural product supply chain dominated by farmer cooperatives in practice.

Keywords: agricultural product supply chain; collaboration mechanism; tripartite evolutionary game; farmer cooperatives; numerical simulation

check for updates

Citation: Huo, Y.; Wang, J.; Guo, X.; Xu, Y. The Collaboration Mechanism of Agricultural Product Supply Chain Dominated by Farmer Cooperatives. *Sustainability* **2022**, *14*, 5824. https://doi.org/10.3390/su14105824

Academic Editors: Dengsheng Lu, Guijun Yang, Langning Huo, Xiujuan Chai and Xiaoli Zhang

Received: 13 April 2022
Accepted: 9 May 2022
Published: 11 May 2022

1. Introduction

With the development and improvement of the global supply chain system, the node enterprises in the supply chain have shown a trend of cross-organizational collaboration. Enterprises gradually realize the importance of collaboration to the development of individuals and the overall supply chain [1–4]. In agricultural production, smallholders have unique advantages in production technology, but there are weaknesses in information and business skills. Therefore, smallholders are in a disadvantageous position in the agricultural product supply chain [5]. Farmer cooperatives are the result of smallholders' collaboration, which enables smallholders to participate in the competition of the international agricultural product supply chain and obtain more profits [6,7]. The key to the stable operation of the agricultural product supply chain is the collaboration between node enterprises [8,9]. Supply chain collaboration refers to the process in which multiple node enterprises in the supply chain cooperate closely towards common goals and interests [10]. Collaboration not only refers to the simple decision of collaboration or non-collaboration, but also includes cooperation based on trust and the stability of cooperative relationship in the process of collaboration. Essentially, collaboration is a necessary way to achieve common goals by reducing the individualistic and opportunistic behavior of participants [11,12]. The collaboration among agricultural enterprises aims at maximizing the overall benefits of the supply chain and can exert synergy effects among partners, and also can promote joint planning and the sharing of information [13,14]. The collaboration in the agricultural product supply chain is conducive to improving the quality of agricultural products [15], reducing carbon emissions [16], enhancing supply chain resilience [17–19], and ultimately improving enterprise performance and overall efficiency of the supply chain [20–23].

At present, with the improvement of residents' consumption level, the demand for agricultural products is gradually developing in the direction of high quality, characteristics, and diversification [24]. Farmer cooperatives produce characteristic agricultural products in short supply in the market due to their conditions that are difficult to replicate, such as land resource endowment, climate, and planting (breeding) technology [25]. In the supply chain of mainly operating characteristic agricultural products, the core competitiveness of the supply chain mainly depends on the characteristic agricultural products that are difficult to replicate [26]. With the enhancement of operational capacity and the expansion of their scale, such farmer cooperatives have gradually become the core enterprises in the supply chain [27]. Agricultural product supply chain collaboration dominated by farmer cooperatives means that, under the supervision of farmer cooperatives, the main subjects in the supply chain form a collaborative relationship based on complementary resources [28], implement joint planning and information sharing [13,14], jointly improve the quality of agricultural products and related services, and create the best benefit for the whole supply chain [15,20–22]. It is more necessary to provide consumers with excellent products and related services for this kind of agricultural product supply chain with farmer cooperatives as the core enterprise due to the characteristic products with high added value. Therefore, the collaboration of the main enterprises in the supply chain is more important to ensure the close connection between the production, processing, and sales, and the continuous and stable supply of high-quality and safe agricultural products [29]. However, the supply chain of agricultural products dominated by farmer cooperatives has not yet achieved comprehensive collaboration in reality [30]. The collaboration cycle between node enterprises is short, and the collaboration relationship is not close [31,32]. From the supply side, the failure of the participant in the supply chain to achieve collaboration results in the high added value of characteristic agricultural products cannot be reflected, so it is difficult for the participants to obtain the best benefits brought by collaboration [33,34]. From the demand side, it is difficult to ensure the continuous supply of high-quality agricultural products due to unstable collaborative relationships in the supply chain [35]. Therefore, establishing a stable collaborative relationship is a practical problem that needs to be solved urgently in the management of the agricultural product supply chain. What factors affect the collaborative behavior of the participants in the agricultural product supply chain dominated by farmer cooperatives? How can the participants in the supply chain achieve stable collaboration? Based on the above problems, the scientific question to be studied in this paper is how to promote the stable collaboration of the agricultural product supply chain dominated by farmer cooperatives. At present, the quantitative research on collaborative behavior is still limited [36]. This paper will use the tripartite evolutionary game method to further analyze the collaborative behavior of participants in the agricultural product supply chain dominated by farmer cooperatives and the related factors affecting collaboration, and propose a stable strategy to achieve comprehensive collaboration. The specific purposes of the research are as follows:

- Analyze the members' behavior of agricultural products supply chain dominated by farmer cooperatives and the possible reasons for failure to collaborate.

- Build a theoretical model and analyze the evolution process of tripartite strategy and evolutionarily stability strategy.
- Analyze how various factors affect the strategic decisions of members through numerical simulation.

The marginal contribution of this paper is mainly reflected in three aspects: First, taking the agricultural product supply chain collaboration mechanism dominated by farmer cooperatives as the research object, this paper expands the research perspective of supply chain collaboration. Second, this paper uses the tripartite evolutionary game method to analyze the dynamic evolution process of collaborative behavior under the changes of different factors, and further improves the research on the influencing factors of collaborative behavior. Third, the enlightenment obtained from the research results provides a practical reference for the realization of comprehensive collaboration in the ag-ricultural product supply chain dominated by farmer cooperatives.

The article is arranged as follows. Section 2 is a literature review. Section 3 discusses model assumption and construction. This part describes the specific parameters involved in the collaboration of the agricultural product supply chain dominated by farmer cooperatives and constructs a tripartite evolutionary game model of farmer cooperatives, manufacturers, and retailers. Section 4 includes the equilibrium analysis of the tripartite game model. Then, numerical simulations are carried out in Section 5 to discuss the effects of different parameters on the collaboration mechanism. Section 6 presents the conclusion and enlightenment. Section 7 discusses the limitations and further research.

2. Literature Review

At present, the research on supply chain collaboration mainly focuses on three aspects: the generation conditions of collaboration, how to improve the degree of collaboration, and the impact of collaboration on the operation of the supply chain.

Regarding the generation conditions of collaboration, Dora [37] proposed that geographical proximity and goal consistency are the catalysts for the formation of collaboration. Based on the resource-based theory and the resource-dependent theory, agricultural enterprises have different competitiveness due to their heterogeneous resources, and they are interdependent with the surrounding environment to obtain more resources at the same time, resulting in a collaborative relationship [28,38]. Moreover, the cooperative behavior of participants in the supply chain affects each other. The behavior of a member depends not only on its strategy, but also on the strategies of other members in the supply chain [39].

On how to improve the degree of collaboration, the interdependence of partners helps to increase the degree of collaboration, so as to improve supply chain efficiency [21,40]. However, the node enterprises in the supply chain will generate certain collaboration costs when they build and maintain collaborative relationships. Under different collaboration levels, the subjects will make different decisions to reduce their collaboration costs [41]. Fynes et al. [42] explored the maintenance of the collaborative relationships between partners from three trust dimensions: contractual trust, ability trust, and goodwill trust. The reliability of a node enterprise in the supply chain to other members and its perceived level of reliability will also affect the collaboration relationship between node enterprises [43,44]. Some scholars believed that in addition to trust, interdependence, power, collaborative value, and supervision also have a significant impact on collaborative relationships. Interdependence and power are the basis for the formation of collaboration and the important influencing factors for the formation of long-term stable collaborative relationships [45,46].

On the impact of collaboration on supply chain operation, the collaborative relationship between each node enterprise in the supply chain will affect the performance of the supply chain in three aspects: social, economic, and environmental [47]. Xie and Lei [48] constructed the evolution strategy of collaboration among manufacturers, suppliers, and distributors, and concluded that the increase in the collaborative innovation revenue coefficient is more conducive to maintaining the stability of the collaborative innovation system. Therefore, the main subject needs to collaborate to promote the stable development of the supply chain. Shen et al. [49] introduced collaborative forecasting into inventory replenishment decision-making and found that collaborative forecasting can reduce the operation costs of perishable agricultural product supply chains. Chen et al. [50] compared the supply chain profits under different modes and found that the supply chain profits under the collaborative mode were always higher than those under the non-collaborative mode. Pero [51] found that environmental collaboration among enterprises within the same supply chain can significantly promote the achievement of sustainability.

The evolutionary game method is widely used in the field of supply chain research, mainly used to study the strategic behavior between two or more stakeholders, and it is an effective quantitative method [52]. Evolutionary game theory expands the idea of classical game theory, assuming that the participants are limited rationally and adjust their strategies through continuous learning and imitation [53]. The evolutionary game method can better deal with the complexity of influencing factors, strategy evolution process, and stability strategies. Building a model to describe and monitor the evolution process of the system is conducive to the identification of supply chain problems [54]. Long et al. [55] constructed a tripartite evolutionary game model of green-sensitive governments, enterprises, and sellers, and concluded that green sensitivity has an important impact on stability strategies. Zhang et al. [14] constructed a two-level supply chain information collaboration evolutionary game model of suppliers and manufacturers, and obtained the formation mechanism of the SME consortium strategy. Chen and Jiang [50] constructed the operation mechanism model of supply chain enterprises from the perspective of an evolutionary game and verified the importance of collaboration in the creative product supply chain. Esmaeili et al. [56] used an evolutionary game model to investigate the long-term process of implementing multiple strategies of enterprises and select the most stable strategy.

The existing literature has studied the generation conditions of collaboration, how to improve the degree of collaboration, and the impact of collaboration on the operation of the supply chain. However, the existing research lacks the analysis of the collaboration mechanism of the agricultural product supply chain, and it is necessary to further consider how to promote the collaboration of the supply chain from the main strategy choice and the specific factors that affect the choice of the strategy. Using the evolutionary game method can effectively establish a collaboration strategy model to show the behavioral interaction between players, but there is little research on the tripartite evolutionary game of an agricultural product supply chain dominated by farmer cooperatives. Therefore, this paper uses a tripartite evolutionary game to deeply study the collaborative mechanism of the agricultural product supply chain dominated by farmer cooperatives.

3. Model Assumptions and Construction

The agricultural product supply chain dominated by farmer cooperatives is a community of interests composed of farmer cooperatives, manufacturers, and retailers. Each node enterprise is not a fully rational economic man, fails to see the best long-term income, and is prone to moral hazard problems such as short-term "free-rider" and credit default in the process of cooperation. Different strategy choices of node enterprises will seriously affect the stability of the collaboration relationship and the maximization of collaboration benefits. Therefore, it is of great significance to explore the strategy choice of different subjects and the mechanism affecting their strategy choice through the evolutionary game process of subjects in the supply chain, and how to achieve the stable state of the strategy choice of subjects in the supply chain. On the premise of considering the supervision of leading enterprises, this paper establishes a tripartite game model among farmer cooperatives, manufacturers, and retailers, and explores how the stakeholders interact to promote the agricultural product supply chain dominated by farmer cooperatives to realize collaborative cooperation. In order to build an evolutionary game model and analyze the stability of the strategies and equilibrium points of each subject, as well as various influencing factors, the following research assumptions are made:

Assumption 1. *The farmer cooperative is the core enterprise in the agricultural product supply chain and the first participant with initial revenue B_1. The manufacturer is the second participant with initial revenue $B_2$and the retailer is the third participant with initial revenue B_3, both of which are limited rational participants. There is information asymmetry in the supply chain. The strategy choice of each subject is dynamically adjusted with time and finally stabilizes at the optimal strategy.*

Assumption 2. *Due to the sense of responsibility of the core enterprises and the functional needs of the downstream enterprises, the farmer cooperatives will collaborate with other node enterprises in the supply chain to maximize the profits of the entire supply chain. Based on the theory of induced institutional change, the core enterprises in the supply chain have the right to supervise the collaboration behavior of the node enterprises in the supply chain. Therefore, the strategic space of the farmer cooperative is "strict supervision" or "loose supervision". The probability of choosing a strict supervision strategy is x, and the probability of choosing a loose supervision strategy is $(1-x)$, $x \in [0, 1]$.*

Assumption 3. *The strategic space of the manufacturer is "collaboration" or "non-collaboration". The probability of choosing collaboration is y, and the probability of choosing non-collaboration is $(1-y)$, $y \in [0, 1]$.The strategic space of the retailer is "collaboration" or "non-collaboration". The probability of choosing collaboration is z, and the probability of choosing non-collaboration is $(1-z)$, $z \in [0, 1]$. x, y, and z are all functions of time t; δ is the synergy coefficient. When subordinate enterprises all collaborate, δ will affect the additional benefits generated by the system collaboration due to synergy effects.*

Assumption 4. *If each node enterprise in the supply chain adopts the strategy of "collaboration", there will be a certain amount of collaboration input in the supply chain, and the proportion of collaboration input of farmer cooperatives, manufacturers, and retailers is* α_1, α_2 and α_3, respectively, and $\alpha_1 + \alpha_2 + \alpha_3 = 1$. *Collaboration between entities stems from the dependence on the partner's endowment and the additional benefits it brings. If one party does not collaborate, it will obtain "free-rider income" due to the collaboration of other entities. The additional income of farmer cooperatives from the collaboration of manufacturers is Q_{12}, and from the collaboration of retailers is Q_{13}. When manufacturers adopt the "collaboration" strategy, the additional income of manufacturers from the collaboration of farmer cooperatives is Q_{21}, and from the collaboration of retailers is Q_{23}. When manufacturers adopt the "non-collaboration" strategy, the free-rider income of manufacturers from the collaboration of farmer cooperatives is M_{21}, and from the collaboration of retailers is M_{23}. When retailers adopt the "collaboration" strategy, the additional income of retailers from the collaboration of farmer cooperatives is Q_{31}, and from the collaboration of manufacturers is Q_{32}. When retailers adopt the "non-collaboration" strategy, the free-rider income of retailers from the collaboration of farmer cooperatives is M_{31}, and from the collaboration of manufacturers is M_{32}.*

Assumption 5. *When farmer cooperatives adopt the "strict supervision" strategy, they develop a reward and punishment mechanism in the supply chain and bring their supervision costs C_1. The farmer cooperatives set the total reward amount for the subordinate enterprises that adopted the "collaboration" strategy as P, and the reward distribution for the manufacturers and retailers due to the collaboration was $\alpha_2 P$* and *$\alpha_3 P$, respectively. The farmer cooperative punishes the subordinate enterprises that adopt the "non-collaboration" strategy with an amount of L. When farmer cooperatives adopt the "loose supervision" strategy, the reward and punishment scheme is not implemented.*

Evolutionary game studies the dynamic process of group evolution and is a repetitive strategy interaction model [57]. Using the evolutionary game method needs to construct the mixed strategy payoff matrix of the game subject firstly, and then solve the game equilibrium point by replication dynamic equation for further analyzing the stability of evolutionarily equilibrium point [58]. In the actual operation of the agricultural product supply chain, the participants are in different market environments, and there is a certain information asymmetry. It is difficult for each subject to predict the possible actions that upstream and downstream enterprises may take. The strategy selection is mainly based on continuous learning and imitation, which meets the basic requirements of the evolutionary game method [59]. Therefore, this paper uses tripartite evolutionary game to deeply study the collaborative mechanism of the agricultural product supply chain dominated by farmer cooperatives.

According to the above assumptions, the mixed strategy game matrix of farmer cooperatives, manufacturers, and retailers is shown in Table 1.

Table 1. Tripartite mixed strategy game matrix.

Farmer Cooperative	Manufacturer Collaboration (y)	Manufacturer Non-Collaboration (1 − y)	Retailer
Strict supervision (x)	$B_1 - C_1 - \alpha_1 I + \delta(Q_{12} + Q_{13})$, $B_2 - \alpha_2 I + \alpha_2 P + \delta(Q_{21} + Q_{23})$, $B_3 - \alpha_3 I + \alpha_3 P + \delta(Q_{31} + Q_{32})$	$B_1 - C_1 - \alpha_1 I + L + Q_{13}$, $B_2 + M_{21} + M_{23} - L$, $B_3 - \alpha_3 I + Q_{31} + \alpha_3 P$	Collaboration (z)
	$B_1 - C_1 - \alpha_1 I + L + Q_{12}$, $B_2 - \alpha_2 I + Q_{21} + \alpha_2 P$, $B_3 + M_{31} + M_{32} - L$	$B_1 - C_1 - \alpha_1 I + 2L$, $B_2 + M_{21} - L$, $B_3 + M_{31} - L$	Non-Collaboration (1 − z)
Loose supervision (1 − x)	$B_1 - \alpha_1 I + \delta(Q_{12} + Q_{13})$, $B_2 - \alpha_2 I + \delta(Q_{21} + Q_{23})$, $B_3 - \alpha_3 I + \delta(Q_{31} + Q_{32})$	$B_1 - \alpha_1 I + Q_{13}$, $B_2 + M_{21} + M_{23}$, $B_3 - \alpha_3 I + Q_{31}$	Collaboration (z)
	$B_1 - \alpha_1 I + Q_{12}$, $B_2 - \alpha_2 I + Q_{21}$, $B_3 + M_{31} + M_{32}$	$B_1 - \alpha_1 I$, $B_2 + M_{21}$, $B_3 + M_{31}$	Non-Collaboration (1 − z)

4. Equilibrium Analysis of Tripartite Game Model

4.1. Expected Revenue Function and Replication Dynamic Equation

The expected revenue of the farmer cooperative's choice of "strict supervision" and "loose supervision" and the average expected revenue are π_{11}, π_{12}, and $\overline{\pi_1}$, respectively:

$$\begin{aligned}\pi_{11} = {} & (1-y)(1-z)(B_1 - C_1 - \alpha_1 I + 2L) + y(1-z)(B_1 - C_1 - \alpha_1 I + L + Q_{12}) \\ & +(1-y)z(B_1 - C_1 - \alpha_1 I + L + Q_{13}) \\ & +yz[B_1 - C_1 - \alpha_1 I + \delta(Q_{12} + Q_{13})]\end{aligned} \tag{1}$$

$$\begin{aligned}\pi_{12} = {} & (1-y)(1-z)(B_1 - \alpha_1 I) + y(1-z)(B_1 - \alpha_1 I + Q_{12}) \\ & +(1-y)z(B_1 - \alpha_1 I + Q_{13}) + yz[B_1 - \alpha_1 I + \delta(Q_{12} + Q_{13})]\end{aligned} \tag{2}$$

$$\overline{\pi_1} = x\pi_{11} + (1-x)\pi_{12} \tag{3}$$

According to the expected revenue function, the replication dynamic equation of the farmer cooperative is:

$$\begin{aligned}F(x) = \tfrac{dx}{dt} & = x(\pi_{11} - \overline{\pi_1}) = x(1-x)(\pi_{11} - \pi_{12}) \\ & = x(1-x)(zC_1 - yC_1 - C_1 + 2L - zL - yL)\end{aligned} \tag{4}$$

Let $F(x) = 0$, then $x = 0$, $x = 1$, $y = \frac{zC_1 - C_1 + 2L - zL}{C_1 + L}$.

If $y = \frac{zC_1 - C_1 + 2L - zL}{C_1 + L}$, then $F(x) \equiv 0$, which means it is in a stable state and the selection of strategy does not change with time.

If $y \neq \frac{zC_1 - C_1 + 2L - zL}{C_1 + L}$, then taking equilibrium points $x = 0$ and $x = 1$ into the $F'(x)$:

$$F'(x) = \frac{d(F(x))}{dx} \tag{5}$$

$$F'(x)\big|_{x=0} = zC_1 - yC_1 - C_1 + 2L - zL - yL \tag{6}$$

$$F'(x)\big|_{x=1} = -(zC_1 - yC_1 - C_1 + 2L - zL - yL) \tag{7}$$

While $y < \frac{zC_1 - C_1 + 2L - zL}{C_1 + L}$, we can get $F'(x)\big|_{x=0} > 0$ and $F'(x)\big|_{x=1} < 0$. Therefore, $x = 1$ is the evolutionarily stable strategy and the farmer cooperative chooses "strict supervision" at this time.

While $y > \frac{zC_1 - C_1 + 2L - zL}{C_1 + L}$, we can get $F'(x)\big|_{x=0} < 0$ and $F'(x)\big|_{x=1} > 0$. Therefore, $x = 0$ is the evolutionarily stable strategy and the farmer cooperative chooses "loose supervision" at this time.

The expected revenue of the manufacturer's choice "collaboration" and "non-collaboration" and the average expected revenue are π_{21}, π_{22}, $\overline{\pi_2}$, respectively:

$$\begin{aligned} \pi_{21} = (1-x)(1-z)(B_2 - \alpha_2 I + Q_{21}) + (1-x)z[B_2 - \alpha_2 I + \delta(Q_{21} + Q_{23})] \\ +x(1-z)(B_2 - \alpha_2 I + Q_{21} + \alpha_2 P) \\ +xz[B_2 - \alpha_2 I + \alpha_2 P + \delta(Q_{21} + Q_{23})] \end{aligned} \tag{8}$$

$$\begin{aligned} \pi_{22} = (1-x)(1-z)(B_2 + M_{21}) + (1-x)z(B_2 + M_{21} + M_{23}) \\ +x(1-z)(B_2 + M_{21} - L) + xz(B_2 + M_{21} + M_{23} - L) \end{aligned} \tag{9}$$

$$\overline{\pi_2} = x\pi_{21} + (1-x)\pi_{22} \tag{10}$$

According to the expected revenue function, the replication dynamic equation of the manufacturer is:

$$\begin{aligned} F(y) = \frac{dy}{dt} = y(\pi_{21} - \overline{\pi_2}) = y(1-y)(\pi_{21} - \pi_{22}) \\ = y(1-y)[z\delta(Q_{21} + Q_{23}) + Q_{21} + x\alpha_2 P + xL - \alpha_2 I - zQ_{21} - M_{21}] \end{aligned} \tag{11}$$

Let $F(y) = 0$, then $y = 0$, $y = 1$, $x = \frac{\alpha_2 I + zQ_{21} + M_{21} - z\delta(Q_{21} + Q_{23}) - Q_{21}}{\alpha_2 P + L}$.

If $x = \frac{\alpha_2 I + zQ_{21} + M_{21} - z\delta(Q_{21} + Q_{23}) - Q_{21}}{\alpha_2 P + L}$, then $F(y) \equiv 0$, which means it is in a stable state and the selection of strategy does not change with time.

If $x \neq \frac{\alpha_2 I + zQ_{21} + M_{21} - z\delta(Q_{21} + Q_{23}) - Q_{21}}{\alpha_2 P + L}$, then taking equilibrium points $y = 0$ and $y = 1$ into the $F'(y)$:

$$F'(y) = \frac{d(F(y))}{dy} \tag{12}$$

$$F'(y)\big|_{y=0} = z\delta(Q_{21} + Q_{23}) + Q_{21} + x\alpha_2 P + xL - \alpha_2 I - zQ_{21} - M_{21} \tag{13}$$

$$F'(y)\big|_{y=1} = -[z\delta(Q_{21} + Q_{23}) + Q_{21} + x\alpha_2 P + xL - \alpha_2 I - zQ_{21} - M_{21}] \tag{14}$$

While $x < \frac{\alpha_2 I + zQ_{21} + M_{21} - z\delta(Q_{21} + Q_{23}) - Q_{21}}{\alpha_2 P + L}$, we can get $F'(y)\big|_{y=0} < 0$ and $F'(y)\big|_{y=1} > 0$. Therefore, $y = 0$ is the evolutionarily stable strategy and the manufacturer chooses "non-collaboration" at this time.

While $x > \frac{\alpha_2 I + zQ_{21} + M_{21} - z\delta(Q_{21} + Q_{23}) - Q_{21}}{\alpha_2 P + L}$, we can get $F'(y)\big|_{y=0} > 0$ and $F'(y)\big|_{y=1} < 0$. Therefore, $y = 1$ is the evolutionarily stable strategy and the manufacturer chooses "collaboration" at this time.

The expected revenue of the retailer's choice "collaboration" and "non-collaboration" and the average expected revenue are π_{31}, π_{32}, $\overline{\pi_3}$, respectively:

$$\begin{aligned} \pi_{31} = (1-x)(1-y)(B_3 - \alpha_3 I + Q_{31}) + (1-x)y[B_3 - \alpha_3 I + \delta(Q_{31} + Q_{32})] \\ +x(1-y)(B_3 - \alpha_3 I + Q_{31} + \alpha_3 P) \\ +xz[B_3 - \alpha_3 I + \alpha_3 P + \delta(Q_{31} + Q_{32})] \end{aligned} \tag{15}$$

$$\begin{aligned} \pi_{32} = (1-x)(1-y)(B_3 + M_{31}) + (1-x)y(B_3 + M_{31} + M_{32}) \\ +x(1-y)(B_3 + M_{31} - L) + xy(B_3 + M_{31} + M_{32} - L) \end{aligned} \tag{16}$$

$$\overline{\pi_3} = z\pi_{31} + (1-z)\pi_{32} \tag{17}$$

According to the expected revenue function, the replication dynamic equation of the retailer is:

$$\begin{aligned}F(z) = \frac{dz}{dt} = z(\pi_{31} - \overline{\pi_3}) = z(1-z)(\pi_{31} - \pi_{32}) \\ = z(1-z)\left[y\delta(Q_{31} + Q_{32}) + Q_{31} + x\alpha_3 P + xL - \alpha_3 I - yQ_{31} - M_{31}\right]\end{aligned} \tag{18}$$

Let $F(z) = 0$, then $z = 0$, $z = 1$, $x = \frac{\alpha_3 I + yQ_{31} + M_{31} - y\delta(Q_{31}+Q_{32}) - Q_{31}}{\alpha_3 P + L}$.

If $x = \frac{\alpha_3 I + yQ_{31} + M_{31} - y\delta(Q_{31}+Q_{32}) - Q_{31}}{\alpha_3 P + L}$, then $F(z) \equiv 0$, which means it is in a stable state and the selection of strategy does not change with time.

If $x \neq \frac{\alpha_3 I + yQ_{31} + M_{31} - y\delta(Q_{31}+Q_{32}) - Q_{31}}{\alpha_3 P + L}$, then taking equilibrium points $z = 0$ and $z = 1$ into the $F'(z)$:

$$F'(z) = \frac{d(F(z))}{dz} \tag{19}$$

$$F'(z)\big|_{z=0} = y\delta(Q_{31} + Q_{32}) + Q_{31} + x\alpha_3 P + xL - \alpha_3 I - yQ_{31} - M_{31} \tag{20}$$

$$F'(z)\big|_{z=1} = -\left[y\delta(Q_{31} + Q_{32}) + Q_{31} + x\alpha_3 P + xL - \alpha_3 I - yQ_{31} - M_{31}\right] \tag{21}$$

While $x < \frac{\alpha_3 I + yQ_{31} + M_{31} - y\delta(Q_{31}+Q_{32}) - Q_{31}}{\alpha_3 P + L}$, we can get $F'(z)\big|_{z=0} < 0$ and $F'(z)\big|_{z=1} > 0$. Therefore, $z = 0$ is the evolutionarily stable strategy and the retailer chooses "non-collaboration" at this time.

While $x > \frac{\alpha_3 I + yQ_{31} + M_{31} - y\delta(Q_{31}+Q_{32}) - Q_{31}}{\alpha_3 P + L}$, we can get $F'(z)\big|_{z=0} > 0$ and $F'(z)\big|_{z=1} < 0$. Therefore, $z = 1$ is the evolutionarily stable strategy and the retailer chooses "collaboration" at this time.

The above strategic analysis of the players shows that the decisions of farmer cooperatives, manufacturers, and retailers influence each other. In other words, the evolutionary steady state of farmer cooperatives is affected by the decisions of manufacturers and retailers, the evolutionary steady state of manufacturers is affected by the decisions of farmer cooperatives and retailers, and the evolutionary steady state of retailers is affected by the decisions of farmer cooperatives and manufacturers. Therefore, the decision-making of farmer cooperatives, manufacturers, and retailers is the result of the tripartite game.

4.2. Analysis of Evolutionarily Stability Strategy

A three-dimensional dynamical system can be obtained from the above replicated dynamic equations.

$$\begin{cases} \frac{dx}{dt} = x(1-x)(zC_1 - yC_1 - C_1 + 2L - zL - yL) \\ \frac{dy}{dt} = y(1-y)[z\delta(Q_{21} + Q_{23}) + Q_{21} + x\alpha_2 P + xL - \alpha_2 I - zQ_{21} - M_{21}] \\ \frac{dz}{dt} = z(1-z)[y\delta(Q_{31} + Q_{32}) + Q_{31} + x\alpha_3 P + xL - \alpha_3 I - yQ_{31} - M_{31}] \end{cases} \tag{22}$$

According to the method proposed by Friedman [57], the stability of the equilibrium point of the evolutionary game model can be judged by the Jacobian matrix. When the eigenvalues of the Jacobian matrix are all less than zero, the corresponding equilibrium point is the evolutionarily stability strategy (ESS) of the system, and the Jacobian matrix is written as J.

$$J = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix} = \begin{bmatrix} (1-2x)(zC_1 - yC_1 - C_1 + 2L - zL - yL) & x(1-x)(-C_1 - L) & x(1-x)(C_1 - L) \\ y(1-y)(\alpha_2 P + L) & (1-2y)[z\delta(Q_{21}+Q_{23}) + Q_{21} + x\alpha_2 P + xL - \alpha_2 I - zQ_{21} - M_{21}] & y(1-y)[\delta(Q_{21}+Q_{23}) - Q_{21}] \\ z(1-z)(\alpha_3 P + L) & z(1-z)[\delta(Q_{31}+Q_{32}) - Q_{31}] & (1-2z)[y\delta(Q_{31}+Q_{32}) + Q_{31} + x\alpha_3 P + xL - \alpha_3 I - yQ_{31} - M_{31}] \end{bmatrix} \tag{23}$$

Then, we can obtain the eigenvalues corresponding to pure strategy equilibrium points, as shown in Table 2. Observing Table 2, it can be seen that the λ_1 in $(0,0,1)$ and $(1,1,1)$ are positive values. Therefore, $(0,0,1)$ and $(1,1,1)$ cannot be asymptotically stable strategy. Next, we will discuss the following six equilibrium points.

(1) When $2L < C_1$, $Q_{21} - \alpha_2 I < M_{21}$, and $Q_{31} - \alpha_3 I < M_{31}$, the equilibrium $(0,0,0)$ is ESS. This shows that when the supervision cost of farmer cooperatives is higher than the penalty amount received from manufacturers and retailers, farmer cooperatives tend to "loose supervision". If the amount of penalty for subordinate enterprises increases, the sum of the two penalties is higher than the supervision cost, and the stability strategy changes. If the difference between the additional income obtained by the manufacturers or the retailers from the farmer cooperative through collaboration and the collaboration cost is less than the "free-rider" income obtained from the farmer cooperative without the collaboration, then the two will tend to "non-collaboration". The evolution strategy is shown in Figure 3.

(2) When $1/2L < C_1$, $Q_{21} - \alpha_2 I > M_{21}$, and $\delta(Q_{31} + Q_{32}) - \alpha_3 I < M_{31}$, the equilibrium $(0,1,0)$ is ESS. This shows that when the supervision cost of farmer cooperatives is higher than half of the penalty amount of "non-collaboration" for manufacturers or retailers, then farmer cooperatives tend to "loose supervision". If the difference between the additional income obtained from the farmer cooperatives and the collaboration input is higher than the "free-rider" income obtained from the farmer cooperatives, the manufacturers will choose the "collaboration" strategy. If the difference between the sum of the additional income obtained from the farmer cooperatives and the manufacturers and the collaboration input is less than the "free-rider" income from the farmer cooperatives for the retailers that do not collaborate, then the retailers will choose the "non-collaboration" strategy. The evolution strategy is shown in Figure 4.

(3) When $\delta(Q_{21} + Q_{23}) - \alpha_2 I > M_{21}$, and $\delta(Q_{31} + Q_{32}) - \alpha_3 I > M_{31}$, the equilibrium $(0,1,1)$ is ESS. In this case, farmer cooperatives tend to "loose supervision". If the manufacturers collaborate with farmer cooperatives and retailers, and the difference between the sum of the additional income obtained from them and the collaboration input is higher than the "free-rider" income obtained by the manufacturers without collaboration, then the manufacturers choose the strategy of "collaboration". If the retailers collaborate with farmer cooperatives and manufacturers, and the difference between the sum of the additional income obtained from farmer cooperatives and manufacturers and the collaboration input is higher than the "free-rider" income obtained without adopting the collaboration strategy, the retailers will choose the "collaboration" strategy. The evolution strategy is shown in Figure 1.

(4) When $2L < C_1$, $\alpha_2 P + Q_{21} - \alpha_2 I < M_{21} - L$, and $\alpha_3 P + Q_{31} - \alpha_3 I < M_{31} - L$, the equilibrium $(1,0,0)$ is ESS. This shows that when the supervision cost of farmer cooperatives is lower than the penalty amount received from manufacturers and retailers, farmer cooperatives tend to adopt the "strict supervision". The net income obtained when manufacturers adopt the "collaboration" strategy is less than the net income obtained without the "collaboration" strategy, then the manufacturers adopt the "non-collaboration" strategy. The net income obtained when manufacturers adopt the "collaboration" strategy means the difference between the reward distribution obtained due to the collaboration adding the additional income obtained from the collaborative farmer cooperatives and the collaboration input of the manufacturers. The net income obtained without the "collaboration" strategy means the difference between the "free-rider" income and the penalty amount. The net income obtained when retailers adopt the "collaboration" strategy is less than the net income obtained without the "collaboration" strategy, and then the retailers adopt the "non-collaboration" strategy. The net income obtained when retailers adopt the "collaboration" strategy means the difference between the reward distribution obtained due to the collaboration adding the additional income obtained from the collaborative farmer cooperatives and the collaboration input of the retailers. The evolution strategy is shown in Figure 5.

(5) When $1/2L > C_1$, $\alpha_2 P + Q_{21} - \alpha_2 I > M_{21} - L$, and $\alpha_3 P + \delta(Q_{31} + Q_{32}) - \alpha_3 I < M_{31} - L$, the equilibrium $(1, 1, 0)$ is ESS. This shows that when the supervision cost of farmer cooperatives is less than half of the penalty amount received from retailers, farmer cooperatives tend to the "strict supervision". The net income obtained when manufacturers adopt the "collaboration" strategy is higher than the net income obtained without the "collaboration" strategy, then the manufacturers adopt the "collaboration" strategy. The net income obtained when manufacturers adopt the "collaboration" strategy means the difference between the reward distribution obtained due to the collaboration adding the additional income obtained from the collaborative farmer cooperatives and the collaboration input of the manufacturers. The net income obtained without the "collaboration" strategy means the difference between the "free-rider" income and the penalty amount. The net income obtained when retailers adopt the "collaboration" strategy is less than the net income obtained without the "collaboration" strategy, and then the retailers adopt the "non-collaboration" strategy. The net income obtained when retailers adopt the "collaboration" strategy means the difference between the reward distribution obtained due to the collaboration adding the additional income obtained from the collaborative farmer cooperatives and manufacturers and the collaboration input of the retailers. The evolution strategy is shown in Figure 6.

(6) When $\alpha_2 P + \delta(Q_{21} + Q_{23}) - \alpha_2 I < M_{21} - L$, and $\alpha_3 P + Q_{31} - \alpha_3 I > M_{31}$, the equilibrium $(1, 0, 1)$ is ESS. In this case, farmer cooperatives tend to choose the "strict supervision". The net income obtained when manufacturers adopt the "collaboration" strategy is less than the net income obtained without the "collaboration" strategy, then the manufacturers adopt the "non-collaboration" strategy. The net income obtained when manufacturers adopt the "collaboration" strategy means the difference between the reward distribution obtained due to the collaboration adding the additional income obtained from the collaborative farmer cooperatives and retailers and the collaboration input of the manufacturers. The net income obtained without the "collaboration" strategy means the difference between the "free-rider" income and the penalty amount. The net income obtained when retailers adopt the "collaboration" strategy is higher than the "free-rider" income without the "collaboration" strategy, then the retailers adopt the "collaboration" strategy. The net income obtained when retailers adopt the "collaboration" strategy means the difference between the reward distribution obtained due to the collaboration adding the additional income obtained from the collaborative farmer cooperatives and the collaboration input of the retailers. The evolution strategy is shown in Figure 2.

Table 2. The pure strategy equilibrium points and eigenvalues.

Equilibrium Points	Eigenvalues		
	λ_1	λ_2	λ_3
$(0,0,0)$	$2L - C_1$	$Q_{21} - \alpha_2 I - M_{21}$	$Q_{31} - \alpha_3 I - M_{31}$
$(0,1,0)$	$L - 2C_1$	$\alpha_2 I - Q_{21} + M_{21}$	$\delta(Q_{31} + Q_{32}) - \alpha_3 I - M_{31}$
$(0,0,1)$	L	$\delta(Q_{21} + Q_{23}) - M_{21} - \alpha_2 I$	$\alpha_3 I + M_{31} - Q_{31}$
$(0,1,1)$	$-C_1$	$\alpha_2 I + M_{21} - \delta(Q_{21} + Q_{23})$	$\alpha_3 I + M_{31} - \delta(Q_{31} + Q_{32})$
$(1,0,0)$	$C_1 - 2L$	$Q_{21} + \alpha_2 P + L - M_{21} - \alpha_2 I$	$Q_{31} + \alpha_3 P + L - M_{31} - \alpha_3 I$
$(1,1,0)$	$2C_1 - L$	$\alpha_2 I + M_{21} - Q_{21} - \alpha_2 P - L$	$\delta(Q_{31} + Q_{32}) + \alpha_3 P + L - \alpha_3 I - M_{31}$
$(1,0,1)$	$-L$	$\delta(Q_{21} + Q_{23}) + \alpha_2 P + L - \alpha_2 I - M_{21}$	$\alpha_3 I + M_{31} - Q_{31} - \alpha_3 P - L$
$(1,1,1)$	C_1	$\alpha_2 I + M_{21} - \delta(Q_{21} + Q_{23}) - \alpha_2 P - L$	$\alpha_3 I + M_{31} - \delta(Q_{31} + Q_{32}) - \alpha_3 P - L$

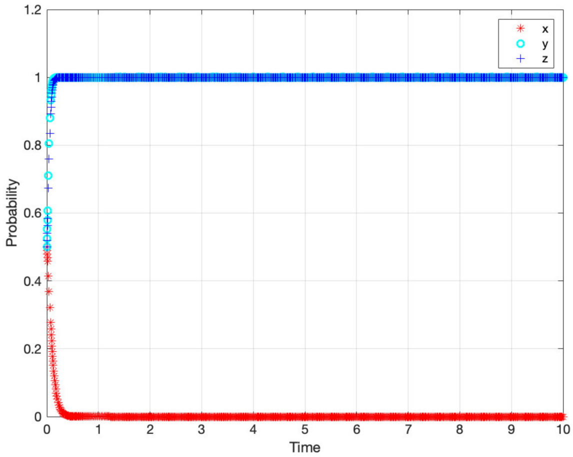


Figure 1. The evolutionarily stability strategy $(0, 1, 1)$.

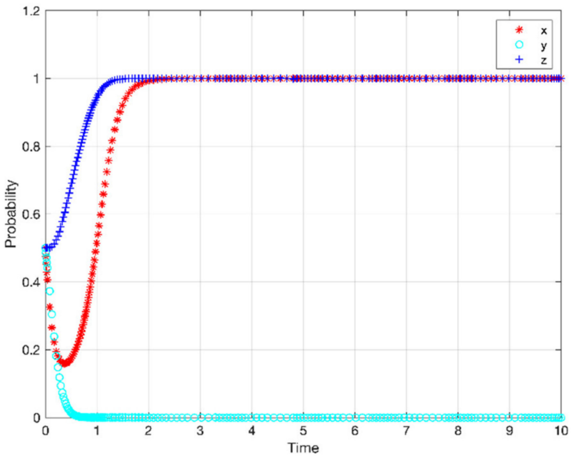


Figure 2. The evolutionarily stability strategy $(1, 0, 1)$.

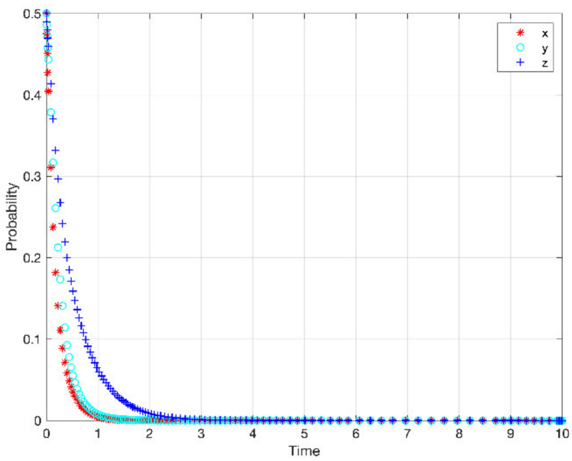


Figure 3. The evolutionarily stability strategy $(0, 0, 0)$.

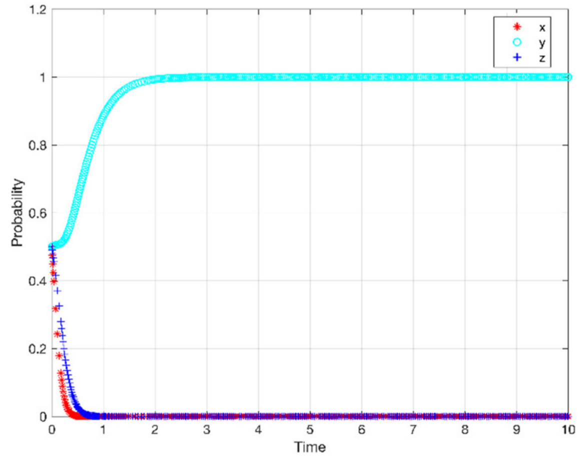


Figure 4. The evolutionarily stability strategy $(0, 1, 0)$.

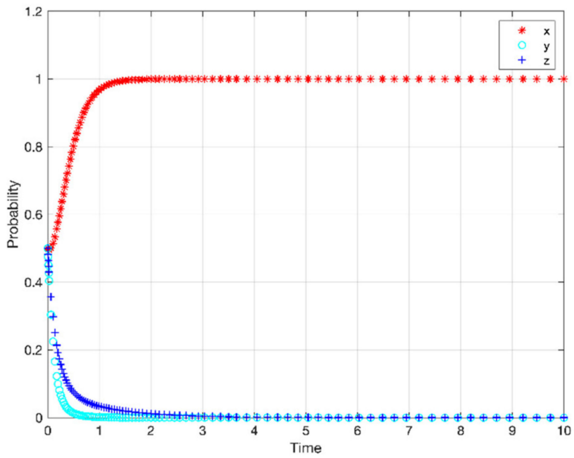


Figure 5. The evolutionarily stability strategy $(1, 0, 0)$.

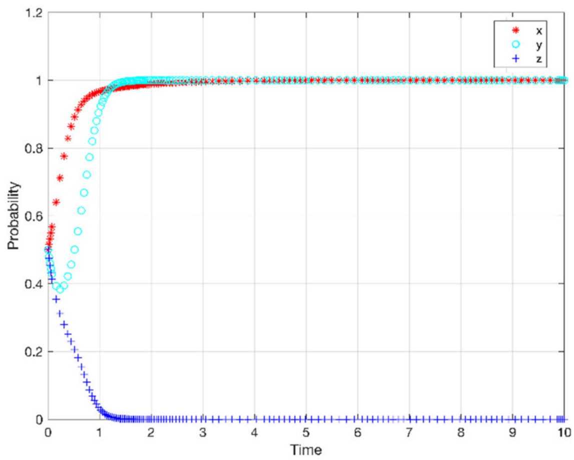


Figure 6. The evolutionarily stability strategy $(1, 1, 0)$.

5. Numerical Simulation and Discussion

In order to verify the evolutionary stability and more intuitively show the influence of different factors on the collaboration of game subjects, this paper takes the agricultural product supply chain dominated by "HX" Ecological Farmer Cooperative, namely "HX Ecological Farmer Cooperative + YH Rice Cooperative Association + HA Food Company" as an example for numerical simulation. "HX" Ecological Farmer Cooperative registered the "HX" rice trademark and obtained the certification of pollution-free agricultural products by the Ministry of Agriculture and Rural Affairs. "HX" Ecological Farmer Cooperative implements large-scale operation and standardized planting. It collaborates with the "YH" Rice Cooperative Association in the processing link. The "YH" Rice Cooperative Association carries out primary processing of rice, retains all natural nutrients in rice, and finally sells it to "HA" Food Company. In the whole supply chain, each participant always uses the brand of "HX", and the "HX" Ecological Farmer Cooperative has established a traceability system for products. If the "HX" brand is not used, there will be a fine. Through interviews with the relevant principals of each subject, we have a further understanding of the collaborative relationship. The average contract signing time is one to two years, which is a relatively short-term collaboration. Collaboration is based on complementary resources, and it can bring additional income to each other. At the same time, the cooperative supervises the extension of downstream brands. There will be defaults and speculation during this period, which may lead to the interruption of collaboration. The parameter value setting method mainly refers to the literatures [60–62]. We get the actual amount of initial revenue, additional income, supervision cost, reward and punishment through interviews. For parameters that are difficult to obtain direct values from interviewees, we refer to the literature [27], such as the synergy coefficient, and discuss with experts based on the actual situation about the "free-rider income". Then the simulation value is processed dimensionless. The specific parameter values do not represent the actual amount, but can represent the relative size of the parameters, so as to generalize the conclusion. The basic parameter values are as follows: $I = 20$, $\alpha_2 = 0.3$, $\alpha_3 = 0.2$, $C_1 = 15$, $P = 10$, $L = 5$, $Q_{21} = 13$, $Q_{23} = 18$, $Q_{31} = 11$, $Q_{32} = 13$, $M_{21} = 10$, $M_{31} = 9$, $\delta = 2$. The setting of parameter values satisfies the premise assumptions and conditions of the stable point (0, 1, 1). Based on the basic parameter values, the initial probability of each subject is (0.5, 0.5, 0.5). Then we analyze the impact of C_1, Q_{21}, Q_{31}, M_{21}, δ, P, L on the evolutionary game of the system.

5.1. The Impact of Supervision Cost on Evolutionary Game

Under the condition that the given conditions remain unchanged, in order to analyze the impact of supervision cost on the evolutionary game, C_1 takes the value of 5, 10, and 15, respectively. The simulation results are shown in Figure 7. In the process of system evolution to the stable point, the increase in supervision cost will accelerate the speed of system evolution, but the probability of farmer cooperatives adopting the "strict supervision" strategy will decrease, and the probability of manufacturers and retailers adopting the "collaboration" strategy will increase. If the supervision cost increases, farmer cooperatives strengthen supervision and invest more energy and funds, their original income may decline as a result, and so the enthusiasm for "strict supervision" will be reduced. On the other hand, the increase in supervision cost means that supervision tends to be strict, which plays a warning role for subordinate enterprises in the supply chain and will promote them to strengthen collaboration, and the probability of subordinate enterprises adopting the "collaboration" will increase. Therefore, strengthening supervision can promote collaboration in the supply chain, but we should comprehensively consider the increase in supervision cost, the amount of additional income created by collaboration, and the behavior preference of subordinate enterprises, so as to determine the supervision strategy.

5.2. The Impact of Additional Income on Evolutionary Game

Under the condition that the given conditions remain unchanged, in order to analyze the impact of additional income on the evolutionary game, Q_{21} and Q_{31} are set values of 0, 10, and 20, respectively. The simulation results are shown in Figure 8. When the additional income of manufacturers from collaboration with farmer cooperatives increases, the speed of system evolution to the stable point is accelerated, and the probability of manufacturers adopting the "collaboration" strategy will increase accordingly. When the additional income obtained by the retailers from the collaboration with farmer cooperatives increases, the probability of the retailers adopting the "collaboration" strategy will also increase. It can be seen from the figure that the collaboration probability of manufacturers and retailers is positively correlated. The collaboration probability is affected by different factors, but the collaboration behaviors of the two subjects promote each other.

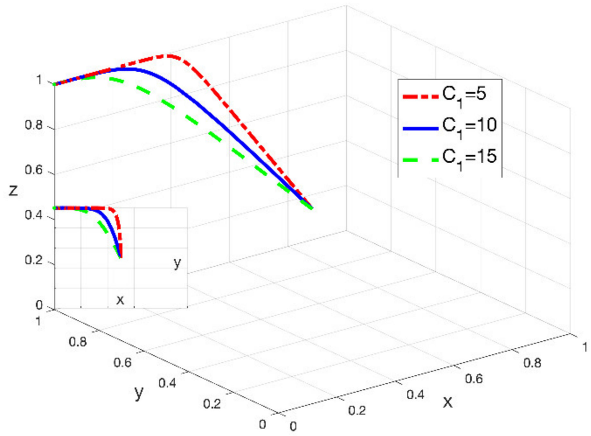
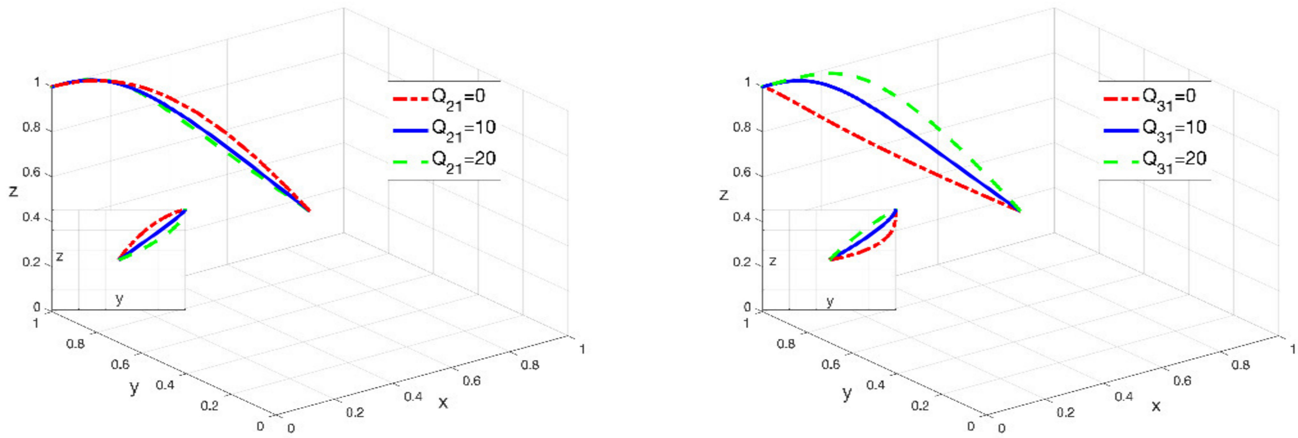


Figure 7. Effect of supervision cost on strategy.

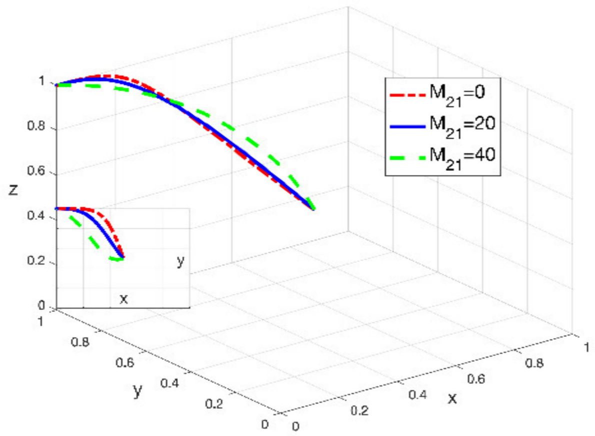


(**a**) (**b**)

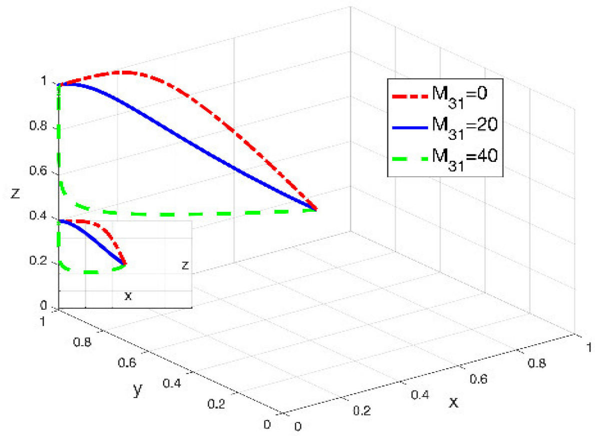
Figure 8. Effect of additional income on strategy. (**a**) The additional income Q_{21}; (**b**) the additional income Q_{31}.

5.3. The Impact of "Free-Rider" Income on Evolutionary Game

Under the condition that the given conditions remain unchanged, in order to analyze the impact of "free-rider" income on the evolutionary game, M_{21} and M_{31} are set values of 0, 20, and 40, respectively. The simulation results are shown in Figure 9. When the "free-rider" income obtained by the manufacturers due to the collaboration of farmer cooperatives decreases, the probability of the manufacturers adopting the "collaboration" strategy increases. When the "free-rider" income obtained by the retailers due to the collaboration of farmer cooperatives decreases, the probability of the retailers adopting the "collaboration" strategy increases. In the process of the system game, the greater the probability of farmer cooperatives adopting the "strict supervision" strategy, the lower the "free-rider" income obtained by the collaboration of farmer cooperatives. The "free-rider" behavior in the operation of the supply chain will bring a certain improvement to the individual income, but it will affect the overall operational efficiency. Continuously reducing the "free-rider" income and increasing the awareness of participants' collaboration is conducive to achieving a stable situation of supply chain coordination and collaboration.



(**a**)



(**b**)

Figure 9. Effect of "free-rider" income on strategy. (**a**) The additional income M_{21}; (**b**) the additional income M_{31}.

5.4. The Impact of Synergy Coefficient on Evolutionary Game

Under the condition that the given conditions remain unchanged, in order to analyze the impact of synergy coefficient on the evolutionary game, δ takes values of 1, 2, and 3, respectively. The simulation results are shown in Figure 10. In the process of the system tending to evolve and stabilize, the increase of the synergy coefficient will speed up the evolution of the system. The increase of the synergy coefficient means that the benefits brought by the collaboration to the supply chain will be enlarged, the probability of manufacturers and retailers choosing "collaboration" increases, and the "collaboration" behavior of subordinate enterprises promotes each other. Therefore, it is an important measure to implement synergy to improve the understanding of the positive synergy effect of each main body in the supply chain and to promote the system to generate a higher synergy coefficient.

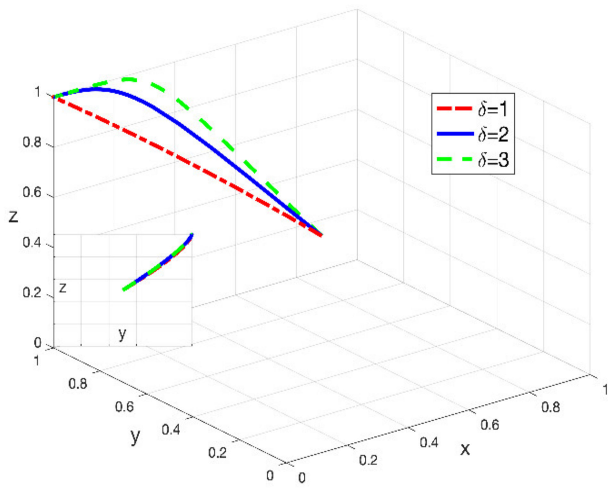
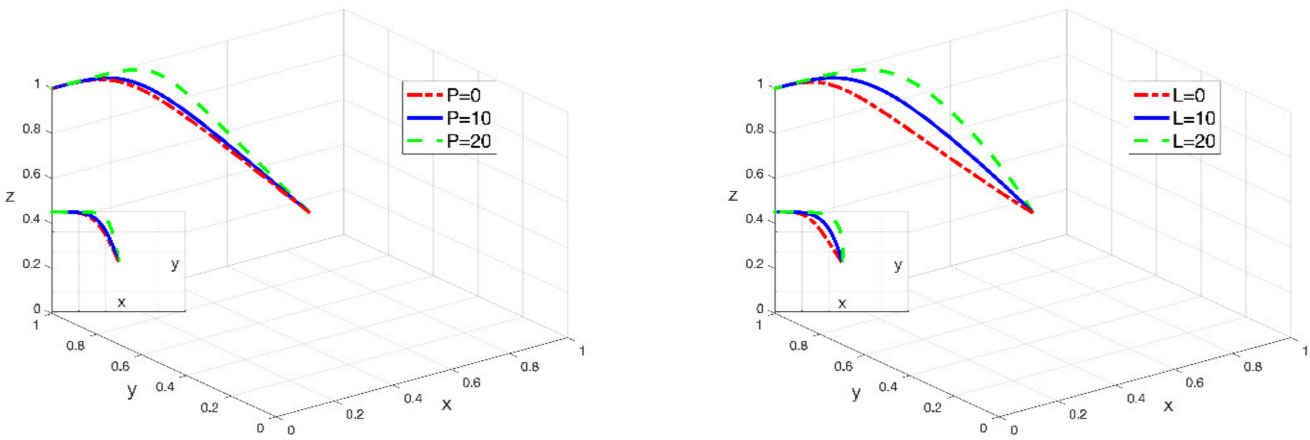


Figure 10. Effect of synergy coefficient on strategy.

5.5. The Impact of Reward and Punishment Mechanism on Evolutionary Game

Under the condition that the given conditions remain unchanged, in order to analyze the impact of the synergy coefficient on the evolutionary game, the reward amount P is set as 0, 50, and 100, respectively, and the punishment amount L is set as 0, 10 and 20, respectively. The simulation results are shown in Figure 11. The greater the reward and punishment for "collaboration" behavior, the faster the system tends to a stable state, and the higher the probability of collaboration in the supply chain. The reward and punishment system has a certain incentive effect on affiliated enterprises, but the degree of incentive is related to the additional income brought by collaboration and the difference in "free-rider" income. The formulation and implementation of a perfect reward and punishment system will inevitably increase the supervision cost of farmer cooperatives, so the above factors should be considered comprehensively.



(**a**) (**b**)

Figure 11. Effect of reward and punishment mechanism on strategy. (**a**) The reward amount P; (**b**) the punishment amount L.

The parameter values are evolved 50 times over the time from different initial strategy combinations, and the simulation results are shown in Figure 12. There is a unique stable equilibrium point (0, 1, 1) in the system, that is, the evolutionary and stable strategies of farmer cooperatives, manufacturers, and retailers are (loose supervision, collaboration, collaboration). The simulation results are consistent with the previous model analysis conclusions, which have practical guiding significance for the collaboration of the agricultural product supply chain led by farmer cooperatives.

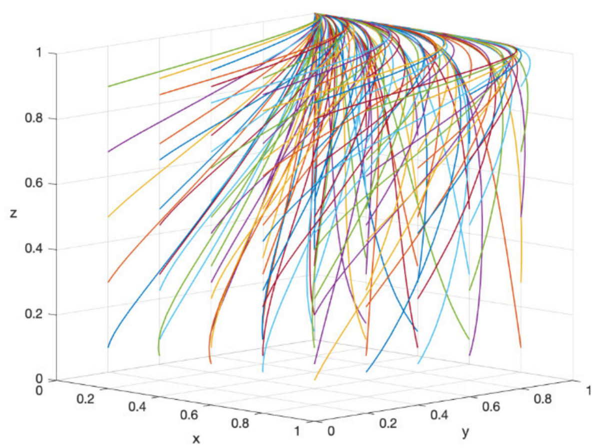


Figure 12. The result of the initial parameter evolving 50 times.

6. Conclusions and Enlightenment

In view of the unstable collaborative relationship in the supply chain, this paper studies the collaborative mechanism in the agricultural product supply chain dominated by farmer cooperatives by constructing the tripartite evolutionary game model of farmer cooperatives, manufacturers, and retailers. This paper analyzes the stability of the main strategy selection and the stability of the system equilibrium strategy combination, and verifies the impact of collaboration input, "free-rider" income, additional income, synergy coefficient, and reward and punishment mechanism on the system collaboration through numerical simulation analysis.

The results show that farmer cooperatives implement strict supervision strategies and increase the intensity of rewards and punishments, which is conducive to promoting collaboration in the supply chain, but the increase in supervision cost is not conducive to the income of farmer cooperatives. Therefore, farmer cooperatives tend towards the "loose supervision" strategy. In the case of loose supervision, the difference between the additional income obtained by subordinate enterprises and the collaboration input paid by themselves is higher than the "free-rider" income obtained without the strategy of collaboration, which is conducive to the evolution of subordinate enterprises in the supply chain to the direction of collaboration. There is an evolutionary stability strategy combination of the system at this time (loose supervision, collaboration, collaboration), which shows that under reasonable constraints, the operation state of the agricultural product supply chain will evolve towards the most efficient direction. In addition, the increase in additional income, reward and punishment, and synergy coefficient will improve the probability of system evolution to the Pareto optimal, and accelerate the realization of comprehensive collaboration of agricultural product supply chain dominated by farmer cooperatives. The increase of collaboration input and "free-rider" income will reduce the probability of realizing comprehensive collaboration. The matching of the additional income and reward distribution coefficient of collaboration with the proportion of collaboration is a necessary condition for the continuous collaboration of stakeholders, which is more conducive to achieving fair distribution and promoting the stable operation of the supply chain.

From the above conclusions, it can be seen that the agricultural product supply chain dominated by farmer cooperatives is not suitable for the strict supervision mode to achieve comprehensive collaboration. Farmer cooperatives adopt the strategy of loose supervision, which can better ensure the stable operation of the supply chain. Farmer cooperatives can enhance the dependence of subordinate enterprises by improving the degree of product characteristics and strengthening the brand effect. In addition, subordinate enterprises should reduce speculation, jointly plan with farmer cooperatives, establish an information sharing platform, improve the synergy coefficient, and create more profits for the whole supply chain. Finally, fairness is the key to maintaining a collaborative relationship. The income distribution and investment proportion in the supply chain should match, fully protect the rights and interests of the participants, and make the comprehensive collaboration state in the supply chain sustainable.

7. Limitations and Future Research

There are still some limitations in this study. First, the supply chain collaboration mechanism is a complex issue. This paper only studies the main influencing factors based on the behavior of agricultural product supply chain dominated by farmer cooperatives. In order to simplify the model, it fails to consider all the influencing factors. In addition, some values come from specific cases in the numerical simulation. Although the simulation results can verify the theoretical model, they still have a certain degree of subjectivity. Therefore, future research should comprehensively consider more practical factors in model construction, and increase the actual sample size in numerical simulation to make the conclusions more objective and scientific.

Author Contributions: Conceptualization, Y.H. and J.W.; methodology, Y.H. and J.W.; validation, X.G.; formal analysis, Y.H., X.G. and J.W.; investigation, Y.H., J.W. and Y.X.; writing—original draft preparation, Y.H.; writing—review and editing, Y.H., Y.X. and J.W.; supervision, X.G. and Y.X.; funding acquisition, J.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Social Science Fund of China, grant number 19BJY169, and "Four Batches" Talent Project of Cultural Famous Masters, grant number ZXB[2015]49.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the authors.

Acknowledgments: The authors are grateful for the patient review and helpful suggestions from the editor of this journal, as well as the anonymous referees.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Thoo, A.C.; Huam, H.T.; Zuraidah, S. Green Supply Chain Management, Environmental Collaboration and Sustainability Performance. *Procedia CIRP* **2015**, *26*, 695–699.
2. Rota, C.; Pugliese, P.; Hashem, S.; Zanasi, C. Assessing the level of collaboration in the egyptian organic and fair trade cotton chain. *J. Clean. Prod.* **2016**, *170*, 1665–1676. [CrossRef]
3. Schggl, J.P.; Fritz, M.M.C.; Baumgartner, R.J. Toward supply chain-wide sustainability assessment: A conceptual framework and an aggregation method to assess supply chain performance. *J. Clean. Prod.* **2016**, *131*, 822–835. [CrossRef]
4. Arora, A.; Arora, A.; Anyu, J.; McIntyre, J.R. Global Value Chains' Disaggregation through Supply Chain Collaboration, Market Turbulence, and Performance Outcomes. *Sustainability* **2021**, *13*, 4151. [CrossRef]
5. Serra, T.; Poli, E. Shadow prices of social capital in rural India, a nonparametric approach. *Eur. J. Oper. Res.* **2015**, *240*, 892–903. [CrossRef]
6. Stefan, G.; Rüdiger, H.; Stefan, S. Sustainable supply chain management in "Base of the Pyramid" food projects—A path to triple bottom line approaches for multinationals? *Int. Bus. Rev.* **2013**, *22*, 784–799.
7. Fayet, L.; Vermeulen, W.J.V. Supporting Smallholders to Access Sustainable Supply Chains: Lessons from the Indian Cotton Supply Chain. *Sustain. Dev.* **2014**, *22*, 289–310. [CrossRef]
8. Touboulic, A.; Walker, H. Love me, love me not: A nuanced view on collaboration in sustainable supply chains. *J. Purch. Supply Manag.* **2015**, *21*, 178–191. [CrossRef]
9. Hernandez, J.E.; Mortimer, M.; Panetto, H. Operations management and collaboration in agri-food supply chains. *Prod. Plan. Control* **2020**, *32*, 1163–1164. [CrossRef]
10. Cao, M.; Zhang, Q.Y. Supply chain collaboration: Impact on collaborative advantage and firm performance. *J. Oper. Manag.* **2011**, *29*, 163–180. [CrossRef]
11. Lozano, R. Collaboration as a pathway for sustainability. *Sustain. Dev.* **2007**, *15*, 370–381. [CrossRef]
12. Perez-Mesa, J.C.; Piedra-Munoz, L.; Galdeano-Gomez, E.; Giagnocavo, C. Management Strategies and Collaborative Relationships for Sustainability in the Agrifood Supply Chain. *Sustainability* **2021**, *13*, 749. [CrossRef]
13. Jraisat, L.; Gotsi, M. Drivers of information sharing and export performance in the jordanian agri-food export supply chain: A qualitative study. *Int. Market. Rev.* **2013**, *30*, 323–356. [CrossRef]
14. Zhang, Z.; Xue, Y.; Li, J.; Gong, L.; Wang, L. Supply chain logistics information collaboration strategy based on evolutionary game theory. *IEEE Access* **2020**, *8*, 46102–46120.
15. Stella, D.; Grammatoula, P.; George, S.; Samir, D. Does collaboration pay in agricultural supply chain? An empirical approach. *Int. J. Prod. Res.* **2018**, *56*, 4396–4417.
16. Ding, H.; Zhao, Q.; An, Z.; Tang, O. Collaborative mechanism of a sustainable supply chain with environmental constraints and carbon caps. *Int. J. Prod. Econ.* **2016**, *181*, 191–207. [CrossRef]
17. Whipple, J.M.; Dawn, R. Building supply chain collaboration: A typology of collaborative approaches. *Int. J. Logist. Manag.* **2007**, *18*, 174–196. [CrossRef]
18. Leat, P.; Revoredo-Giha, C. Risk and resilience in agri-food supply chains: The case of the ASDA PorkLink supply chain in Scotland. *Supply Chain Manag.* **2013**, *18*, 219–231. [CrossRef]
19. Umar, M.; Wilson, M. Supply Chain Resilience: Unleashing the Power of Collaboration in Disaster Management. *Sustainability* **2021**, *13*, 10573. [CrossRef]
20. Allaoui, H.; Guo, Y.H.; Sarkis, J. Decision support for collaboration planning in sustainable supply chains. *J. Clean. Prod.* **2019**, *229*, 761–774. [CrossRef]
21. Scholten, K.; Schilder, S. The role of collaboration in supply chain resilience. *Supply Chain Manag.* **2015**, *20*, 471–484. [CrossRef]
22. Grekova, K.; Calantone, R.J.; Bremmers, H.J.; Trienekens, J.H.; Omta, S. How environmental collaboration with suppliers and customers influences firm performance: Evidence from dutch food and beverage processors. *J. Clean. Prod.* **2016**, *112*, 1861–1871. [CrossRef]
23. Leon-Bravo, V.; Caniato, F.; Caridi, M.; Johnsen, T. Collaboration for Sustainability in the Food Supply Chain: A Multi-Stage Study in Italy. *Sustainability* **2017**, *9*, 1253. [CrossRef]
24. Yan, B.; Chen, X.X.; Cai, C.Y.; Guan, S.Y. Supply chain coordination of fresh agricultural products based on consumer behavior. *Comput. Oper. Res.* **2020**, *123*, 105038. [CrossRef]
25. Liu, J.; Li, C.; Li, S.Z. Agricultural Standardization Effect of Demonstration Cooperatives: An econometric Analysis Based on ESR Model. *J. Agrotech. Econ.* 2021; *in press*. (In Chinese). [CrossRef]

26. Yang, H.; Liu, K.F. A Study on Place Branding Strategy of Characteristic Agricultural Products in Xinjiang Based on Brand Ecosystem. *Ekoloji* **2018**, *27*, 1021–1028.
27. Wang, J.L.; Peng, X.; Du, Y.; Wang, F. A tripartite evolutionary game research on information sharing of the subjects of agricultural product supply chain with a farmer cooperative as the core enterprise. *Manag. Decis. Econ.* **2021**, *43*, 159–177. [CrossRef]
28. Sambasivan, M.; Siew-Phaik, L.; Mohamed, Z.A.; Leong, Y.C. Factors influencing strategic alliance outcomes in a manufacturing supply chain: Role of alliance motives, interdependence, asset specificity and relational capital. *Int. J. Prod. Econ.* **2013**, *141*, 339–351. [CrossRef]
29. Zi, W.C.; Zhou, J.Y.; Xu, H.L.; Li, G.D.; Lin, G. Preserving relational contract stability of fresh agricultural product supply chains. *J. Ind. Manag. Optim.* **2021**, *17*, 2505–2518. [CrossRef]
30. Wang, L.; Luo, J.L. Vegetable supply chain integration: The case of a trinity cooperative in China. *Int. Food Agribus. Manag. Rev.* **2019**, *22*, 767–780. [CrossRef]
31. Fu, S.L.; Zhan, Y.Z.; Ouyang, J.; Ding, Y.L.; Tan, K.H.; Fu, L.M. Power, supply chain integration and quality performance of agricultural products: Evidence from contract farming in China. *Prod. Plan. Control* **2020**, *32*, 1119–1135. [CrossRef]
32. Fu, S.L.; Li, Z.W.; Wang, B.; Han, Z.J.; Huo, B.F. Cooperative behavior between companies and contract farmers in Chinese agricultural supply chains: Relational antecedents and consequences. *Ind. Manag. Data Syst.* **2018**, *118*, 1033–1051. [CrossRef]
33. Heimeriks, K.H.; Schreiner, M. Relational quality, alliance capability, and alliance performance: An integrated framework. In *Enhancing Competences for Competitive Advantage*; Sanchez, R., Heene, A., Eds.; Emerald Group Publishing Limited: Bingley, UK, 2010; Volume 12, pp. 145–171.
34. Fischer, C.; Reynolds, N. Collaborative Advantage, Relational Risks and Sustainable Relationships: A Literature Review and Definition. In *Agri-Food Chain Relationships*; Fischer, C., Hartmann, M., Eds.; CAB International: London, UK, 2010; pp. 74–89.
35. Sun, Y.L.; Zhu, Z.Y.; Yang, H. Fairness Perception, Trust Perception, and Relationship Quality in Agricultural Supply Chains. *J. Food Qual.* **2021**, *2021*, 8817003. [CrossRef]
36. Bezuidenhout, C.N.; Bodhanya, S.; Brenchley, L. An analysis of collaboration in a sugarcane production and processing supply chain. *Br. Food J.* **2012**, *114*, 880–895. [CrossRef]
37. Dora, M. Collaboration in a circular economy: Learning from the farmers to reduce food waste. *J. Enterp. Inf. Manag.* **2019**, *33*, 769–789. [CrossRef]
38. Shin, N.; Park, S.H.; Park, S. Partnership-Based Supply Chain Collaboration: Impact on Commitment, Innovation, and Firm Performance. *Sustainability* **2019**, *11*, 449. [CrossRef]
39. Tabrizi, S.; Ghodsypour, S.H.; Ahmadi, A. Modelling three-echelon warm-water fish supply chain: A bi-level optimization approach under nash–cournot equilibrium. *Appl. Soft. Comput.* **2017**, *71*, 1035–1053. [CrossRef]
40. Aggarwal, S.; Srivastava, M.K. Towards a grounded view of collaboration in Indian agri-food supply chains. *Br. Food J.* **2016**, *118*, 1085–1106. [CrossRef]
41. Lozano, S.; Moreno, P.; Adenso-Díaz, B.; Algaba, E. Cooperative game theory approach to allocating benefits of horizontal cooperation. *Eur. J. Oper. Res.* **2013**, *229*, 444–452. [CrossRef]
42. Fynes, B.; Voss, C.; Búrca, S.D. The impact of supply chain relationship quality on quality performance. *Int. J. Prod. Econ.* **2005**, *96*, 339–354. [CrossRef]
43. Boer, H.; Gertsen, F.; Kaltoft, R.; Nielsen, J.S. Factors affecting the development of collaborative improvement with strategic suppliers. *Prod. Plan. Control* **2005**, *16*, 356–367. [CrossRef]
44. Hausman, A.; Johnston, W.J. The impact of coercive and non-coercive forms of influence on trust, commitment, and compliance in supply chains. *Ind. Mark. Manag.* **2010**, *39*, 519–526. [CrossRef]
45. Dania, W.; Xing, K.; Amer, Y. Collaboration behavioural factors for sustainable agri-food supply chains: A systematic review. *J. Clean. Prod.* **2018**, *186*, 851–864. [CrossRef]
46. Chen, X.; Wang, X.; Zhou, M. Firms' green R&D cooperation behaviour in a supply chain: Technological spillover, power and coordination. *Int. J. Prod. Econ.* **2019**, *218*, 118–134.
47. Hollos, D.; Blome, C.; Kai, F. Does sustainable supplier co-operation affect performance? Examining implications for the triple bottom line. *Int. J. Prod. Res.* **2012**, *50*, 2968–2986. [CrossRef]
48. Xie, J.P.; Lei, H.Y. Simulation study on the evolutionary game mechanism of collaborative innovation in supply chain enterprises and its influencing elements. *J. Math.* **2021**, *2021*, 8038672. [CrossRef]
49. Shen, D.; Lai, K.K.; Leung, S.C.H.; Liang, L. Modelling and analysis of inventory replenishment for perishable agricultural products with buyer-seller collaboration. *Int. J. Syst. Sci.* **2011**, *42*, 1207–1217. [CrossRef]
50. Chen, T.; Jiang, Y. Research on operating mechanism for creative products supply chain based on game theory. *Discret. Contin. Dyn. Syst. Ser. S* **2017**, *8*, 1103–1112. [CrossRef]
51. Pero, M.; Moretto, A.; Bottani, E.; Bigliardi, B. Environmental Collaboration for Sustainability in the Construction Industry: An Exploratory Study in Italy. *Sustainability* **2017**, *9*, 125. [CrossRef]
52. Barari, S.; Agarwal, G.; Zhang, W.J.; Mahanty, B.; Tiwari, M.K. A decision framework for the analysis of green supply chain contracts: An evolutionary game approach. *Expert Syst. Appl.* **2012**, *39*, 2965–2976. [CrossRef]
53. Helbing, D. Evolutionary Game Theory. In *Quantitative Sociodynamics*; Springer: Dordrecht, The Netherlands, 1995; Volume 31, pp. 227–254.

54. Ming, Y.; Grabot, B.; Houé, R. A typology of the situations of cooperation in supply chains. *Comput. Ind. Eng.* **2014**, *67*, 56–71. [CrossRef]
55. Long, Q.; Tao, X.; Shi, Y.; Zhang, S. Evolutionary game analysis among three green-sensitive parties in green supply chains. *IEEE Trans. Evol. Comput.* **2021**, *25*, 508–523. [CrossRef]
56. Esmaeili, M.; Allameh, G.; Tajvidi, T. Using game theory for analysing pricing models in closed-loop supply chain from short- and long-term perspectives. *Int. J. Prod. Res.* **2016**, *54*, 2152–2169. [CrossRef]
57. Friedman, D. Evolutionary game in economics. *Econometrica* **1991**, *59*, 637–666. [CrossRef]
58. Sun, S.M.; Yang, H.; Yang, G.H.; Pi, J.X. Evolutionary games and dynamics in public goods supply with repetitive actions. *Mathematics* **2021**, *9*, 1726. [CrossRef]
59. Hao, C.C.; Du, Q.; Huang, Y.D.; Shao, L.; Yan, Y.Q. Evolutionary Game Analysis on Knowledge-Sharing Behavior in the Construction Supply Chain. *Sustainability* **2019**, *9*, 5319. [CrossRef]
60. Li, B.Z.; Wang, X.; Su, Y.; Luo, X.F. Evolutionary Game Research on Collaborative Innovation of Supply Chain Enterprises from Different Strategic Emerging Industries in China. *Chin. J. Manag. Sci.* **2021**, *29*, 136–147. (In Chinese)
61. Ma, Z.Q.; Chen, J.J.; Tian, G.; Gong, Y.; Guo, B.H.; Cheng, F.X. Regulations on the corporate social irresponsibility in the supply chain under the multiparty game: Taking China's organic food supply chain as an example. *J. Clean. Prod.* **2021**, *317*, 128459. [CrossRef]
62. Zhang, H.; Su, X. The Applications and Complexity Analysis Based on Supply Chain Enterprises' Green Behaviors under Evolutionary Game Framework. *Sustainability* **2021**, *13*, 10987. [CrossRef]