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# Differential Game Analysis of Optimal Strategies and Cooperation in Omni-Channel Organic Agricultural Supply Chain

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**Abstract:** This paper aims to investigate the optimal strategies for both centralized and decentralized modes in a two-echelon omni-channel organic agricultural supply chain (OASC) which consists of one farmer cooperative and one online retailer. Furthermore, the contracts of cooperation between the members in OASC are discussed. Based on both theory differential game and bi-level programming, we utilize the Nerlove–Arrow model and Stackelberg model to examine five cases of decision modes for both agents in the OASC. Then, we achieve the optimal strategies where the specified sets of organic growing effort, organic traceability technology effort, propaganda input, and service input can guarantee the maximization of the related profits. As a result, we could obtain the values of the corresponding optimal profits. For the centralized decision mode, the farmer cooperative and the online retailer make decisions with the goal of maximizing the overall profits of the OASC. Meanwhile, for the decentralized decision mode with four different cases, each member will independently make a decision with the goal of maximizing his own profit respectively. In detail, as for the fully decentralized decision mode, no contracts exist in OASC; regarding the decentralized decision mode with an information traceability cost sharing contract, two members pay the information traceability cost together; and for the decentralized decision mode with a revenue sharing contract, two members share the revenue together; as to the decentralized decision mode with a comprehensive contract, there are two cooperative ways that information traceability cost sharing and revenue sharing can be achieved. In addition, we also considered factors such as the consumer preferences of organic products and the cross influence between channels in models. Finally, through sensitivity analysis and comparison of optimal strategies and profits, we found that: (1) high consumer preferences of organic products and high cross influence between channels are profitable; and (2) the choice of contract is influenced by the relative size of the offline marginal income ratio and the online marginal income ratio.

**Keywords:** sustainability; organic agricultural supply chain; differential game; omni-channel

## 1. Introduction

In the planting process of organic agriculture, soluble mineral fertilizers, synthetic herbicides, and pesticides are forbidden, and the environmental impacts of organic agriculture include lower emissions of $CO_2$, $N_2O$, and $CH_4$, enhanced soil and water quality, higher energy efficiency per land area and so on [1]. Organic agriculture is considered to be a sustainable ecosystem and beneficial to environment. Moreover, organic agriculture and organic food are good for human health, such as reducing the risk of allergic disease and of overweight and obesity, with modestly higher contents of phenolic compounds in organic fruit and vegetables [2]. The concentration of antioxidants in organic foods is higher than non-organic foods, while the level of toxic heavy metals like cadmium and pesticides residues are lower in organic foods [3,4]. With the improvement of people's quality of life, people's health awareness has gradually increased. And compared with conventional food, people with health awareness are more willing to buy organic food, and this trend is on the rise [5]. In addition, organic farming may raise farmers' income [6]. Crowder and Reganold draw the conclusion that despite lower yields in organic farming, its economic profitability is significantly higher (22–35%) than others in a global meta-analysis which is concerning the economic competitiveness of organic farming in five continents [7]. Because of the benefits of organic agriculture, it has attracted the attention of farmers and consumers. In 2009, the area of organic agricultural land accounted for about 1% of the world's total agricultural area, which was 37.5 million hectares, 3.55 times as much as that of a decade ago [8]. The consumption of organic food has steadily risen over the past two decades [9]. Sustainable production and sustainable consumption are mutually reinforcing and indispensable, which are the main ways to achieve sustainable development [10].

An increasing number of pick-your-own (PYO) farms offer various kinds of conventional agricultural products or organic agricultural products for consumers to pick on the farm [11]. The Swanton Organic Apple Orchard opened U-Pick apples to the public during the apple harvest season. Customers can pick organic apples such as Ginger Gold, Lodi, Royal Gala, Red Delicious, Yellow Newtown, and Red Fuji in organic orchards [12]. There are many similar organic farms that provide PYO operations, such as Wolfsen Farms with organic Blueberry in California [13]. This is not just an interesting way of shopping. It is worth mentioning that it can be effectively reduced "food miles". "Food miles" means the distance from farm to retailer or "direct transport" which used to measure environmental impact in terms of contribution to greenhouse gas emissions [14]. In a sense, PYO operations are beneficial to the sustainable development of the environment, which have reference and inspiration for the innovation of sustainable consumption mode. Along with the rapid development of economy and network technology, in order to expand sales and facilitate consumers, some PYO farms have also opened online channels for consumers to purchase agricultural products online. For example, many PYO farms in China have corresponding online stores on Taobao. Furthermore, in the prevailing environment of the O2O model, some farms have designed an experiential game for consumers to grow agricultural products online, allowing consumers to purchase agricultural products online, and when the agricultural products are mature, they can go to the farm to pick up the products. Consumers purchase the organic products online and then pick up on the farm which is a mode of buy online and pick up in store (BOPS). BOPS is considered as the most important omni-channel fulfillment initiative in the survey of Forrester Research [15]. Omni-channel is the product of some retailers who integrate their existing channels to improve customer value proposition and operational efficiency, giving a seamless shopping experience to customers by all available shopping channels [15–17].

PYO, buy online and deliver home, and BOPS are three shopping ways of organic agricultural products in practice. It is of practical significance to study the operation of omni-channel supply chain composed of these three ways. At the same time, it also has theoretical significance. In particular, although PYO is a popular sustainable consumption mode, few literatures have studied PYO farms as members of supply chains. Therefore, we focus on an omni-channel organic agricultural supply chain (OASC) consisting of one single farmer cooperative and one single online retailer, which provides three shopping ways, namely PYO, buy online and deliver home, BOPS. In the process of planting and operation, people should pay attention to many issues. For example, organic agriculture has certain requirements for soil, so it is necessary to improve and manage the soil, and soil nutrient management may affect the production of organic agricultural products [6,18,19]. Another example is that the traceability of organic agricultural products involves the collection of information in the supply chain and the corresponding technology and equipment implementation [20]. To this end, the farmer cooperative and the online retailer have to make corresponding efforts such as growing efforts and traceability efforts, at the same time, it means that they have to pay the corresponding costs. How much effort in the process of production and traceability should be made? In the same way, there are propaganda input and service input. In addition, because of BOPS, farmer cooperatives, and online retailer are no longer competitive relationship, but cooperation. Under the circumstance of omni-channel introduced by one retailer, BOPS revenue can be shared across channels to alleviate incentive conflicts [15]. But in this paper, the farmer cooperative and the online retailer operate the omni-channel supply chain together. So, what is the optimal profit of supply chain, and how should BOPS revenue be allocated between two agents of supply chain members in the OASC? We establish five models based on differential game theory to address these questions.

The rest of this paper is organized into seven sections. Section 2 presents the literature review. Section 3 introduces problem statement and formulation. Section 4 develops five decision modes for the OASC and obtains the optimal decision strategies for farmer cooperatives and online retailers. Section 5 compares the five decision modes. Section 6 presents the numerical analysis. Section 7 discusses the findings and managerial implications. Section 8 summarizes the research. All proofs of propositions and corollaries are in the Appendix A.

## 2. Literature Review

This paper studies the optimal decisions and cooperation of the omni-channel OASC, and there are three related streams of literature. One stream is about the channel management of supply chain. Generally, the channel structure of supply chain can be divided into four categories by these studies. The four categories are: (1) a single channel [21,22], where customers can only buy products through one channel. In most cases, it means bricks-and-mortar stores of retailers which are often referred to as traditional channels; (2) dual-channel, in which customers can shopping through two channels, always means a traditional retail channel plus a channel without bricks-and-mortar stores which provide information of productions by email, TV, net and so on. There are generally two types, one is that manufacturers introduce direct sale channel based on the channel of retailers [23–26]. The other is that retailers open online channels [27,28]; (3) multi-channel, in which customers can shopping through more than two channels. There are several different forms, for example, manufacturer has direct online channel and retailers introduce online channel based on its traditional channel [29]; (4) omni-channel, where customers can buy products by all available shopping channels and, at the same time, the integration of channels is emphasized in omni-channel mode [15–17]. Such as, BOPS [15,30,31].

Since the omni-channel supply chain is most closely related to this paper, it is elaborated in detail. Some studies have focused on the impact of information mechanisms. Bell et al. analyzed the impact on market and operator based on the physical showrooms in omni-channel environment, and showed that showrooms bring benefits for both of them [32]. Gao et al. studied the influence of physical showrooms, virtual showrooms and availability information three information mechanisms on the omni-channel customers' shopping choice, and they found that, in general, these information mechanisms increase the likelihood that consumers will buy goods and thus make retailers more profitable [33]. Therefore, in this paper, we consider the positive impact of information on demand in an omni-channel environment. Some studies have focused on the specific form of operation. Cao et al. used consumer utility functions and profit models to study the demand allocations and profitability of an omni-channel retailer, and showed that the retailer benefits from the online-to-store channel [34]. Gao et al. established theoretical model to discuss what types of product suit for BOPS, the impact of BOPS and how to deal with the BOPS revenue, and they found that BOPS revenue could be shared by channels [15]. Jin et al. compared the optimal decisions including pricing and the size of the service area of the retailer introducing BOPS and ROPS, at the same time, order cancellation policies were also considered [31]. In summary, most of these studies are targeted at an omni-channel retailer, or a retailer who operate the omni-channel, while this paper is targeted at two members in omni-channel supply chain and how they cooperate to operate the omni-channel.

Regarding the optimal strategy, the dual-channel supply chain's optimal strategies include pricing, inventory policy, supply chain coordination, and others, namely, cooperative advertising, retailer service, information sharing and so on [26,35–37]. Similarly, pricing, quality, service, and advertising is also included in the study of the optimal strategy for an omni-channel supply chain [31,38]. He et al. studied the optimal decisions of a supplier and a retailer under O2O environment from the perspective of reference quality based on differential game models [38]. Our paper is closely related to this research. However, the structure of offline sales is different. In their research, the supplier sells products through the retailer's offline channel, while in our research, the farmer cooperative carries out PYO operation, which is direct marketing. There is very little literature on the omni-channel supply chain of offline direct marketing. Besides, their research is on the general supply chain, and they focus on the impact of reference quality behavioral factor on supply chain decisions, which differs with ours. We take OASC as the research object and study the decisions of organic growing effort, organic traceability technology effort, propaganda input and service input in the omni-channel supply chain based on the characteristics of OASC.

Another related stream of literature is about organic agriculture and organic product. Some scholars affirmed the positive significance of organic agriculture for sustainable development, and put forward some strategies for sustainable development [39,40]. Krystallis et al. studied the people's willingness to pay for organic food through empirical methods and found that food quality and security, trust in the certification, and, for some products, brand name influence consumers' purchase intention, while organoleptic characteristics, prices, and consumers' socio-demographic profiles have no influence [41]. These studies used empirical methods. Other studies used mathematical methods to study organic products from the perspective of supply chain. Longo et al. used life cycle assessment methodology to compare the influence of organic apple supply chain and conventional apple supply chain on energy and environment in the North of Italy [42]. Sazvar et al. compared the effects of organic agricultural product supply chain and conventional agricultural product supply chain on the global warming, climate change, and social health by mathematical programming method [43]. None of the above-mentioned literatures have studied the optimal strategy of the OASC in an omni-channel environment. This paper proposes suggestions for the OASC from the perspective of optimal supply chain decisions based on differential game theory. Although PYO organic farms are very common and popular in real life, there are few theoretical studies on PYO operation. Existing studies mostly focus on how to operate PYO farms, and the factors influencing consumers' purchase of PYO products [44,45]. And most of them are qualitative research or empirical research. In this paper, we take the farmer cooperative that carries out PYO operation as a member of the omni-supply chain to conduct quantitative research. This plays a supplementary role in theoretical research, and also provides practical suggestions for the operation and cooperation in the omni-supply chain.

The third stream is using the differential game model to find the optimal decision of the supply chain. Differential game model has been widely used in the field of supply chain management from different angles, such as goodwill [38], dynamic advertising [46,47], and carbon emission [48,49]. Different from these studies, this paper establishes differential game model to solve the optimal organic growing effort and organic traceability technology effort.

## 3. Problem Statement and Formulation

### *3.1. Problem Description*

There is an omni-channel supply chain consisting of a farmer cooperative and an online retailer. Customers could get organic agricultural products from three ways. The first, they could go to the PYO farm to pick organic agricultural products by themselves and enjoy the picking experience. In this way, the farmer cooperative produces organic agricultural products and operates the organic farm. The way will be denoted by sub $f$, abbreviated as PYO. The second, they could buy organic agricultural products on the online channel and wait the delivering. The online retailer wholesale the organic products from the farmer cooperative with the wholesale price $w$, operates the online channel and delivers production to customers. This way will be denoted by sub $o$. The third, customers could order and pay for products online, then go to the organic farm to pick up their goods. It is known that online channel is operated by online retailer while the organic farm is operated by a farmer cooperative, so we use sub $of$ to denote the third way which is abbreviated as BOPS.

The farmer cooperative pays growing effort $M(t)$ to grow organic agriculture products by improving soil, controlling pests, recording information about organic agricultural products, and other method. Besides, in order to give tourists a better experience, the farmer cooperative provide service $S$. For example, some farmer cooperative will decorate the organic farms and provide tools like scissors for customer to pick fruits more convenient. The online retailer pays traceability technology effort $E(t)$ to purchase equipment, master technology, and make barcodes for recording information traceability of organic agriculture products. Moreover, the online retailer propaganda the organic agriculture products and the sustainable environment their growth by effort $A$ in the form of pictures, videos, and words online. The structure of the OASC is shown in Figure 1.

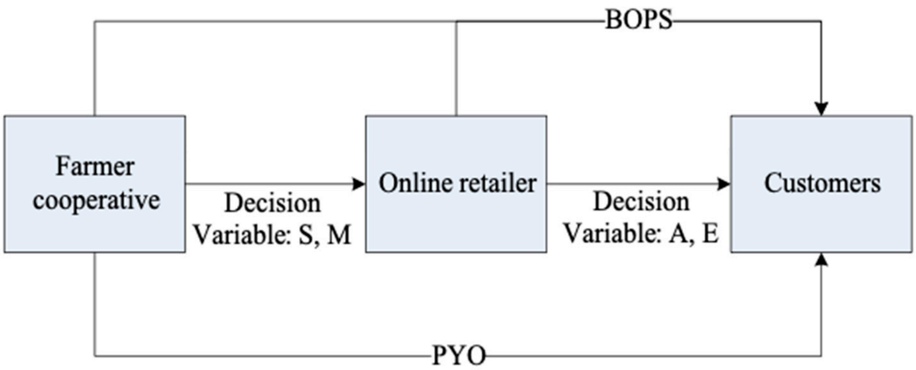



**Figure 1.** Problem Structure. PYO: Pick-your-own; BOPS: Buy online and pick up in store.

### 3.2. Model Assumptions

(I) Assume that the organic level of an organic product is a state variable, as the Nerlove–Arrow model [50,51], the time-varying state differential equation follows

$$G(t) = \lambda M(t) + \gamma E(t) - \sigma G(t) \tag{1}$$

In Equation (1), $G(t)$ denotes the organic level of an organic product, and when $t = 0$, $G(0) = G_0 > 0$. Consumers perceive the organic level of organic products through two parts, one is the growing effort, that is, the organic level of organic products in the growth process, the other is the traceability effort of organic products, that is, the richness of information about organic products that consumers can obtain through traceability. And the organic level of organic products will decline with time due to aging of invested planting facilities and traceability equipment. $M(t)$ denotes the level of effort that the farmer cooperative pays for growing organic product, $\lambda$ denotes the impact of growing efforts on organic level, $E(t)$ denotes the level of effort that the online retailer pays for traceability technology of organic products, $\gamma$ denotes the impact of traceability technology efforts on organic level, $\sigma$ denotes the decline rate of organic level.

(II) As in many researches [46,48,49], assume that the organic growing cost of farmer cooperatives and the organic traceability technology cost of online retailers are convex functions of their organic effort inputs. And the organic growing cost refers to the cost of the farmer cooperative during the planting process, including soil improvement costs and pest control costs. The organic traceability technology cost refers to the cost of all online retailer involved in the traceability, including the cost of learning traceability technology and the cost of equipment purchase. The specific forms are as follows.

$$C_m = \frac{K_m}{2} M(t)^2 \qquad C_e = \frac{K_e}{2} E(t)^2 \tag{2}$$

In Equation (2), $C_m$ and $C_e$ denote the organic growing cost of a farmer cooperative and the organic traceability cost of online retailer respectively, $K_m$ and $K_e$ denote the cost coefficient of the organic growing cost and the organic traceability cost respectively.

(III) Assume that the experience service cost of farmer cooperative and the propaganda cost of online retailer are convex functions of their effort inputs. Experience service cost includes the cost of decorating PYO farms by the farmer cooperative, providing some tools and services that are helpful for picking, etc. Propaganda cost includes the cost of the online retailer collecting, designing, and producing corresponding advertising pictures, texts, and videos, as well as the cost of advertising. The specific forms are as follows.

$$C_s = \frac{K_s}{2}S(t)^2 \qquad C_a = \frac{K_a}{2}A(t)^2 \tag{3}$$

In Equation (3), $C_s$ and $C_a$ denote the experience service cost of a farmer cooperative and the propaganda cost of online retailer respectively, $K_s$ and $K_a$ denote the cost coefficient of the experience service cost and the propaganda cost respectively.

(IV) Demand of organic products is not only affected by organic level, but also influenced by experience service and propaganda level. The demands of different shopping ways can be expressed as follows.

$$d_i = \begin{cases} \alpha_i + \beta S(t) + \eta[G(t) + \varepsilon A(t)] & i = f \\ \alpha_i + \eta[G(t) + A(t)] & i = o \\ \alpha_i + \varepsilon\beta S(t) + \eta[G(t) + A(t)] & i = of \end{cases} \tag{4}$$

In Equation (4), $d_i$ denotes the demand of organic products by shopping mode $i$, $\alpha_i > 0$ denotes the potential market capacity of shopping mode $i$, $\beta > 0$ denotes the impact of experience service level on demand, $\eta > 0$ denotes the consumer preferences of organic products, $\varepsilon > 0$ denotes the cross influence between channels.

(V) Assume that the farmer cooperative and the online retailer have the same discount rate, and they make rational decisions based on complete information. Their goals are to find strategies for maximizing their own profits in an endless period of time. Parameters in the model are time independent constants. For writing convenience, $t$ is omitted later. Their profit functions are as follows.

$$J_o = \int_0^\infty e^{-\rho t}[p_o(d_o + d_{of}) - \frac{1}{2}K_a A^2 - \frac{1}{2}K_e E^2]dt \tag{5}$$

$$J_f = \int_0^\infty e^{-\rho t}[p_f d_f + w(d_o + d_{of}) - \frac{1}{2}K_m M^2 - \frac{1}{2}K_s S^2]dt \tag{6}$$

In Equations (5) and (6), $p_f$ denotes the offline marginal income ratio of a farmer cooperative in the shopping way $f$, $p_o$ denotes the online marginal income ratio of online retailer in the shopping way $o$ and $of$, $w$ denotes the wholesale price of organic products, $\rho$ denotes the discount rate. The notations used through the paper are summarized in Table 1.

**Table 1.** Notations.

| Symbols | Descriptions |
|---|---|
| $\lambda$ | the impact factor of growing efforts on organic level |
| $\gamma$ | the impact factor of traceability technology efforts on organic level |
| $\sigma$ | the decline rate of organic level |
| $C_m$ | the organic growing cost of a farmer cooperative |
| $C_e$ | the propaganda cost of online retailer |
| $K_m$ | the cost coefficient of the organic growing cost |
| $K_a$ | the cost coefficient of the organic traceability cost |
| $C_s$ | the experience service cost of a farmer cooperative |
| $C_a$ | the propaganda cost of online retailer |
| $K_s$ | the cost coefficient of the experience service cost |
| $K_a$ | the cost coefficient of the propaganda cost |
| $d_i$ | the demand of organic products by shopping mode |
| $\alpha_i$ | the potential market capacity of shopping mode |
| $\beta$ | the impact factor of experience service level on demand |
| $\eta$ | the consumer preferences of organic products |
| $\varepsilon$ | the cross influence factor between channels |
| $p_f$ | the offline marginal income ratio of a farmer cooperative |
| $p_o$ | the online marginal income ratio of online retailer |
| $\rho$ | the discount rate |
| $t$ | time |
| $M(t)$ | organic growing effort of the farmer cooperative, decision variable |
| $E(t)$ | organic traceability technology effort of the online retailer, decision variable |
| $S$ | service input of the farmer cooperative, decision variable |
| $A$ | propaganda input of the online retailer, decision variable |
| $G(t)$ | the organic level of an organic product |

We established five models to solve the optimal decisions and profits in different scenarios. The assumptions in different scenarios are shown in Table 2.

**Table 2.** Assumptions in five scenarios.

| Mode | Members | Cooperation | Goal |
|---|---|---|---|
| Centralized decision mode | The farmer cooperative, the online retailer | Make decisions together with same goal | Maximizing the overall profit of the omni-channel organic agricultural supply chain (OASC) |
| Fully decentralized decision mode | | Compete against each other with their own goals | Maximizing their own profit respectively |
| Decentralized decision mode with an information traceability cost sharing contract | | Paying the information traceability cost together during decentralized decision-making | |
| Decentralized decision mode with a revenue sharing contract | | Sharing the revenue together during decentralized decision-making | |
| Decentralized decision mode with a comprehensive contract | | Paying the information traceability cost and sharing the revenue during decentralized decision-making | |

## 4. The Differential Game Model

### 4.1. Centralized Decision Mode

In centralized decision mode, the farmer cooperative and the online retailer make decisions together such as organic growing effort, organic traceability technology effort, propaganda input and service input with the goal of maximizing the profit of the OASC. Denoted this mode by sup *c*. The decision model is as follows.

$$\max_{A,S,E,M} J^c = \int_0^{\infty} e^{-\rho t}[(p_o + w)(d_o + d_{of}) + p_f d_f - \frac{1}{2}K_a A^2 - \frac{1}{2}K_e E^2 - \frac{1}{2}K_s S^2 - \frac{1}{2}K_m M^2]dt \quad (7)$$

**Proposition 1.** *In centralized decision mode, the optimal equilibrium strategies about organic growing effort, organic traceability technology effort, propaganda input and service input are as follows.*

$$E^c = \frac{(2w + p_f + 2p_o)\eta\gamma}{(\rho+\sigma)K_e}, M^c = \frac{(2w + p_f + 2p_o)\eta\lambda}{(\rho+\sigma)K_m}, S^c = \frac{(\varepsilon w + p_f + \varepsilon p_o)\beta}{K_s}, \\ A^c = \frac{(2w + \varepsilon p_f + 2p_o)\eta}{K_a} \quad (8)$$

In centralized decision mode, the optimal equilibrium strategy about organic growing effort, organic traceability technology effort, propaganda input, and service input are directly proportional to offline marginal income ratio, online marginal income ratio, and wholesale price, while inversely proportional to their cost coefficient respectively. Besides, the growing effort and organic traceability technology effort are directly proportional to consumer preferences of organic products, and directly proportional to their impact of efforts on the organic level respectively. Organic growing effort and organic traceability technology effort are inversely proportional to discount rate and decline rate. Propaganda input and service input are directly proportional to cross influence between channels. Propaganda input is directly proportional to consumer preferences of organic products. Service input is directly proportional to impact of experience service level on demand.

**Proposition 2.** *In centralized decision mode, the optimal state trajectory of organic level is*

$$G^c(t) = G^c_{RSS} + (G_0 - G^c_{RSS})e^{-\sigma t} \quad (9)$$

And $G^c_{RSS} = \frac{2w+p_f+2p_o}{\rho+\sigma}(\frac{\gamma^2}{K_e} + \frac{\lambda^2}{K_m})\eta$ is the steady-state value of the organic level ($t \to \infty$).

In centralized decision mode, the optimal state trajectory of the organic level is monotonic. The optimal state trajectory of the organic level is monotonically increasing when $G_0 < G^c_{RSS}$, the optimal state trajectory of the organic level is monotonically decreasing when $G_0 > G^c_{RSS}$.

**Proposition 3.** *In centralized decision mode, the overall long-term profit of the organic supply chain is*

$$J^c = a^c_1 G_0 + (\alpha_o + \alpha_{of})B + p_f \alpha_f + \frac{(\varepsilon B + p_f)^2\beta^2}{2K_s} + \frac{(\varepsilon p_f + 2B)^2\eta^2}{2K_a} + (\frac{\lambda^2}{K_m} + \frac{\gamma^2}{K_e})\frac{a^{c2}_1}{2} \quad (10)$$

The values of $a^c_1$ and $B$, and the proofs of propositions 1, 2, and 3 are shown in Appendix A.

*4.2. Fully Decentralized Decision Mode*

In fully decentralized decision mode, the farmer cooperative and the online retailer make their respective decisions such as organic growing effort, organic traceability technology effort, propaganda input and service input in the aim of maximizing their own profits. Denoted this mode by sup *d*. Assume that the farmer cooperative decides the organic growing effort and service input, then the online retailer decides the organic traceability technology effort and propaganda input. The decision model is the bi-level programming as follows.

$$\max_{S,M} J_f = \int_0^{\infty} e^{-\rho t}[p_f d_f + w(d_o + d_{of}) - \frac{1}{2}K_m M^2 - \frac{1}{2}K_s S^2]dt \tag{11}$$

$$s.t. \quad \max_{A,E} J_o = \int_0^{\infty} e^{-\rho t}[p_o(d_o + d_{of}) - \frac{1}{2}K_a A^2 - \frac{1}{2}K_e E^2]dt \tag{12}$$

**Proposition 4.** *In fully decentralized decision mode, the optimal equilibrium strategies for the organic growing effort, service input of a farmer cooperative and the organic traceability technology effort, and propaganda input of online retailer are as follows.*

$$E^d = \frac{2\eta\gamma p_o}{(\rho+\sigma)K_e}, M^d = \frac{(2w + p_f)\eta\lambda}{(\rho+\sigma)K_m}, S^d = \frac{(\varepsilon w + p_f)\beta}{K_s}, A^d = \frac{2\eta p_o}{K_a} \tag{13}$$

In fully decentralized decision mode, the optimal equilibrium strategies for organic growing effort, organic traceability technology effort, propaganda input and service input are inversely proportional to their cost coefficient respectively. Besides, the organic growing effort and organic traceability technology effort are directly proportional to consumer preferences of organic products, and directly proportional to their impact of efforts on the organic level respectively. Organic growing effort and organic traceability technology effort are inversely proportional to discount rate and decline rate. Propaganda input is directly proportional to consumer preferences of organic products. Service input is directly proportional to impact of experience service level on demand and cross influence between channels. The farmer cooperative's optimal equilibrium strategies, including organic growing effort and service input, are directly proportional to offline marginal income ratio and wholesale price. The online retailer's optimal equilibrium strategies including organic traceability technology effort and propaganda input are directly proportional to online marginal income ratio.

**Proposition 5.** *In fully decentralized decision mode, the optimal state trajectory of the organic level is*

$$G^d(t) = G^d_{RSS} + (G_0 - G^d_{RSS})e^{-\sigma t} \tag{14}$$

And $G^d_{RSS} = \frac{\eta}{\rho+\sigma}[\frac{2\gamma^2 p_o}{K_e} + \frac{(2w+p_f)\lambda^2}{K_m}]$ is the steady-state value of the organic level ($t \to \infty$).

In fully decentralized decision, the nature of optimal state trajectory of the organic level is the same as in centralized decision.

**Proposition 6.** *In fully decentralized decision mode, farmer cooperative's profit, online retailer's profit, and the overall long-term profit of the organic supply chain are*

$$J^d_f = a^d_1 G_0 + (\alpha_o + \alpha_{of})w + \alpha_f p_f + \frac{\beta^2(w\varepsilon + p_f)^2}{2K_s} + \frac{2(p_f\varepsilon + 2w)\eta^2 p_o}{K_a} + (\frac{a^d_1\lambda^2}{2K_m} + \frac{b^d_1\gamma^2}{K_e})a^d_1 \tag{15}$$

$$J^d_o = b^d_1 G_0 + (\alpha_o + \alpha_{of})p_o + \frac{(w\varepsilon + p_f)^2\varepsilon\beta^2 p_o}{K_s} + \frac{2\eta^2 {p_o}^2}{K_a} + (\frac{a^d_1\lambda^2}{K_m} + \frac{b^d_1\gamma^2}{2K_e})b^d_1 \tag{16}$$

$$\begin{aligned} J^d = {} & (a^d_1 + b^d_1)G_0 + (\alpha_o + \alpha_{of})B + \alpha_f p_f + \frac{\beta^2(w\varepsilon + p_f)(w\varepsilon + p_f + 2\varepsilon p_o)}{2K_s} \\ & + \frac{2(p_f\varepsilon + 2w + p_o)\eta^2 p_o}{K_a} + \frac{a^d_1\lambda^2}{K_m}(\frac{a^d_1}{2} + b^d_1) + \frac{b^d_1\gamma^2}{K_e}(a^d_1 + \frac{b^d_1}{2}) \end{aligned} \tag{17}$$

The values of $a_1^d$ and $b_1^d$, and the proofs of propositions 4, 5, and 6 are shown in Appendix A.

*4.3. Decentralized Decision Mode with Information Traceability Cost Sharing*

In omni-channel supply chain system, the relationship between online retailer and a farmer cooperative is complex, not just competition. The efforts made by online retailers for organic information traceability are not only beneficial to itself, but also beneficial to a farmer cooperative. Consumers can obtain the organic information traceability online for the organic fruits which are picked offline. For the sake of this, a farmer cooperative should share the cost of information traceability which paid by online retailer.

With an information traceability cost sharing contract, the farmer cooperative pays the information traceability cost of ratio $\theta(0 \leq \theta \leq 1)$ and the online retailer pays the information traceability cost of ratio $1-\theta$. The farmer cooperative decides the organic growing effort and service input, together with information traceability cost sharing ratio, then the online retailer decides the organic traceability technology effort and propaganda input, with the goal of maximizing their own profits. Denoted this mode by sup $i$. The decision model is the bi-level programming as follows.

$$\max_{S,M,\theta} J_f = \int_0^\infty e^{-\rho t}[p_f d_f + w(d_o + d_{of}) - \frac{1}{2}K_m M^2 - \frac{1}{2}K_s S^2 - \frac{1}{2}\theta K_e E^2]dt \tag{18}$$

$$s.t. \quad \max_{A,E} J_o = \int_0^\infty e^{-\rho t}[p_o(d_o + d_{of}) - \frac{1}{2}K_a A^2 - \frac{1}{2}(1-\theta)K_e E^2]dt \tag{19}$$

**Proposition 7.** *In decentralized decision mode with an information traceability cost sharing contract, the optimal equilibrium strategies for the organic growing effort, service input, sharing ratio of farmer cooperatives, and the organic traceability technology effort, propaganda input of online retailer are as follows.*

$$\begin{gathered} E^i = \frac{\eta\gamma(2w + p_f + p_o)}{(\rho+\sigma)K_e}, M^i = \frac{(2w + p_f)\eta\lambda}{(\rho+\sigma)K_m}, S^i = \frac{(\varepsilon w + p_f)\beta}{K_s}, A^i = \frac{2\eta p_o}{K_a}, \\ \theta^i = \begin{cases} \dfrac{2w + p_f - p_o}{2w + p_f + p_o}, & 2w + p_f > p_o \\ 0, & 2w + p_f < p_o \end{cases} \end{gathered} \tag{20}$$

With an information traceability cost sharing contract, organic traceability technology effort is directly proportional to consumer preferences of organic products, offline marginal income ratio, online marginal income ratio, wholesale price, and its impact of efforts on the organic level. The organic traceability technology effort is inversely proportional to discount rate, decline rate, and its cost coefficient respectively. An information traceability cost sharing ratio is directly proportional to online marginal income ratio, wholesale price, and is inversely proportional to offline marginal income ratio. The other strategies are the same as Proposition 4.

**Proposition 8.** *In decentralized decision mode with an information traceability cost sharing contract, the optimal state trajectory of the organic level is*

$$G^i(t) = G^i_{RSS} + (G_0 - G^i_{RSS})e^{-\sigma t} \tag{21}$$

And $G^i_{RSS} = \frac{\eta}{\rho+\sigma}[\frac{(2w+p_f+p_o)\gamma^2}{K_e} + \frac{(2w+p_f)\lambda^2}{K_m}]$ is the steady-state value of the organic level ($t \to \infty$).

In decentralized decision mode with an information traceability cost sharing contract, the nature of optimal state trajectory of the organic level is the same as in centralized decision mode.

**Proposition 9.** *In decentralized decision mode with an information traceability cost sharing contract, farmer cooperative's profit, online retailer's profit and the overall long-term profit of the organic supply chain are*

$$J_f^i = a_1^i G_0 + (\alpha_o + \alpha_{of})w + p_f\alpha_f + \frac{p_o\eta^2(p_f\varepsilon + 2w)}{K_a} + \frac{\beta^2(w\varepsilon + p_f)^2}{2K_s} + \frac{\lambda^2(a_1^i)^2}{2K_m} + \frac{\gamma^2(2a_1^i + b_1^i)^2}{8K_e} \quad (22)$$

$$J_o^i = b_1^i G_0 + (\alpha_o + \alpha_{of})p_o + \frac{2\eta^2 {p_o}^2}{K_a} + \frac{\varepsilon\beta^2 p_o(w\varepsilon + p_f)}{K_s} + \frac{a_1^i b_1^i \lambda^2}{K_m} + \frac{(2a_1^i + b_1^i)b_1^i\gamma^2}{4K_e} \quad (23)$$

$$\begin{aligned} J^i = \ & (a_1^i + b_1^i)G_0 + (\alpha_o + \alpha_{of})B + \alpha_f p_f + \frac{\beta^2(w\varepsilon + p_f)(w\varepsilon + p_f + 2\varepsilon p_o)}{2K_s} \\ & + \frac{2(p_f\varepsilon + 2w + p_o)\eta^2 p_o}{K_a} + \frac{a_1^d\lambda^2}{K_m}(\frac{a_1^d}{2} + b_1^d) + \frac{\gamma^2(2a_1^i + b_1^i)}{8K_e}(2a_1^i + 3b_1^i) \end{aligned} \quad (24)$$

The values of $a_1^i$ and $b_1^i$, and the proofs of propositions 7, 8, 9 are shown in Appendix A.

*4.4. Decentralized Decision Mode with A Revenue Sharing Contract*

In the shopping way BOPS, customers could order and pay for products online, then go to the organic farm to pick up their goods. For this sake, online retailers and farmer cooperatives should cooperate with each other. With a revenue sharing contract, online retailers and farmer cooperatives share the revenue of the third shopping way. They negotiated that the farmer cooperative shares the revenue of ratio $\mu(0 \leq \mu \leq 1)$ and the online retailer the shares revenue of ratio $1 - \mu$. The farmer cooperative decides the organic growing effort and service input, and information traceability cost sharing ratio, then the online retailer decides the organic traceability technology effort and propaganda input, with the goal of maximizing their own profits. Denoted this mode by sup $r$. The decision model is as follows.

$$\max_{S,M} J_f = \int_0^\infty e^{-\rho t}[p_f d_f + w(d_o + d_{of}) + \mu p_o d_{of} - \frac{1}{2}K_m M^2 - \frac{1}{2}K_s S^2]dt \quad (25)$$

$$s.t. \ \max_{A,E} J_o = \int_0^\infty e^{-\rho t}[p_o d_o + (1-\mu)p_o d_{of} - \frac{1}{2}K_a A^2 - \frac{1}{2}K_e E^2]dt \quad (26)$$

**Proposition 10.** *In decentralized decision mode with a revenue sharing contract, the optimal equilibrium strategies for the organic growing effort, service input of a farmer cooperative and the organic traceability technology effort, and propaganda input of online retailer are as follows.*

$$\begin{gathered} E^r = \frac{\eta\gamma(2-\mu)p_o}{(\rho+\sigma)K_e}, M^r = \frac{(2w + p_f + \mu p_o)\eta\lambda}{(\rho+\sigma)K_m}, S^r = \frac{(\varepsilon w + p_f + \mu\varepsilon p_o)\beta}{K_s}, \\ A^r = \frac{(2-\mu)\eta p_o}{K_a} \end{gathered} \quad (27)$$

In decentralized decision mode with a revenue sharing contract, the optimal equilibrium strategies for organic growing effort, organic traceability technology effort, propaganda input and service input are inversely proportional to their cost coefficient respectively. Besides, organic growing effort and organic traceability technology effort are directly proportional to consumer preferences of organic products, and directly proportional to their impact of efforts on the organic level respectively. Organic growing effort and organic traceability technology effort are inversely proportional to discount rate and decline rate. Propaganda input is directly proportional to consumer preferences of organic products. Service input is directly proportional to the impact of experience service level on demand and cross influence between channels. The farmer cooperative's optimal equilibrium strategies are directly proportional to offline marginal income ratio, wholesale price and sharing revenue. The online retailer's optimal equilibrium strategies are directly proportional to online marginal income ratio, inversely proportional to sharing revenue.

**Proposition 11.** *In decentralized decision mode with a revenue sharing contract, the optimal state trajectory of the organic level is*

$$G^r(t) = G^r_{RSS} + (G_0 - G^r_{RSS})e^{-\sigma t} \tag{28}$$

And $G^r_{RSS} = \frac{\eta}{\rho+\sigma}[\frac{(2-\mu)p_o\gamma^2}{K_e} + \frac{(2w+p_f+\mu p_o)\lambda^2}{K_m}]$ is the steady-state value of the organic level ($t \to \infty$).

In this mode, the nature of optimal state trajectory of the organic level is the same as in centralized decision.

**Proposition 12.** *In decentralized decision mode with a revenue sharing contract, farmer cooperative's profit, online retailer's profit and the overall long-term profit of the organic supply chain are*

$$\begin{aligned} J^r_f = {} & a^r_1 G_0 + p_o\alpha_{of}\mu + (\alpha_o + \alpha_{of})w + p_f\alpha_f + \frac{(2-\mu)(p_f\varepsilon + p_o\mu + 2w)p_o\eta^2}{K_a} \\ & + \frac{\beta^2(\mu\varepsilon p_o + w\varepsilon + p_f)^2}{2K_s} + a^r_1(\frac{b^r_1\gamma^2}{K_e} + \frac{a^r_1\lambda^2}{2K_m}) \end{aligned} \tag{29}$$

$$\begin{aligned} J^r_o = {} & b^r_1 G_0 + (\alpha_{of} - \mu\alpha_{of} + \alpha_o)p_o + b^r_1(\frac{b^r_1\gamma^2}{2K_e} + \frac{a^r_1\lambda^2}{K_m}) + \frac{{p_o}^2\eta^2(2-\mu)^2}{2K_a} \\ & + \frac{(1-\mu)p_o\varepsilon\beta^2[\varepsilon\mu p_o + \beta^2(w\varepsilon + p_f)]}{K_s} \end{aligned} \tag{30}$$

$$\begin{aligned} J^r = {} & (a^r_1 + b^r_1)G_0 + (\alpha_{of} + \alpha_o)B + p_f\alpha_f + \frac{(\mu\varepsilon p_o + w\varepsilon + p_f)[(2-\mu)\varepsilon p_o + w\varepsilon + p_f]\beta^2}{2K_s} \\ & + \frac{(2-\mu)[(\mu+2)p_o + 2p_f\varepsilon + 4w]p_o\eta^2}{2K_a} + a^r_1(\frac{b^r_1\gamma^2}{K_e} + \frac{a^r_1\lambda^2}{2K_m}) + b^r_1(\frac{b^r_1\gamma^2}{2K_e} + \frac{a^r_1\lambda^2}{K_m}) \end{aligned} \tag{31}$$

The values of $a^r_1$ and $b^r_1$, and the proofs of propositions 10, 11, 12 are shown in Appendix A.

### 4.5. Decentralized Decision Mode with a Comprehensive Contract (Information Traceability Cost Sharing and Revenue Sharing)

In this mode, we use two cooperative ways that information traceability cost sharing and revenue sharing. The farmer cooperative decides the organic growing effort and service input, and information traceability cost sharing ratio, then the online retailer decides the organic traceability technology effort and propaganda input, with the goal of maximizing their own profits. Denoted this mode by sup *ir*. The decision model is as follows.

$$\max_{S,M} J_f = \int_0^\infty e^{-\rho t}[p_f d_f + w(d_o + d_{of}) + \mu p_o d_{of} - \frac{1}{2}K_m M^2 - \frac{1}{2}K_s S^2 - \frac{1}{2}\theta K_e E^2]dt \tag{32}$$

$$s.t. \quad \max_{A,E} J_o = \int_0^\infty e^{-\rho t}[p_o d_o + (1-\mu)p_o d_{of} - \frac{1}{2}K_a A^2 - \frac{1}{2}(1-\theta)K_e E^2]dt \tag{33}$$

**Proposition 13.** *In decentralized decision mode with a comprehensive contract, the optimal equilibrium strategies for the organic growing effort, service input, sharing ratio of a farmer cooperative, and the organic traceability technology effort, propaganda input of online retailer are as follows.*

$$\begin{gathered}E^{ir} = \frac{\eta\gamma(2p_o + \mu p_o + 2p_f + 4w)}{2(\rho+\sigma)K_e}, M^{ir} = \frac{(2w + p_f + \mu p_o)\eta\lambda}{(\rho+\sigma)K_m}, \\ S^{ir} = \frac{(\varepsilon w + p_f + \mu\varepsilon p_o)\beta}{K_s}, A^{ir} = \frac{(2-\mu)\eta p_o}{K_a}, \\ \theta^{ir} = \begin{cases} \dfrac{2w + p_f - (1-\frac{3}{2}\mu)p_o}{2w + p_f + (1+\frac{1}{2}\mu)p_o}, & 2w + p_f > (1-\frac{3}{2}\mu)p_o \\ 0, & 2w + p_f < (1-\frac{3}{2}\mu)p_o \end{cases}\end{gathered} \tag{34}$$

With a comprehensive contract, organic traceability technology effort is directly proportional to consumer preferences of organic products, offline marginal income ratio, online marginal income ratio, wholesale price, sharing revenue and its impact of efforts on organic level. Organic traceability technology effort is inversely proportional to discount rate, decline rate and its cost coefficient respectively. The information traceability cost sharing ratio is directly proportional to online marginal income ratio, wholesale price, sharing revenue and is inversely proportional to offline marginal income ratio. The other strategies are the same as Proposition 10.

**Proposition 14.** *In decentralized decision mode with a comprehensive contract, the optimal state trajectory of the organic level is*

$$G^{ir}(t) = G^{ir}_{RSS} + (G_0 - G^{ir}_{RSS})e^{-\sigma t} \tag{35}$$

And $G^{ir}_{RSS} = \frac{\eta}{\rho+\sigma}[\frac{(2p_o+\mu p_o+4w+2p_f)\gamma^2}{2K_e} + \frac{(2w+p_f+\mu p_o)\lambda^2}{K_m}]$ is the steady-state value of the organic level ($t \to \infty$).

In this mode, the nature of optimal state trajectory of the organic level is the same as in the centralized decision.

**Proposition 15.** *In decentralized decision mode with a comprehensive contract, farmer cooperative's profit, online retailer's profit and the overall long-term profit of the organic supply chain are*

$$\begin{aligned}J^{ir}_f = {} & a^{ir}_1 G_0 + p_o\alpha_{of}\mu + (\alpha_o + \alpha_{of})w + p_f\alpha_f + \frac{(2-\mu)(p_f\varepsilon + p_o\mu + 2w)p_o\eta^2}{K_a} \\ & + \frac{\beta^2(\mu\varepsilon p_o + w\varepsilon + p_f)^2}{2K_s} + \frac{(2a^{ir}_1 + b^{ir}_1)^2\gamma^2}{8K_e} + \frac{a^{ir2}_1\lambda^2}{2K_m}\end{aligned} \tag{36}$$

$$\begin{aligned}J^{ir}_o = {} & b^{ir}_1 G_0 + (\alpha_{of} - \mu\alpha_{of} + \alpha_o)p_o + b^{ir}_1[\frac{(2a^{ir}_1 + b^{ir}_1)\gamma^2}{4K_e} + \frac{a^{ir}_1\lambda^2}{K_m}] + \frac{{p_o}^2\eta^2(2-\mu)^2}{2K_a} \\ & + \frac{(1-\mu)p_o\varepsilon\beta^2(w\varepsilon + p_f + \varepsilon\mu p_o)}{K_s}\end{aligned} \tag{37}$$

$$\begin{aligned}J^{ir} = {} & (a^{ir}_1 + b^{ir}_1)G_0 + (\alpha_{of} + \alpha_o)B + p_f\alpha_f + \frac{(\mu\varepsilon p_o + w\varepsilon + p_f)[(2-\mu)\varepsilon p_o + w\varepsilon + p_f]\beta^2}{2K_s} \\ & + \frac{(2-\mu)(2p_o + 2p_f\varepsilon + \mu p_o + 4w)p_o\eta^2}{2K_a} + [\frac{(2a^{ir}_1 + b^{ir}_1)^2\gamma^2}{8K_e} + \frac{a^{ir2}_1\lambda^2}{2K_m}] \\ & + b^{ir}_1[\frac{(2a^{ir}_1 + b^{ir}_1)^2\gamma^2}{4K_e} + \frac{a^{ir2}_1\lambda^2}{K_m}]\end{aligned} \tag{38}$$

The values of $a_1^{ir}$ and $b_1^{ir}$, and the proofs of propositions 13, 14, 15 are shown in Appendix A.

## 5. Model Comparison

By comparing the optimal solutions of five different decision models, obtain the following conclusions. And the proofs of corollaries are shown in Appendix A.

**Corollary 1.** *The optimal organic traceability technology efforts of the five modes in descending order are:*

$$\begin{cases} E^c > E^{ir} > E^i > E^d > E^r & p_f > p_o - 2w \\ E^c > E^{ir} > E^d > E^i > E^r & (1-\frac{1}{2}\mu)p_o - 2w < p_f < p_o - 2w \\ E^c > E^d > E^{ir} > E^i > E^r & (1-\mu)p_o - 2w < p_f < (1-\frac{1}{2}\mu)p_o - 2w \\ E^c > E^d > E^{ir} > E^r > E^i & (1-\frac{3}{2}\mu)p_o - 2w < p_f < (1-\mu)p_o - 2w \\ E^c > E^d > E^r > E^{ir} > E^i & p_f < (1-\frac{3}{2}\mu)p_o - 2w \end{cases}$$

The organic traceability technology effort in the centralized decision mode is always the highest. When the relationship among offline marginal income ratio, offline marginal income ratio, and wholesale price is different, the relationship among organic traceability technology efforts in different decision modes except the centralized-decision mode is different.

**Corollary 2.** *The optimal organic growing efforts, service inputs and propaganda inputs in the five modes in descending order are:*

$$M^c > M^{ir} = M^r > M^i = M^d,\ S^c > S^{ir} = S^r > S^i = S^d,\ A^c > A^i = A^d > A^r = A^{ir}$$

The organic growing effort in the centralized decision mode is the highest, followed by organic growing effort in the decentralized decision mode with a comprehensive contract and a revenue sharing contract, and organic growing effort in the decentralized decision mode with an information traceability cost sharing contract and the fully decentralized decision at the end. The service input in the centralized decision mode is the highest, followed by the service input in the decentralized decision mode with a comprehensive contract and a revenue sharing contract, and service input in the decentralized decision mode with an information traceability cost sharing contract and fully decentralized decision at the end. The propaganda input in the centralized decision is the highest, followed by propaganda input in the decentralized decision mode with an information traceability cost sharing contract and fully decentralized decision, and propaganda input in the decentralized decision mode with a comprehensive contract and a revenue sharing contract at the end.

**Corollary 3.** *The information traceability cost of ratio of the two modes in descending order are:*

$$\begin{cases} \theta^{ir} > \theta^i, & 2w + p_f > (1-\frac{3}{2}\mu)p_o \\ \theta^{ir} = \theta^i = 0, & 2w + p_f < (1-\frac{3}{2}\mu)p_o \end{cases}$$

The information traceability cost of ratio in the decentralized decision mode with a comprehensive contract is greater than or equal to the information traceability cost of ratio in the decentralized decision mode with an information traceability cost sharing contract.

**Corollary 4.** *Let* $H = \frac{\lambda^2 K_e}{\gamma^2 K_m}$ *and when* $0 < H < \frac{1}{4}$, *the optimal steady-state value of organic levels of the five modes in descending order are:*

$$\begin{cases} G^c_{RSS} > G^{ir}_{RSS} > G^i_{RSS} > G^d_{RSS} > G^r_{RSS} & p_f > p_o - 2w \\ G^c_{RSS} > G^{ir}_{RSS} > G^d_{RSS} > G^i_{RSS} > G^r_{RSS} & (1 - \frac{1}{2}\mu - H\mu)p_o - 2w < p_f < p_o - 2w \\ G^c_{RSS} > G^d_{RSS} > G^{ir}_{RSS} > G^i_{RSS} > G^r_{RSS} & (1 - \mu + H\mu)p_o - 2w < p_f < (1 - \frac{1}{2}\mu - H\mu)p_o - 2w \\ G^c_{RSS} > G^d_{RSS} > G^{ir}_{RSS} > G^r_{RSS} > G^i_{RSS} & (1 - \frac{3}{2}\mu)p_o - 2w < p_f < (1 - \mu + H\mu)p_o - 2w \\ G^c_{RSS} > G^d_{RSS} > G^r_{RSS} > G^{ir}_{RSS} > G^i_{RSS} & p_f < (1 - \frac{3}{2}\mu)p_o - 2w \end{cases}$$

When $\frac{1}{4} < H < 1$, the optimal steady-state value of organic levels of the five models in descending order are:

$$\begin{cases} G^c_{RSS} > G^{ir}_{RSS} > G^i_{RSS} > G^d_{RSS} > G^r_{RSS} & p_f > p_o - 2w \\ G^c_{RSS} > G^{ir}_{RSS} > G^d_{RSS} > G^i_{RSS} > G^r_{RSS} & (1 - \mu + H\mu)p_o - 2w < p_f < p_o - 2w \\ G^c_{RSS} > G^{ir}_{RSS} > G^d_{RSS} > G^r_{RSS} > G^i_{RSS} & (1 - \frac{1}{2}\mu - H\mu)p_o - 2w < p_f < (1 - \mu + H\mu)p_o - 2w \\ G^c_{RSS} > G^d_{RSS} > G^{ir}_{RSS} > G^r_{RSS} > G^i_{RSS} & (1 - \frac{3}{2}\mu)p_o - 2w < p_f < (1 - \frac{1}{2}\mu - H\mu)p_o - 2w \\ G^c_{RSS} > G^d_{RSS} > G^r_{RSS} > G^{ir}_{RSS} > G^i_{RSS} & p_f < (1 - \frac{3}{2}\mu)p_o - 2w \end{cases}$$

When $H > 1$, the optimal steady-state value of organic levels of the five models in descending order are:

$$\begin{cases} G^c_{RSS} > G^{ir}_{RSS} > G^i_{RSS} > G^r_{RSS} > G^d_{RSS} & p_f > (1 - \mu + H\mu)p_o - 2w \\ G^c_{RSS} > G^{ir}_{RSS} > G^r_{RSS} > G^i_{RSS} > G^d_{RSS} & p_o - 2w < p_f < (1 - \mu + H\mu)p_o - 2w \\ G^c_{RSS} > G^{ir}_{RSS} > G^r_{RSS} > G^d_{RSS} > G^i_{RSS} & (1 - \frac{3}{2}\mu)p_o - 2w < p_f < p_o - 2w \\ G^c_{RSS} > G^r_{RSS} > G^{ir}_{RSS} > G^d_{RSS} > G^i_{RSS} & (1 - \frac{1}{2}\mu - H\mu)p_o - 2w < p_f < (1 - \frac{3}{2}\mu)p_o - 2w \\ G^c_{RSS} > G^r_{RSS} > G^d_{RSS} > G^{ir}_{RSS} > G^i_{RSS} & p_f < (1 - \frac{1}{2}\mu - H\mu)p_o - 2w \end{cases}$$

The optimal steady-state value of the organic level in the centralized decision mode is always the highest. When the relationship among offline marginal income ratio, offline marginal income ratio, and wholesale price, and the relationship among cost coefficient of organic growing cost, cost coefficient of organic traceability cost, the impact of growing efforts on organic level, and the impact of traceability technology efforts on the organic level are different, the relative size of the optimal steady-state value of organic levels in different decision modes except the centralized decision mode is different.

**Corollary 5.** *The optimal overall long-term profits of the organic supply chain in descending order are:*

$$J^c > J^d,\ J^c > J^i,\ J^c > J^r,\ J^c > J^{ir} \text{(I)}$$

$$\begin{cases} J^i > J^d & p_f > p_o - 2w \\ J^i < J^d & p_f < p_o - 2w \end{cases} \quad \text{(II)}$$

The optimal overall long-term profit of the organic supply chain in the centralized decision mode is always the highest. When the offline marginal income ratio is larger than the boundary value, the overall long-term profit of the organic supply chain in the decentralized decision mode with an information traceability cost sharing contract is more than in the fully decentralized decision. When the offline marginal income ratio is lower than the boundary value, the overall long-term profit of the organic supply chain in the decentralized decision mode with an information traceability cost sharing contract is less than in the fully decentralized decision mode.

**Corollary 6.** *The optimal farmer cooperative's profits and online retailer's profits in descending order are:*

$$J_f^i > J_f^d \quad \text{(I)}$$

$$\begin{cases} J_o^i > J_o^d & p_f > p_o - 2w \\ J_o^i < J_o^d & p_f < p_o - 2w \end{cases} \quad \text{(II)}$$

A farmer cooperative's profit in the decentralized decision mode with an information traceability cost sharing contract is always more than in the fully decentralized decision mode. When the offline marginal income ratio is larger than the boundary value, the online retailer's profit in the decentralized decision mode with an information traceability cost sharing contract is more than in the fully decentralized decision. When the offline marginal income ratio is lower than the boundary value, the online retailer's profit in the decentralized decision mode with the information traceability cost sharing contract is less than in the fully decentralized decision.

## 6. Numerical Analysis

According to the assumptions and constraints in the five modes mentioned above, the specific values of the model parameters are set as: $\alpha_o = 0.3$, $\alpha_f = 0.5$, $\alpha_{of} = 0.2$, $K_a = 0.03$, $K_m = 0.05$, $K_s = 0.04$, $K_e = 0.025$, $p_f = 0.9$, $p_o = 0.6$, $w = 0.1$, $G_0 = 0.2$, $\beta = 0.2$, $\lambda = 0.4$, $\sigma = 0.3$, $\gamma = 0.3$, $\varepsilon = 0.3$, $\mu = 0.2$, $\rho = 0.053$, $\eta = 0.3$. The results are detailed in Table 3.

**Table 3.** Pricing, demand, and profit under different channels.

| Decision Conditions | Centralized Decision Mode (CD) | Fully Decentralized Decision Mode (DD) | Decentralized Decision Mode with Information Traceability Cost Sharing (IS) | Decentralized Decision Mode with Revenue Sharing (RS) | Decentralized Decision Mode with a comprehensive contract (IRS) |
|---|---|---|---|---|---|
| Organic growing effort (M) | 75.616 | 36.164 | 36.164 | 40.110 | 40.110 |
| Organic traceability technology effort (E) | 113.425 | 59.178 | 83.836 | 53.260 | 86.795 |
| Service input (S) | 5.550 | 4.650 | 4.650 | 4.830 | 4.830 |
| Propaganda input (A) | 16.700 | 12.000 | 12.000 | 10.800 | 10.800 |
| Information traceability cost sharing ratio ($\theta$) | - | - | 0.294 | - | 0.386 |
| Steady-state value of the organic level ($G_{RSS}$) | 64.274 | 32.219 | 39.616 | 32.022 | 42.082 |
| Farmer cooperative's profit ($J^f$) | - | 116.480 | 124.080 | 124.234 | 138.291 |
| Online retailer's profit ($J^o$) | - | 118.727 | 136.967 | 109.719 | 132.044 |
| Overall long-term profit ($J$) | 311.250 | 235.208 | 261.047 | 233.953 | 270.335 |

In this numerical example, we have $p_f > p_o - 2w$. As shown in Table 3, the optimal decision variables in the centralized decision mode are larger than others. The organic growing efforts and service inputs in the decentralized decision mode with a revenue sharing contract and a comprehensive contract are larger than those in the fully decentralized decision mode and the decentralized decision mode with an information traceability cost sharing contract. The organic traceability technology effort and the steady-state value of the organic level in the decentralized decision mode with a comprehensive contract is the largest, followed by the decentralized decision mode with an information traceability cost sharing contract, and then the fully decentralized decision, the decentralized decision mode with a revenue sharing contract, is at the end. The propaganda input in the fully decentralized decision mode and the decentralized decision mode with an information traceability cost sharing contract is larger than in the decentralized decision mode with a revenue sharing contract and the decentralized decision mode with a comprehensive contract. The farmer cooperative's profit in the decentralized decision mode with a comprehensive contract is the largest, followed by the decentralized decision mode with a revenue sharing contract, and then the decentralized decision mode with information traceability cost sharing contract, the fully decentralized decision mode is at the end. The online retailer's profit in the decentralized decision mode with an information traceability cost sharing contract is the largest, followed by the decentralized decision mode with a comprehensive contract, and then the fully decentralized decision mode, the decentralized decision mode with a revenue sharing contract is at the end. The overall long-term profit in the decentralized decision mode with a comprehensive contract is the largest, followed by the decentralized decision mode with an information traceability cost sharing contract, and then the fully decentralized decision, the decentralized decision mode with a revenue sharing contract is at the end.

As shown in Figure 2, even if the organic level is disturbed by technical errors and other factors deviating from the stable state, it can return over time. And the numerical example is one of the cases of $p_f > p_o - 2w$ and $\frac{1}{4} < H < 1$, $G^c_{RSS} > G^{ir}_{RSS} > G^i_{RSS} > G^d_{RSS} > G^r_{RSS} > G_0$. The organic level is monotonically increasing.

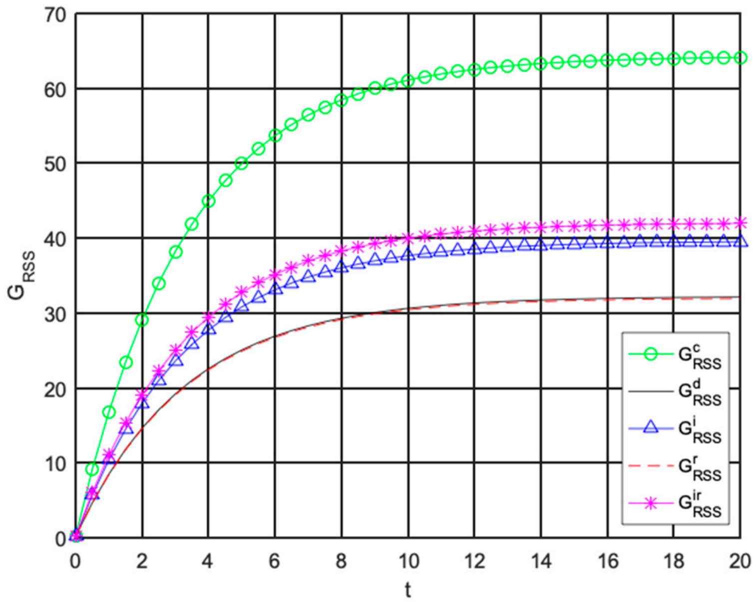



**Figure 2.** The optimal trajectories of the organic level.

As shown in Figure 3, the optimal overall long-term profit of the OASC ($J$) increase with the increase of the cross influence between channels ($\varepsilon$) and the consumer preferences of organic products ($\eta$). Correspondingly, when the cross influence between channels and the consumer preferences of organic products are at the maximum, the optimal overall long-term profit of the OASC reaches the maximum. The degree of influence of the cross influence between channels on the optimal overall long-term profit of the OASC is smaller than that of the consumer preferences of organic products. These indicate that the cross influence between channels and consumers' preferences of organic products could bring more long-term profit of the OASC.

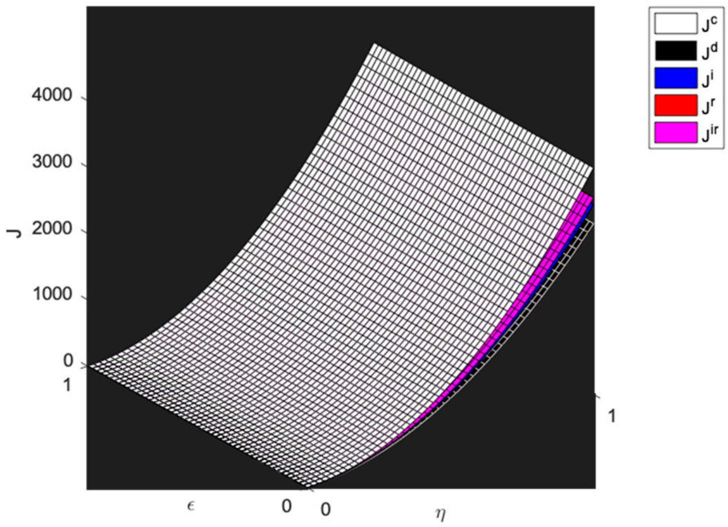
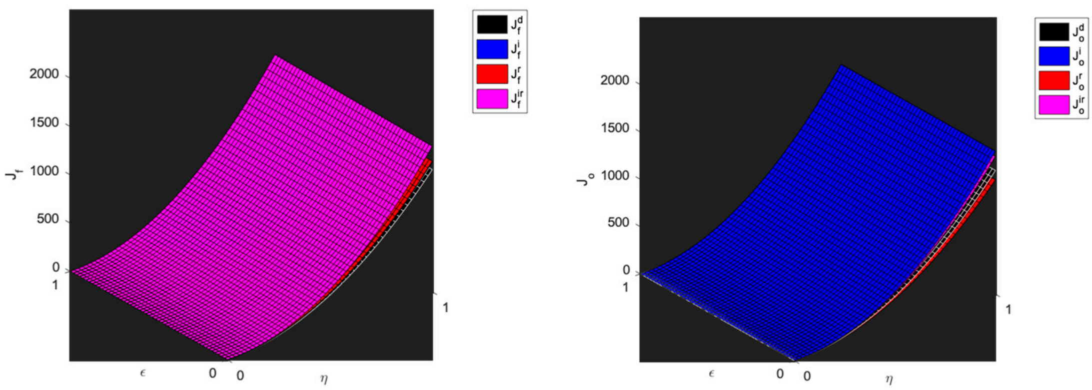



**Figure 3.** The optimal overall long-term profit of the OASC versus $\varepsilon$ and $\eta$.

As shown in Figure 4, the optimal farmer cooperative's profit ($J_f$), online retailer's profit ($J_o$) increase with the increase of the cross influence between channels ($\varepsilon$) and the consumer preferences of organic products ($\eta$). Correspondingly, when the cross influence between channels and the consumer preferences of organic products are at the maximum, the optimal farmer cooperative's profit, online retailer's profit reaches the maximum. The degree of influence of the cross influence between channels on the optimal farmer cooperative's profit, online retailer's profit is smaller than that of the consumer preferences of organic products. These indicate that the cross influence between channels and consumers' preferences of organic products could bring more long-term profit of the participants in the OASC. And from Figure 4, we know that the optimal farmer cooperative's profit in a comprehensive contract is the most, while the online retailer's profit in an information traceability cost sharing contract is the most. Have they always been like this? We change the range of the offline marginal income ratio of a farmer cooperative, and get the Table 4.



(A) The optimal farmer cooperative's profit. (B) The optimal online retailer's profit.

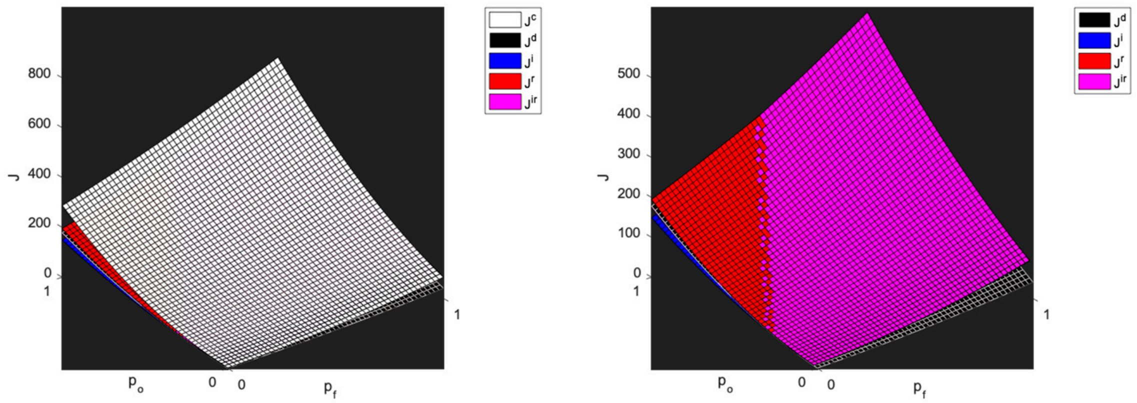
**Figure 4.** The optimal farmer cooperative's profit, online retailer's profit versus $\varepsilon$ and $\eta$.

**Table 4.** Optimal decisions of different members.

| Members | Decisions and Optimal Strategies | | |
|---|---|---|---|
| Organic Supply Chain | $0 < p_f < 0.220$<br>RS | $0.220 < p_f < 1$<br>IRS | -<br>- |
| Farmer Cooperative | $0 < p_f < 0.2199$<br>IRS | $0.2199 < p_f < 0.2200$<br>RS | $0.2200 < p_f < 1$<br>IRS |
| Online Retailer | $0 < p_f < 0.3938$<br>DC | $0.3938 < p_f < 0.4159$<br>IRS | $0.4159 < p_f < 1$<br>IS |

As shown in Table 2, when the offline marginal income ratio of a farmer cooperative ($p_f$) is less than the boundary value, the optimal decision mode for the OASC is the decentralized decision mode with a revenue sharing contract. And when the offline marginal income ratio of a farmer cooperative is greater than the boundary value, the optimal decision mode for the OASC is the decentralized decision mode with a comprehensive contract. When the offline marginal income ratio of a farmer cooperative is less than the boundary value (0.2199), the optimal decision mode for the farmer cooperative is the decentralized decision mode with a comprehensive contract. When the offline marginal income ratio of a farmer cooperative is greater than the boundary value (0.2200), the optimal decision mode for the farmer cooperative is the decentralized decision mode with a comprehensive contract. When the value of an offline marginal income ratio of a farmer cooperative lies between the two boundary values (0.2199, 0.2200), the optimal decision mode for the farmer cooperative is the decentralized decision mode with a revenue sharing contract. When the offline marginal income ratio of a farmer cooperative is less than the boundary value (0.3938), the optimal decision mode for the online retailer is the fully decentralized decision. When the offline marginal income ratio of a farmer cooperative is greater than the boundary value (0.4159), the optimal decision mode for the online retailer is the decentralized decision mode with an information traceability cost sharing contract. When the value of offline marginal income ratio of a farmer cooperative lies between the two boundary values (0.3938, 0.4159), the optimal decision mode for the online retailer is the decentralized decision mode with a comprehensive contract. Furthermore, we simultaneously change the values of the offline marginal income ratio of a farmer cooperative and the online marginal income ratio of online retailer, and get the following figures.

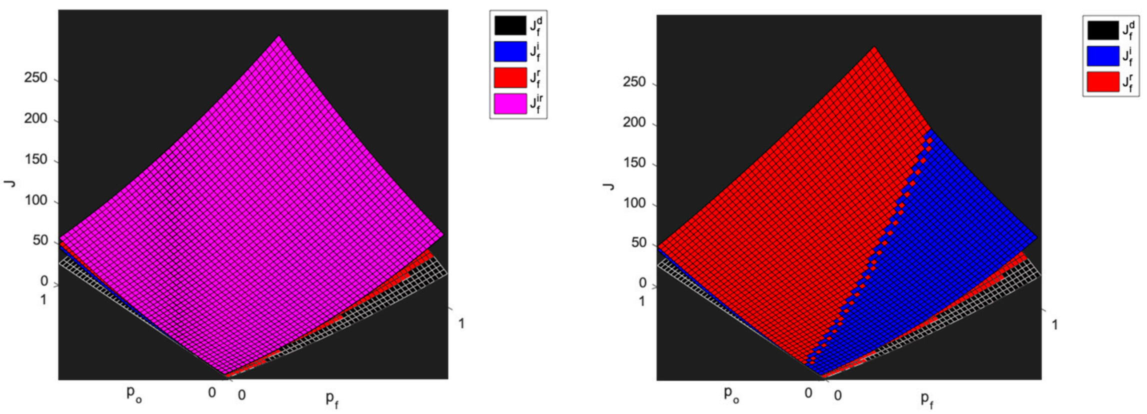
As shown in Figure 5, the optimal overall long-term profit of the OASC ($J$) increase with the increase of the online marginal income ratio of online retailer ($p_o$) and the offline marginal income ratio of a farmer cooperative ($p_f$). In the left part of Figure 5, the optimal overall long-term profit of the OASC in centralized decision is the most. And then we remove the centralized decision mode, get the right part of Figure 5. When the ratio of the offline marginal income ratio of a farmer cooperative to the online marginal income ratio of online retailer is larger than the boundary value, the optimal decision mode for the OASC is the decentralized decision mode with a comprehensive contract. When the ratio of the offline marginal income ratio of a farmer cooperative to the online marginal income ratio of online retailer is smaller than the boundary value, the optimal decision mode for the OASC is the decentralized decision mode with a revenue sharing contract.




(A) Five modes. (B) Four modes except for the centralized decision mode.

**Figure 5.** The optimal overall long-term profit of the OASC versus $p_o$ and $p_f$.

As shown in Figure 6, the optimal farmer cooperative's profit ($J_f$) increase with the increase of the online marginal income ratio of online retailer ($p_o$) and the offline marginal income ratio of a farmer cooperative ($p_f$). In the left part of Figure 6, the optimal farmer cooperative's profit in a comprehensive contract is the most. And then we remove the decentralized decision mode with a comprehensive contract, get the right part of Figure 6. When the ratio of the offline marginal income ratio of a farmer cooperative to the online marginal income ratio of online retailer is larger than the boundary value, the optimal decision mode for the farmer cooperative is the decentralized decision mode with a revenue sharing contract. When the ratio of the offline marginal income ratio of a farmer cooperative to the online marginal income ratio of online retailer is smaller than the boundary value, the optimal decision mode for the farmer cooperative is the decentralized decision mode with an information traceability cost sharing contract.




(A) Four modes. (B) Three modes except for the decentralized decision mode with a comprehensive contract.

**Figure 6.** The optimal farmer cooperative's profit versus $p_o$ and $p_f$.

As shown in Figure 7, the optimal online retailer's profit ($J_o$) increases with the increase of the online marginal income ratio of online retailer ($p_o$) and the offline marginal income ratio of a farmer cooperative ($p_f$). When the ratio of the offline marginal income ratio of a farmer cooperative to the online marginal income ratio of online retailer is larger than the boundary value, the optimal decision mode for the online retailer is the decentralized decision mode with an information traceability cost sharing contract. When the ratio of the offline marginal income ratio of a farmer cooperative to the online marginal income ratio of online retailer is smaller than the boundary value, the optimal decision mode for the online retailer is the fully decentralized decision. When the ratio of the offline marginal income ratio of a farmer cooperative to the online marginal income ratio of online retailer is near the boundary value, the optimal decision mode for the online retailer is the decentralized decision mode with a comprehensive contract.

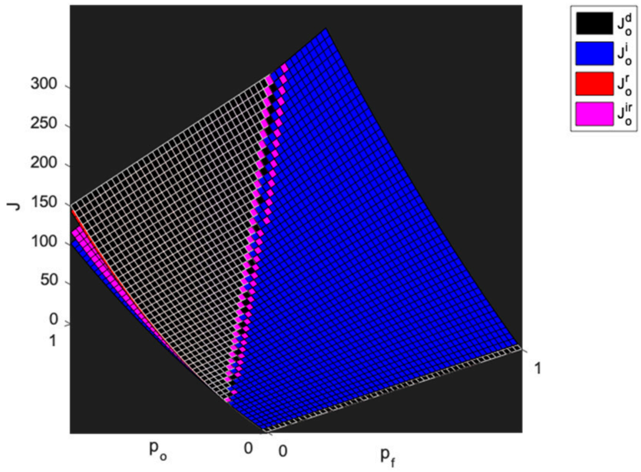



**Figure 7.** The optimal online retailer's profit versus $p_o$ and $p_f$.

## 7. Discussion

### *7.1. Findings*

We designed different contracts, as in the literature [25,49], and summarized the following findings by analyzing and comparing them.

(1) Even if the optimal state trajectory of the organic level is disturbed by technical errors and other factors deviating from the stable state, it can return over time. It is monotone and time-varying, similar to the literature [46]. The sequence of the optimal state trajectory of the organic level in different decision modes is related to the impact of growing efforts and traceability technology efforts on organic level, the cost coefficient of organic growing cost and the organic traceability cost, the offline and online marginal income ratio, the wholesale price of organic products, and sharing revenue ratio. The optimal state trajectory of the organic level in the centralized decision mode is always the highest. The rest can be divided into two cases. The first case is, the ratio of the cost coefficient of organic growing cost to the square of the impact of growing efforts on the organic level is more than the ratio of the cost coefficient of organic traceability cost to the square of the impact of traceability technology efforts on organic level. When the offline marginal income ratio is relatively large, the decentralized decision mode with a comprehensive contract is a better choice from the perspective of the organic level, otherwise, the fully decentralized decision mode is a better choice. In other words, in some cases, non-cooperation is the better choice. This is different from the literature [25] that finds that cooperation is always better than non-cooperation. The second case is, the ratio of the cost coefficient of the organic growing cost to the square of the impact of growing efforts on the organic level is less than the ratio of the cost coefficient of the organic traceability cost to the square of the impact of traceability technology efforts on organic level. When the offline marginal income ratio is relatively large, the decentralized decision mode with a comprehensive contract is a better choice from the perspective of the organic level, otherwise, the decentralized decision mode with a revenue sharing contract is a better choice.

(2) Regarding the service input, the incentive of the decentralized decision mode with a comprehensive contract and the decentralized decision mode with a revenue sharing contract to a farmer cooperative is bigger than that of the decentralized decision mode with an information

traceability cost sharing contract and the fully decentralized decision mode. Regarding the propaganda input, the incentive of the decentralized decision mode with an information traceability cost sharing contract and the fully decentralized decision mode to online retailer is bigger than that of the decentralized decision mode with a comprehensive contract and the decentralized decision mode with a revenue sharing contract. From the perspective of an information traceability cost sharing, cooperation in the comprehensive contract is more vigorous than an information traceability cost sharing contract.

(3) The higher the cross influence between channels is, the profits of the farmer cooperative, the online retailer and the OASC are more. As mentioned in literature [32,33], for the omni-channel supply chain system, the cross-influence of information transmission between channels can bring more profits. Improving the consumer preferences of organic products is good for farmer cooperatives, online retailers, and the OASC in that they can get more profits. This is consistent with the conclusion in the literature [25]. The improvement of consumers' sustainable consciousness is beneficial to all members of the sustainable supply chain system.

(4) The optimal profits of participants in the OASC in the centralized decision mode are always the highest. But because this cooperation is hard to achieve, we will not discuss it for the time being. For the OASC, in most cases, choosing the comprehensive contract is beneficial to profit, while in a few cases, choosing a revenue sharing contract is beneficial to profit, which means in all cases BOPS revenue should be shared, and this result is consistent with the literature [15]. For the farmer cooperative, in almost all cases, choosing the decentralized decision mode with a comprehensive contract is beneficial to profit. For the online retailer, in most cases, choosing the decentralized decision mode with an information traceability cost sharing contract is beneficial to profit, while in a few cases, choosing the fully decentralized decision mode is beneficial to profit, in addition, a very small fraction, choosing the decentralized decision mode with a comprehensive contract is beneficial to profit. Generally speaking, the OASC and the farmer cooperative are more inclined to the decentralized decision mode with a comprehensive contract. In a very small fraction, the decentralized decision mode with a comprehensive contract is best choice for the farmer cooperative, the online retailer and the OASC.

### *7.2. Managerial Implications*

(1) Farmer cooperatives and online retailers should propagate the advantages of organic agricultural products and their significance to the sustainable development of ecological environment in order to improve consumers' organic product preferences. People's preference for organic products and their concern for sustainable development make the members of supply chains profitable from the microcosmic point of view, and it is beneficial to the sustainable development of the whole society from the macroscopic point of view.

(2) It shows that the interaction between channels is beneficial to each other in the environment of omni-channel. Participants should look at the problem more cooperatively than pure competitive relationship, which is conducive to the sustainable development of the market.

(3) Participants in the OASC should choose the mode of cooperation according to the actual situation. Before deciding which contract to choose, farmer cooperatives and online retailers should be fully aware of their own and the other party's business situation. The relative situation between them will affect the effect of the contract. In most cases, their respective best contracts are not consistent, and at this point, if they can stand in the overall perspective of the supply chain to make decisions is the best. They can choose the best contract for the whole, and then negotiate additional agreements on profit sharing.

## 8. Conclusions

This paper focuses on competition and cooperation between the farmer cooperative and the online retailer in the omni-channel OASC. There are three shopping ways in the omni-channel OASC, compared with dual-channel supply chain, customers have a new shopping way that they could buy organic agricultural products in online channel and then pick up in offline channel. For this sake, the relationship between the farmer cooperative and the online retailer in the omni-channel OASC is more complex. We establish five models characterizing five decision modes based on differential game theory to discuss the optimal decisions of organic growing effort, organic traceability technology effort, propaganda input, and service input, and the profits of the farmer cooperative, the online retailer and the overall supply chain. In addition, coefficients which represent consumer preferences of organic products, cross influence between channels, marginal income ratio of a farmer cooperative and online retailer, are introduced into the five models, namely the centralized decision mode, the fully decentralized decision mode, the decentralized decision mode with an information traceability cost sharing contract, the decentralized decision mode with a revenue sharing contract, and the decentralized decision mode with a comprehensive contract. By analyzing and comparing the optimal decisions of five models, we have come to some conclusions. In each mode, the higher consumer preferences of organic products and cross influence between channels are, the more benefits the farmer cooperative and the online retailer will have. When choosing the optimal contract, the members in the OASC will be affected by the relative size of the offline marginal income ratio of a farmer cooperative and the online marginal income ratio of online retailer.

We made some assumptions for the sake of simplicity of calculation, and there are some limitations, and these can also be regarded as the direction of our extended research. Firstly, we have given the demand function by assumption and assigned values directly to the parameters in numerical experiments according to the earlier studies. The demand function based on the consumer utility function may be closer to reality. Data obtained through field surveys may be more specific. Secondly, we assumed that the freshness of organic agricultural products does not change over time in a short period of time. In extended research, we will consider the time-varying freshness of organic agricultural products. Finally, consumers are considered to be homogeneous and non-strategic in this paper. However, when the freshness of organic agricultural products decreases with time, the price may be discounted. Some consumers may become strategic consumers which have been studied more recently [52–55]. We will consider the impact of strategic consumers on optimal decision making in extended research.

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## Appendix A

$$a_1^c = \frac{(2w + 2p_o + p_f)\eta}{\rho + \sigma},\ B = w + p_o,\ a_1^d = \frac{(2w + p_f)\eta}{\rho + \sigma},\ b_1^d = \frac{2p_o\eta}{\rho + \sigma},$$
$$a_1^i = \frac{(2w + p_f)\eta}{\rho + \sigma},\ b_1^i = \frac{2p_o\eta}{\rho + \sigma},$$
$$a_1^r = \frac{(2w + p_f + \mu p_o)\eta}{\rho + \sigma},\ b_1^r = \frac{(2 - \mu)p_o\eta}{\rho + \sigma},\ a_1^{ir} = \frac{(2w + p_f + \mu p_o)\eta}{\rho + \sigma},$$
$$b_1^{ir} = \frac{(2 - \mu)p_o\eta}{\rho + \sigma}.$$

**Proof of Proposition 1, 2, 3.** The optimal value function of the OASC's profit at time t is

$$J^c(E,M,S,A) = e^{-\rho t}V^c(E,M) \tag{A1}$$

According to the optimal control theory, for any $E \geq 0$ and $M \geq 0$, $V^c(E,M)$ satisfies the Hamilton–Jacobi–Bellman function as

$$\begin{aligned}\rho V^c(E,M) = \max_{A,S,E,M}&[(p_o+w)(d_o+d_{of})+p_f d_f-\frac{1}{2}K_a A^2-\frac{1}{2}K_e E^2\\ &-\frac{1}{2}K_s S^2-\frac{1}{2}K_m M^2+V^{c\prime}(\lambda M+\gamma E-\sigma G)]\end{aligned} \tag{A2}$$

By solving the necessary conditions for the optimal decisions which are

$$\frac{\partial \rho V^c(E,M)}{\partial A}=0,\ \frac{\partial \rho V^c(E,M)}{\partial S}=0,\ \frac{\partial \rho V^c(E,M)}{\partial E}=0,\ \frac{\partial \rho V^c(E,M)}{\partial M}=0, \tag{A3}$$

we get:

$$E^c=\frac{\gamma V^{c\prime}}{K_e}, M^c=\frac{\lambda V^{c\prime}}{K_m}, S^c=\frac{(\varepsilon w+p_f+\varepsilon p_o)\beta}{K_s}, A^c=\frac{(2w+\varepsilon p_f+2p_o)\eta}{K_a} \tag{A4}$$

Substitute Equation (A4) into Equation (A2), and get Equation (A5)

$$\begin{aligned}\rho V^c(E,M) &= [2\eta p_o+(p_f+2w)\eta-V^{c\prime}\sigma]G_0+(\alpha_o+\alpha_{of})(p_o+w)+\alpha_f p_f\\ &+\frac{\beta^2(w\varepsilon+\varepsilon p_o+p_f)^2}{2K_s}+\frac{\eta^2(\varepsilon p_f+2w+2p_o)^2}{2K_a}+\frac{(\gamma V^{c\prime})^2}{2K_e}+\frac{(\lambda V^{c\prime})^2}{2K_m}\end{aligned} \tag{A5}$$

Assume $V^c(E,M)$ is a linear expression of $G_0$,

$$V^c(E,M)=a_1^c G_0+a_2^c \tag{A6}$$

where $a_1^c$ and $a_2^c$ are unknown constants.

From Equations (A5) and (A6), we get

$$\begin{aligned}a_1^c &= \frac{(2w+2p_o+p_f)\eta}{\rho+\sigma}\\ a_2^c &= (\alpha_o+\alpha_{of})(p_o+w)+p_f\alpha_f+\frac{(\varepsilon B+p_f)^2\beta^2}{2K_s}+\frac{(\varepsilon p_f+2B)^2\eta^2}{2K_a}+(\frac{\lambda^2}{K_m}+\frac{\gamma^2}{K_e})\frac{a_1^{c2}}{2}\end{aligned} \tag{A7}$$

According to $V^{c\prime}=a_1^c$, substitute Equation (A7) into Equations (A4), (A6) and (1), and then get the optimal decisions of the OASC in the centralized decision mode shown in (8)–(10). □

**Proof of Proposition 4, 5, and 6.** The optimal value function of the farmer cooperative's profit at time t is

$$J_f^d(M,S)=e^{-\rho t}V_f^d(E,M) \tag{A8}$$

The optimal value function of the online retailer's profit at time t is

$$J_o^d(E,A)=e^{-\rho t}V_o^d(E,M) \tag{A9}$$

According to the optimal control theory, for any $E \geq 0$ and $M \geq 0$, $V_f^d(E,M)$ and $V_o^d(E,M)$ satisfy the Hamilton–Jacobi–Bellman function as

$$\rho V_f^d(E,M)=\max_{S,M}[p_f d_f+w(d_o+d_{of})-\frac{1}{2}K_m M^2-\frac{1}{2}K_s S^2+V_f^{d\prime}(\lambda M+\gamma E-\sigma G)] \tag{A10}$$

$$\rho V_o^d(E,M) = \max_{A,E}[p_o(d_o + d_{of}) - \frac{1}{2}K_a A^2 - \frac{1}{2}K_e E^2 + V_o^{d\prime}(\lambda M + \gamma E - \sigma G)] \tag{A11}$$

Using the backward induction method, the necessary conditions for the optimal decisions of the online retailer is

$$\frac{\partial \rho V_o^d(E,M)}{\partial A} = 0,\ \frac{\partial \rho V_o^d(E,M)}{\partial E} = 0, \tag{A12}$$

By solving the Equation (A12), we get

$$E^d = \frac{\gamma V_o^{d\prime}}{K_e}, A^d = \frac{2\eta p_o}{K_a} \tag{A13}$$

Substitute Equation (A13) into Equation (A10), and then solve the necessary conditions for the optimal decisions of a farmer cooperative,

$$\frac{\partial \rho V_f^d(E,M)}{\partial S} = 0,\ \frac{\partial \rho V_f^d(E,M)}{\partial M} = 0, \tag{A14}$$

we get

$$S^d = \frac{(\varepsilon w + p_f)\beta}{K_s}, M^d = \frac{\lambda V_f^{d\prime}}{K_m}, \tag{A15}$$

Substitute Equations (A13) and (A15) into Equations (A10) and (A11), and get Equations (A16) and (A17)

$$\begin{aligned}\rho V_f^d(E,M) &= [(2w + p_f)\eta - \sigma V_f^{d\prime}]G_0 + (\alpha_o + \alpha_{of})w + \alpha_f p_f + \frac{\beta^2(w\varepsilon + p_f)^2}{2K_s} \\ &+ \frac{2(p_f\varepsilon + 2w)\eta^2 p_o}{K_a} + \frac{\lambda^2 (V_f^{d\prime})^2}{2K_m} + \frac{\gamma^2 V_f^{d\prime} V_o^{d\prime}}{K_e}\end{aligned} \tag{A16}$$

$$\begin{aligned}\rho V_o^d(E,M) &= (2p_o\eta - \sigma V_o^{d\prime})G_0 + (\alpha_o + \alpha_{of})p_o + \frac{(w\varepsilon + p_f)\varepsilon\beta^2 p_o}{K_s} + \frac{2\eta^2 {p_o}^2}{K_a} \\ &+ \frac{\lambda^2 V_f^{d\prime} V_o^{d\prime}}{K_m} + \frac{\gamma^2 (V_o^{d\prime})^2}{2K_e}\end{aligned} \tag{A17}$$

Assume $V_f^d(E,M)$ and $V_o^d(E,M)$ are linear expressions of $G_0$,

$$V_f^d(E,M) = a_1^d G_0 + a_2^d \tag{A18}$$

$$V_o^d(E,M) = b_1^d G_0 + b_2^d \tag{A19}$$

where $a_1^d$, $a_2^d$, $b_1^d$, $b_2^d$ are unknown constants.

From Equations (A16)–(A19), we get

$$\begin{aligned} a_1^d &= \frac{(2w + p_f)\eta}{\rho + \sigma},\ b_1^d = \frac{2p_o\eta}{\rho + \sigma}, \\ a_2^d &= (\alpha_o + \alpha_{of})w + \alpha_f p_f + \frac{\beta^2(w\varepsilon + p_f)^2}{2K_s} + \frac{2(p_f\varepsilon + 2w)\eta^2 p_o}{K_a} + \frac{\lambda^2 (a_1^d)^2}{2K_m} + \frac{\gamma^2 a_1^d b_1^d}{K_e}, \\ b_2^d &= (\alpha_o + \alpha_{of})p_o + \frac{(w\varepsilon + p_f)\varepsilon\beta^2 p_o}{K_s} + \frac{2\eta^2 {p_o}^2}{K_a} + \frac{\lambda^2 a_1^d b_1^d}{K_m} + \frac{\gamma^2 (b_1^d)^2}{2K_e}\end{aligned} \tag{A20}$$

According to $V_f^{d\prime} = a_1^d$ and $V_o^{d\prime} = b_1^d$, substitute Equation (A20) into Equations (A13), (A15), (A18), (A19), and (1), and then get the optimal decisions of the farmer cooperative and the online retailer in the fully decentralized decision mode shown in (13)–(17). □

**Proof of Proposition 7, 8, and 9.** The optimal value function of the farmer cooperative's profit at time t is

$$J_f^i(M,S,\theta) = e^{-\rho t} V_f^i(E,M) \tag{A21}$$

The optimal value function of the online retailer's profit at time t is

$$J_o^i(E,A) = e^{-\rho t} V_o^i(E,M) \tag{A22}$$

According to the optimal control theory, for any $E \geq 0$ and $M \geq 0$, $V_f^i(E,M)$ and $V_o^i(E,M)$ satisfy the Hamilton–Jacobi–Bellman function as

$$\rho V_f^i(E,M) = \max_{S,M,\theta} [p_f d_f + w(d_o + d_{of}) - \frac{1}{2} K_m M^2 - \frac{1}{2} K_s S^2 - \frac{1}{2} \theta K_e E^2 + V_f^{i\prime}(\lambda M + \gamma E - \sigma G)] \tag{A23}$$

$$\rho V_o^i(E,M) = \max_{A,E} [p_o(d_o + d_{of}) - \frac{1}{2} K_a A^2 - \frac{1}{2}(1-\theta) K_e E^2 + V_o^{i\prime}(\lambda M + \gamma E - \sigma G)] \tag{A24}$$

Using the backward induction method, the necessary conditions for the optimal decisions of the online retailer is

$$\frac{\partial \rho V_o^i(E,M)}{\partial A} = 0,\ \frac{\partial \rho V_o^i(E,M)}{\partial E} = 0, \tag{A25}$$

By solving the Equation (A25), we get

$$E^i = \frac{\gamma V_o^{i\prime}}{(1-\theta) K_e}, A^i = \frac{2\eta p_o}{K_a} \tag{A26}$$

Substitute Equation (A26) into Equation (A23), and then solve the necessary conditions for the optimal decisions of a farmer cooperative,

$$\frac{\partial \rho V_f^i(E,M)}{\partial S} = 0,\ \frac{\partial \rho V_f^i(E,M)}{\partial M} = 0,\ \frac{\partial \rho V_f^i(E,M)}{\partial \theta} = 0, \tag{A27}$$

we get

$$S^i = \frac{(\varepsilon w + p_f)\beta}{K_s}, M^i = \frac{\lambda V_f^{i\prime}}{K_m},\ \theta^i = \frac{2V_f^{i\prime} - V_o^{i\prime}}{2V_f^{i\prime} + V_o^{i\prime}} \tag{A28}$$

Substitute Equation (A28) into Equation (A25), and then substitute into (A23) and (A24), and get Equations (A29) and (A30)

$$\begin{aligned} \rho V_f^i(E,M) &= [(2w + p_f)\eta - \sigma V_f^{i\prime}] G_0 + (\alpha_o + \alpha_{of}) w + \alpha_f p_f + \frac{\beta^2 (w\varepsilon + p_f)^2}{2K_s} \\ &+ \frac{(p_f \varepsilon + 2w)\eta^2 p_o}{K_a} + \frac{\lambda^2 (V_f^{i\prime})^2}{2K_m} + \frac{\gamma^2 (2V_f^{i\prime} + V_o^{i\prime})^2}{8K_e} \end{aligned} \tag{A29}$$

$$\begin{aligned} \rho V_o^i(E,M) &= (2p_o \eta - \sigma V_o^{i\prime}) G_0 + (\alpha_o + \alpha_{of}) w + \frac{(w\varepsilon + p_f)\varepsilon \beta^2 p_o}{K_s} + \frac{2\eta^2 p_o}{K_a} \\ &+ \frac{\lambda^2 V_f^{i\prime} V_o^{i\prime}}{K_m} + \frac{\gamma^2 V_o^{i\prime} (2V_f^{i\prime} + V_o^{i\prime})}{4K_e} \end{aligned} \tag{A30}$$

Assume $V_f^i(E,M)$ and $V_o^i(E,M)$ are linear expressions of $G_0$,

$$V_f^i(E,M) = a_1^i G_0 + a_2^i \tag{A31}$$

$$V_o^i(E,M) = b_1^i G_0 + b_2^i \tag{A32}$$

where $a_1^i$, $a_2^i$, $b_1^i$, $b_2^i$ are unknown constants.

From Equations (A29)–(A32), we get

$$\begin{aligned} a_1^d &= \frac{(2w+p_f)\eta}{\rho+\sigma},\ b_1^d = \frac{2p_o\eta}{\rho+\sigma}, \\ a_2^i &= (\alpha_o+\alpha_{of})w + \alpha_f p_f + \frac{\beta^2(w\varepsilon+p_f)^2}{2K_s} + \frac{(p_f\varepsilon+2w)\eta^2 p_o}{K_a} + \frac{\lambda^2(a_1^i)^2}{2K_m} + \frac{\gamma^2(2a_1^i+b_1^i)^2}{8K_e}, \\ b_2^i &= (\alpha_o+\alpha_{of})p_o + \frac{(w\varepsilon+p_f)\varepsilon\beta^2 p_o}{K_s} + \frac{2\eta^2 {p_o}^2}{K_a} + \frac{\lambda^2 a_1^i b_1^i}{K_m} + \frac{\gamma^2 b_1^i(2a_1^i+b_1^i)}{4K_e} \end{aligned} \tag{A33}$$

According to $V_f^{i\prime} = a_1^i$ and $V_o^{i\prime} = b_1^i$, substitute Equation (A33) into Equations (A26), (A28), (A31), (A32), and (1), and then get the optimal decisions of the farmer cooperative and the online retailer in the decentralized decision mode with an information traceability cost sharing contract shown in (20)–(24). □

**Proof of Proposition 10, 11, and 12.** The optimal value function of the farmer cooperative's profit at time t is

$$J_f^r(M,S) = e^{-\rho t} V_f^r(E,M) \tag{A34}$$

The optimal value function of the online retailer's profit at time t is

$$J_o^r(E,A) = e^{-\rho t} V_o^r(E,M) \tag{A35}$$

According to the optimal control theory, for any $E \geq 0$ and $M \geq 0$, $V_f^r(E,M)$ and $V_o^r(E,M)$ satisfy the Hamilton–Jacobi–Bellman function as

$$\rho V_f^r(E,M) = \max_{S,M}[p_f d_f + w(d_o+d_{of}) + \mu p_o d_{of} - \frac{1}{2}K_m M^2 - \frac{1}{2}K_s S^2 + V_f^{r\prime}(\lambda M + \gamma E - \sigma G)] \tag{A36}$$

$$\rho V_o^r(E,M) = \max_{A,E}[p_o d_o + (1-\mu)p_o d_{of} - \frac{1}{2}K_a A^2 - \frac{1}{2}K_e E^2 + V_o^{r\prime}(\lambda M + \gamma E - \sigma G)] \tag{A37}$$

Using the backward induction method, the necessary conditions for the optimal decisions of the online retailer is

$$\frac{\partial \rho V_o^r(E,M)}{\partial A} = 0,\ \frac{\partial \rho V_o^r(E,M)}{\partial E} = 0, \tag{A38}$$

By solving the Equation (A38), we get

$$E^r = \frac{\gamma V_o^{r\prime}}{K_e}, A^r = \frac{(2-\mu)\eta p_o}{K_a} \tag{A39}$$

Substitute Equation (A39) into Equation (A36), and then solve the necessary conditions for the optimal decisions of a farmer cooperative,

$$\frac{\partial \rho V_f^r(E,M)}{\partial S} = 0,\ \frac{\partial \rho V_f^r(E,M)}{\partial M} = 0, \tag{A40}$$

we get

$$S^r = \frac{(\varepsilon w + p_f + \mu\varepsilon p_o)\beta}{K_s}, M^r = \frac{\lambda V_f^{r\prime}}{K_m} \tag{A41}$$

Substitute Equations (A41) and (A39) into Equations (A36) and (A37), and get Equations (A42) and (A43)

$$\begin{aligned}\rho V_f^r(E,M) =& [(2w+p_f+\mu p_o)\eta - \sigma V_f^{i\prime}]G_0 + p_o\alpha_{of}\mu + (\alpha_o+\alpha_{of})w + p_f\alpha_f \\ &+\frac{(2-\mu)(p_f\varepsilon + p_o\mu + 2w)p_o\eta^2}{K_a} + \frac{\beta^2(\mu\varepsilon p_o + w\varepsilon + p_f)^2}{2K_s} \\ &+V_f^{i\prime}(\frac{\gamma^2 V_o^{i\prime}}{K_e} + \frac{\lambda^2 V_f^{i\prime}}{2K_m})\end{aligned} \tag{A42}$$

$$\begin{aligned}\rho V_o^r(E,M) =& (2p_o\eta - \sigma V_o^{r\prime})G_0 + (\alpha_{of} - \mu\alpha_{of} + \alpha_o)p_o + \frac{p_o\eta^2(2-\mu)^2}{2K_a} \\ &+\frac{(1-\mu)p_o\varepsilon\beta^2[\varepsilon\mu p_o + \beta^2(w\varepsilon + p_f)]}{K_s} + V_o^{r\prime}(\frac{\gamma^2 V_o^{r\prime}}{2K_e} + \frac{\lambda^2 V_f^{r\prime}}{K_m})\end{aligned} \tag{A43}$$

Assume $V_f^r(E,M)$ and $V_o^r(E,M)$ are linear expressions of $G_0$,

$$V_f^r(E,M) = a_1^r G_0 + a_2^r \tag{A44}$$

$$V_o^r(E,M) = b_1^r G_0 + b_2^r \tag{A45}$$

where $a_1^r$, $a_2^r$, $b_1^r$, $b_2^r$ are unknown constants.

From Equations (A42)–(A45), we get

$$\begin{aligned} a_1^r =& \frac{(2w+p_f+\mu p_o)\eta}{\rho+\sigma},\ b_1^r = \frac{(2-\mu)p_o\eta}{\rho+\sigma}. \\ a_2^r =& \ p_o\alpha_{of}\mu + (\alpha_o+\alpha_{of})w + p_f\alpha_f + \frac{(2-\mu)(p_f\varepsilon + p_o\mu + 2w)p_o\eta^2}{K_a} \\ &+\frac{\beta^2(\mu\varepsilon p_o + w\varepsilon + p_f)^2}{2K_s} + a_1^r(\frac{\gamma^2 b_1^r}{K_e} + \frac{\lambda^2 a_1^r}{2K_m}) \\ b_2^r =& \ (\alpha_{of} - \mu\alpha_{of} + \alpha_o)p_o + \frac{(1-\mu)p_o\varepsilon\beta^2[\varepsilon\mu p_o + \beta^2(w\varepsilon+p_f)]}{K_s} \\ &+\frac{{p_o}^2\eta^2(2-\mu)^2}{2K_a} + b_1^r(\frac{\gamma^2 b_1^r}{2K_e} + \frac{\lambda^2 a_1^r}{K_m}) \end{aligned}, \tag{A46}$$

According to $V_f^{r\prime} = a_1^r$ and $V_o^{r\prime} = b_1^r$, substitute Equation (A46) into Equations (A39), (A41), (A44), (A45), and (1), and then get the optimal decisions of the farmer cooperative and the online retailer in the decentralized decision mode with a revenue sharing contract shown in (27)–(31). □

**Proof of Proposition 13, 14, and 15.** The optimal value function of the farmer cooperative's profit at time t is

$$J_f^{ir}(M,S,\theta) = e^{-\rho t}V_f^{ir}(E,M) \tag{A47}$$

The optimal value function of the online retailer's profit at time t is

$$J_o^{ir}(E,A) = e^{-\rho t}V_o^{ir}(E,M) \tag{A48}$$

According to the optimal control theory, for any $E \geq 0$ and $M \geq 0$, $V_f^{ir}(E,M)$ and $V_o^{ir}(E,M)$ satisfy the Hamilton–Jacobi–Bellman function as

$$\begin{aligned}\rho V_f^{ir}(E,M) =& \max_{S,M,\theta}[p_f d_f + w(d_o + d_{of}) + \mu p_o d_{of} - \frac{1}{2}K_m M^2 - \frac{1}{2}K_s S^2 \\ &-\frac{1}{2}\theta K_e E^2 + V_f^{ir\prime}(\lambda M + \gamma E - \sigma G)]\end{aligned} \tag{A49}$$

$$\begin{aligned}\rho V_o^{ir}(E,M) &= \max_{A,E}[p_o d_o + (1-\mu)p_o d_{of} - \frac{1}{2}K_a A^2 - \frac{1}{2}(1-\theta)K_e E^2 \\ &+ V_o^{ir\prime}(\lambda M + \gamma E - \sigma G)]\end{aligned} \tag{A50}$$

Using the backward induction method, the necessary conditions for the optimal decisions of the online retailer is

$$\frac{\partial \rho V_o^{ir}(E,M)}{\partial A} = 0,\ \frac{\partial \rho V_o^{ir}(E,M)}{\partial E} = 0, \tag{A51}$$

By solving the Equation (A51), we get

$$E^{ir} = \frac{\gamma V_o^{ir\prime}}{(1-\theta)K_e}, A^{ir} = \frac{(2-\mu)\eta p_o}{K_a} \tag{A52}$$

Substitute Equation (A52) into Equation (A49), and then solve the necessary conditions for the optimal decisions of a farmer cooperative,

$$\frac{\partial \rho V_f^{ir}(E,M)}{\partial S} = 0,\ \frac{\partial \rho V_f^{ir}(E,M)}{\partial M} = 0,\ \frac{\partial \rho V_f^{ir}(E,M)}{\partial \theta} = 0, \tag{A53}$$

we get

$$S^{ir} = \frac{(\varepsilon w + p_f + \mu\varepsilon p_o)\beta}{K_s}, M^{ir} = \frac{\lambda V_f^{ir\prime}}{K_m},\ \theta^{ir} = \frac{2V_f^{ir\prime} - V_o^{ir\prime}}{2V_f^{ir\prime} + V_o^{ir\prime}} \tag{A54}$$

Substitute Equation (A54) into Equation (A52), and then substitute into (A49) and (A50), and get Equations (A55) and (A56)

$$\begin{aligned}\rho V_f^{ir}(E,M) &= [(2w + p_f + \mu p_o)\eta - \sigma V_f^{ir\prime}]G_0 + p_o\alpha_{of}\mu + (\alpha_o + \alpha_{of})w + p_f\alpha_f \\ &+ \frac{(2-\mu)(p_f\varepsilon + p_o\mu + 2w)p_o\eta^2}{K_a} + \frac{\beta^2(\mu\varepsilon p_o + w\varepsilon + p_f)^2}{2K_s} \\ &+ \frac{(2V_f^{ir\prime} + V_o^{ir\prime})^2\gamma^2}{8K_e} + \frac{\lambda^2(V_f^{ir\prime})^2}{2K_m}\end{aligned} \tag{A55}$$

$$\begin{aligned}\rho V_o^{ir}(E,M) &= (2p_o\eta - \mu p_o\eta - \sigma V_o^{ir\prime})G_0 + (\alpha_{of} - \mu\alpha_{of} + \alpha_o)p_o + \frac{{p_o}^2\eta^2(2-\mu)^2}{2K_a} \\ &+ \frac{(1-\mu)p_o\varepsilon\beta^2(w\varepsilon + p_f + \varepsilon\mu p_o)}{K_s} + V_o^{ir\prime}[\frac{(2V_f^{ir\prime} + V_o^{ir\prime})\gamma^2}{4K_e} + \frac{\lambda^2 V_f^{ir\prime}}{K_m}]\end{aligned} \tag{A56}$$

Assume $V_f^{ir}(E,M)$ and $V_o^{ir}(E,M)$ are linear expressions of $G_0$,

$$V_f^{ir}(E,M) = a_1^{ir}G_0 + a_2^{ir} \tag{A57}$$

$$V_o^{ir}(E,M) = b_1^{ir}G_0 + b_2^{ir} \tag{A58}$$

where $a_1^{ir}$, $a_2^{ir}$, $b_1^{ir}$, $b_2^{ir}$ are unknown constants.

From Equations (A55)–(A58), we get

$$
\begin{aligned}
a_1^{ir} &= \frac{(2w + p_f + \mu p_o)\eta}{\rho + \sigma},\ b_1^{ir} = \frac{(2-\mu)p_o\eta}{\rho+\sigma}, \\
a_2^{ir} =&\ \ p_o\alpha_{of}\mu + (\alpha_o + \alpha_{of})w + p_f\alpha_f + \frac{(2-\mu)(p_f\varepsilon + p_o\mu + 2w)p_o\eta^2}{K_a} \\
&+ \frac{\beta^2(\mu\varepsilon p_o + w\varepsilon + p_f)^2}{2K_s} + \frac{(2a_1^{ir} + b_1^{ir})^2\gamma^2}{8K_e} + \frac{\lambda^2(a_1^{ir})^2}{2K_m} \\
b_2^{ir} =&\ \ (\alpha_{of} - \mu\alpha_{of} + \alpha_o)p_o + \frac{{p_o}^2\eta^2(2-\mu)^2}{2K_a} + \frac{(1-\mu)p_o\varepsilon\beta^2(w\varepsilon + p_f + \varepsilon\mu p_o)}{K_s} \\
&+ b_1^{ir}\left[\frac{(2a_1^{ir} + b_1^{ir})\gamma^2}{4K_e} + \frac{\lambda^2 a_1^{ir}}{K_m}\right]
\end{aligned}
\tag{A59}
$$

According to $V_f^{ir\prime} = a_1^{ir}$ and $V_o^{ir\prime} = b_1^{ir}$, substitute Equation (A59) into Equations (A52), (A54), (A57), (A58), and (1), and then get the optimal decisions of the farmer cooperative and the online retailer in the decentralized decision mode with a comprehensive contract shown in (34)–(38). □

**Proof of Corollary 1.** From Equations (8), (13), (20), (27), and (34), we know

$$E^c - E^d = \frac{\gamma\eta(2w + p_f)}{(\rho+\sigma)K_e} > 0,$$

$$E^c - E^i = \frac{\gamma\eta p_o}{(\rho+\sigma)K_e} > 0,$$

$$E^c - E^r = \frac{\gamma\eta(2w + \mu p_o + p_f)}{(\rho+\sigma)K_e} > 0,$$

$$E^c - E^{ir} = \frac{\gamma\eta p_o(2-\mu)}{(\rho+\sigma)K_e} > 0,$$

$$E^r - E^d = -\frac{\gamma\eta\mu p_o}{(\rho+\sigma)K_e} < 0,$$

$$E^i - E^r = \frac{\gamma\eta[2w + p_f - (1-\mu)p_o]}{(\rho+\sigma)K_e},$$

$$E^i - E^d = \frac{\gamma\eta(2w + p_f - p_o)}{(\rho+\sigma)K_e},$$

$$E^i - E^{ir} = -\frac{\gamma\eta\mu p_o}{2(\rho+\sigma)K_e} < 0,$$

$$E^{ir} - E^r = \frac{\gamma\eta[2w + p_f - (1-\frac{3}{2}\mu)p_o]}{(\rho+\sigma)K_e},$$

$$E^{ir} - E^d = \frac{\gamma\eta[2w + p_f - (1-\frac{1}{2}\mu)p_o]}{(\rho+\sigma)K_e}.$$

And $p_f > 0$,$p_o > 0$,$w > 0$,$0 < \mu < 1$, we know $p_o > (1-\frac{1}{2}\mu)p_o > (1-\mu)p_o > (1-\frac{3}{2}\mu)p_o$. When $2w + p_f > p_o$, $E^c > E^{ir} > E^i > E^d > E^r$. We can get other conditions likewise. □

**Proof of Corollary 2.** From Equations (8), (13), (20), (27), and (34), we know

$$M^c - M^d = M^c - M^i = \frac{2\lambda\eta p_o}{(\rho+\sigma)K_m} > 0,$$

$$M^c - M^r = M^c - M^{ir} = \frac{(2-\mu)\lambda\eta p_o}{(\rho+\sigma)K_m} > 0,$$

$$M^d - M^r = -\frac{\mu\lambda\eta p_o}{(\rho+\sigma)K_m} < 0,$$

and get

$$M^c > M^{ir} = M^r > M^i = M^d.$$

Similarly,

$$S^c > S^{ir} = S^r > S^i = S^d,\ A^c > A^i = A^d > A^r = A^{ir}. \square$$

**Proof of Corollary 3.** We know

$$p_o > (1-\frac{3}{2}\mu)p_o,$$

and from Equations (20) and (34),

We know when

$$2w + p_f > (1-\frac{3}{2}\mu)p_o,$$

$$\theta^{ir} - \theta^i = \frac{2\mu p_o(2w+p_f+2p_o)}{(2w+p_f+p_o)(4w+2p_f+2p_o+\mu p_o)} > 0,$$

so $\theta^{ir} > \theta^i$.

When

$$2w + p_f < (1-\frac{3}{2}\mu)p_o,\ \theta^{ir} = \theta^i = 0. \square$$

**Proof of Corollary 4.** From Equations (8), (13), (20), (27), and (34), we know

$$G^c_{RSS} - G^d_{RSS} = \frac{2\eta[(w+\frac{1}{2}p_f)\gamma^2 K_m + \lambda^2 K_e p_o]}{(\rho+\sigma)K_m K_e} > 0,$$

$$G^c_{RSS} - G^i_{RSS} = \frac{\eta p_o(\gamma^2 K_m + 2\lambda^2 K_e)}{(\rho+\sigma)K_m K_e} > 0,$$

$$G^c_{RSS} - G^r_{RSS} = \frac{\eta[(\gamma^2 K_m(\mu p_o + 2w + p_f) + \lambda^2 K_e p_o(2-\mu)]}{(\rho+\sigma)K_m K_e} > 0,$$

$$G^i_{RSS} - G^d_{RSS} = \frac{\gamma^2\eta[2w + p_f - p_o]}{(\rho+\sigma)K_e},$$

$$G^c_{RSS} - G^{ir}_{RSS} = \frac{\eta p_o(\gamma^2 K_m + 2\lambda^2 K_e)(2-\mu)}{2(\rho+\sigma)K_m K_e} > 0,$$

$$G^i_{RSS} - G^{ir}_{RSS} = -\frac{\eta p_o\mu(\gamma^2 K_m + 2\lambda^2 K_e)}{2(\rho+\sigma)K_m K_e} < 0,$$

$$G^{ir}_{RSS} - G^r_{RSS} = \frac{\gamma^2\eta[2w + p_f - (1-\frac{3}{2}\mu)p_o]}{(\rho+\sigma)K_e},$$

$$G^i_{RSS} - G^r_{RSS} = \frac{\eta\gamma^2 K_m[2w + p_f - (1-\mu+\frac{\lambda^2 K_e}{\gamma^2 K_m}\mu)p_o]}{(\rho+\sigma)K_e K_m},$$

$$G^d_{RSS} - G^r_{RSS} = \frac{\mu\eta p_o(\gamma^2 K_m - \lambda^2 K_e)}{(\rho+\sigma)K_e K_m},$$

$$G_{RSS}^{ir} - G_{RSS}^{d} = \frac{\eta\gamma^2 K_m[2w + p_f - (1 - \frac{1}{2}\mu - \frac{\lambda^2 K_e}{\gamma^2 K_m}\mu)p_o]}{(\rho+\sigma)K_e K_m}.$$

And $p_f > 0$, $p_o > 0$, $w > 0$, $0 < \mu < 1$, $\lambda > 0$, $\gamma > 0$, $K_e > 0$, $K_m > 0$, assume $H = \frac{\lambda^2 K_e}{\gamma^2 K_m}$, we know when $0 < H < \frac{1}{4}$, $p_o > 1 - \frac{1}{2}\mu - H\mu > 1 - \mu + H\mu > 1 - \frac{3}{2}\mu$, easy to get when $2w + p_f > p_o$,$G_{RSS}^{c} > G_{RSS}^{ir} > G_{RSS}^{i} > G_{RSS}^{d} > G_{RSS}^{r}$. We can get other conditions likewise. □

**Proof of Corollary 5, 6.** From Equations (10), (15)–(17), (22)–(24), (31), and (38), we know

$$J^c - J^d = \frac{(\varepsilon p_f + 2w)^2\eta^2}{2K_a} + \frac{{p_o}^2\varepsilon^2\beta^2}{2K_s} + \frac{(2w+p_f)^2\eta^2\gamma^2}{2(\sigma+\rho)^2 K_e} + \frac{2\eta^2\lambda^2{p_o}^2}{(\sigma+\rho)^2 K_m} > 0,$$

so $J^c > J^d$.

Similarly,

$$J^c > J^i,\ J^c > J^r,\ J^c > J^{ir},\ J_f^i > J_f^d,$$

$$J^i - J^d = \frac{\eta^2\gamma^2[(2w+p_f)+p_o][(2w+p_f)-p_o]}{2(\sigma+\rho)^2 K_e},$$

$$J_o^i - J_o^d = \frac{\eta^2 p_o\gamma^2(2w+p_f-p_o)}{(\sigma+\rho)^2 K_e},$$

we get when

$$2w + p_f > p_o,\ J^i > J^d,\ J_f^i > J_f^d$$

and when

$$2w + p_f < p_o,\ J^i < J^d,\ J_f^i < J_f^d. \ \square$$

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