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Operational Decision and Sustainability of Green Agricultural Supply Chain with Consumer-Oriented Altruism

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Abstract: The agricultural supply chain has to balance the economic, environmental, and social dimensions of sustainability. This paper investigates the green agricultural supply chain, consisting of a manufacturer and a retailer, who are both altruistic towards consumers. Such consumer-oriented altruism is different from the widely adopted enterprise-oriented altruism, which only measures the altruistic behaviors among supply chain enterprises. In the approach of game theory, the optimal operational decision is obtained, and thereby the economic, environmental, and social dimensions of sustainability are described rationally and attained, respectively. The impacts of consumer-oriented altruism on the sustainability of the green agricultural supply chain are analyzed and compared in a systematic way. A case study is carried out before drawing conclusions and managerial implications. The findings can be concluded as follows. Firstly, consumer-oriented altruism changes the operational performance of the green agricultural supply chain by enhancing the green level of agricultural products, cutting down the pricing decisions and marginal profit of each supply chain enterprise. Secondly, consumer-oriented altruism simultaneously facilitates each dimension of sustainability to different extents, and economic sustainability is promoted the most prominently, whereas environmental sustainability is improved the least. Thirdly, the retailer's consumer-oriented altruism always improves each dimension of sustainability more than the manufacturer's altruism does, and the advantage in the economic dimension is the most significant, while that in the environmental dimension is the smallest.

Keywords: green agricultural supply chain; consumer-oriented altruism; sustainability; operational decision

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Citation: Wei, G.; Zhou, L.; Bary, B. Operational Decision and Sustainability of Green Agricultural Supply Chain with Consumer-Oriented Altruism. *Sustainability* **2022**, *14*, 12210. https://doi.org/10.3390/su141912210

Academic Editors: Giuseppina Migliore, Riccardo Testa, József Tóth and Giorgio Schifani

Received: 16 August 2022
Accepted: 23 September 2022
Published: 26 September 2022

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1. Introduction

The agricultural sector is the primary food provider to the increasing population across the world, which is estimated to reach 10 billion by 2050 [1]. According to the State of Food Security and Nutrition in the World 2022, nearly one-tenth of the world population, 828 million people, suffered from hunger in 2021 [2]. The demand growth challenges the agricultural supply chain, which covers the complete process from field to fork and should increase productivity to solve potential shortages. Although increasing agricultural production offers a platform for economic growth, it also leads to environmental pollution such as more greenhouse gas emissions, severer land erosion, and deforestation. Actually, as one of the largest pollution sectors [3], agriculture generated nearly 24 percent of the world's greenhouse gas emissions [1], which is one of the main topics regulated by the United Nations' 2030 Agenda for Sustainable Development. Although there is no consensus on the definition of sustainability, the most well-known definition states that sustainability requires meeting the needs of the present without compromising the ability of future generations to meet their needs [4]. According to the widely adopted triple bottom line approach to sustainability [5,6], it is very important for the agricultural supply chain to balance the economic, environmental, and social dimensions of sustainability. Green strategy can contribute to the tradeoff because it decreases the need for chemical substances, such as pesticides, fertilizers, herbicides, and additives, whereas it increases the need for decomposable, degradable, and recyclable materials. The green agricultural supply chain involves the production, distribution, and sales of green agricultural products to consumers following a green strategy that encompasses the three generally accepted dimensions of sustainability. Therefore, it does not only focus on the economic goal but also takes into account the social and environmental aspects. Consequently, how the green agricultural supply chain weighs each dimension of sustainability has become a hot field for both practitioners and scholars.

Much attention has been paid to the sustainability of the green agricultural supply chain in previous literature. However, there are three limitations still present, as follows.

Firstly, social sustainability has hardly been discussed, although a lot has explored the economic and environmental sustainability of supply chains. It has been widely recognized that the attention paid to social sustainability of the supply chain is insufficient [7,8]. In the sustainable agricultural supply chain literature reviewed by Nematollahi et al. [9], 107 papers investigated social sustainability, less than half of 235 papers on the economic and environmental dimensions.

Secondly, the economic, environmental, and social dimensions of supply chain sustainability have hardly been discussed in a systematic way. Although economic sustainability is usually combined with environmental or social sustainability, environmental sustainability and social sustainability are generally investigated separately. In the sustainable agricultural supply chain literature reviewed by Nematollahi et al. [9], 128 papers investigated the cross-section of economic and environmental dimensions, 53 discussed the cross-section of economic and social dimensions, and only two papers touched the cross-section of environmental and social dimensions.

Thirdly, consumer-oriented altruism has never been touched before, whereas enterprise-oriented altruism has widely been adopted. Consumer-oriented altruism measures the altruistic behaviors of supply chain enterprises towards consumers outside the supply chain system. It is different from enterprise-oriented altruism, which has been popular in previous literature and captures the altruistic behaviors among supply chain enterprises. For example, the dominant retailer is altruistic toward small and medium-sized manufacturers in a retailer-led low-carbon supply chain [10]. Although it has been neglected, consumer-oriented altruism can affect the operational performance and sustainability of the supply chain dramatically. For example, by investing in technologies for accelerating carbon emission reduction, supply chain enterprises can gain more profits because consumers with low-carbon awareness would like to buy more products at a higher price [11].

Consequently, aiming at the above limitations in previous literature, this paper incorporates consumer-oriented altruism instead of the widely adopted enterprise-oriented altruism into the green agricultural supply chain to explore the following questions.

(1) What is the optimal operational decision of the green agricultural supply chain with consumer-oriented altruism?
(2) How can we systematically describe the economic, environmental, and social sustainability of the green agricultural supply chain?
(3) How does consumer-oriented altruism influence the economic, environmental, and social sustainability of the green agricultural supply chain, respectively, and systematically?
(4) What are the differences between the impact of the manufacturer's consumer-oriented altruism and that of the retailer's on each dimension of sustainability?

By introducing never touched consumer-oriented altruism into the green agricultural supply chain, this paper explores the economic, environmental, and social dimensions of sustainability systematically, which acquires the following original contributions.

Firstly, consumer-oriented altruism instead of the widely adopted enterprise-oriented altruism is incorporated into the operational decisions of the green agricultural supply chain. This paper explores the altruism orienting consumers who change randomly outside the supply chain system, including the consumer-oriented altruism of the manufacturer and that of the retailer. Previous literature focused on the altruism orienting a specific downstream or upstream enterprise within the supply chain system, including the downstream retailer's altruism orienting the upstream manufacturer, the manufacturer's altruism orienting the retailer, and their reciprocal altruism.

Secondly, all the three dimensions, including the economic, environmental, and social sustainability of the green agricultural supply chain, are analyzed in a joint way. This paper deals with all the three dimensions of sustainability systematically. Except for the usual economic sustainability and environmental sustainability, social sustainability is represented by the consumer surplus defined in economics, which is reasonable and necessary in the green agricultural supply chain. Previous literature investigated economic sustainability either with the environmental or social dimensions, usually probing the environmental sustainability and social sustainability separately, and hardly probing the three dimensions simultaneously.

Thirdly, the impacts of consumer-oriented altruism on each sustainability dimension of the green agricultural supply chain are examined carefully and compared systematically. Previous literature focused on the impact of enterprise-oriented altruism on economic sustainability and environmental sustainability, whereas rarely discussed the impact of enterprise-oriented altruism on social sustainability. None of them reached consumer-oriented altruism nor the impact of consumer-oriented altruism on economic, environmental, and social sustainability for the green agricultural supply chain.

The remainder of this paper is organized as follows. The literature related to sustainability and altruism in the agricultural supply chain is reviewed in Section 2, and the assumptions and notations are formulated in Section 3. Section 4 develops the optimization model and gains the operational decision. Section 5 mathematically formulates the economic, environmental, and social sustainability of the green agricultural supply chain. The impact of consumer-oriented altruism on each dimension of sustainability is analyzed in Section 6, including that of the manufacturer's altruism, that of the retailer's altruism, and their comparison. Section 7 gives a case study on the DFF supply chain. Conclusions and managerial implications are drawn in Section 8.

2. Literature Review

The previous literature is reviewed in the following two branches, sustainability in the agricultural supply chain and altruism in the agricultural supply chain, which together can constitute a sufficient foundation for the topic of this paper.

2.1. Sustainability in Agricultural Supply Chain

The triple bottom line, which classifies sustainability into economic, environmental, and social dimensions, is the basic approach for analyzing sustainability in the agricultural supply chain [5,6]. For years, the focus on economic sustainability has dominated environmental and social sustainability, while social sustainability has received the least attention in both generic [7] and agricultural [8] supply chains. Because almost none has investigated the economic sustainability exclusively [9], the following reviews the related studies in three subbranches: (1) environmental cross-economic sustainability; (2) social cross-economic sustainability; and (3) mingled ternary sustainability where each dimension is considered simultaneously.

(1) Environmental cross economic sustainability of agricultural supply chain.

Various indicators are adopted, such as greenhouse gas emissions, carbon footprint, land overuse, and soil erosion, to describe environmental sustainability. Among them, greenhouse gas emissions and carbon footprint are the most widely adopted. Agriculture is one of the largest pollution sectors [3] and generates nearly 24 percent of the world's greenhouse gas emissions [1]. The reduction of greenhouse gases and carbon emissions are embedded in every segment of the agricultural supply chain. For example, in a segment of the sustainable network of the agricultural supply chain, Meneghetti et al. [12] offered an optimization model of refrigerated automatic storage and retrieval systems, which reduced carbon dioxide emissions to minimize the total yearly cost of the automatic storage facility. Colicchia et al. [13] used the method of multi-objective mathematical programming to design an ecologically efficient supply chain that encompassed the environmental influence of transportation and warehousing. Jonkman et al. [14] incorporated the impacts of seasonality, harvesting, perishability, and processing to enhance the economic and environmental performance of the agri-food supply chain. Manteghi et al. [15] found that the more customers were sensitive to the price, the less the manufacturer wanted to reduce greenhouse gas emissions. Moreover, in a segment of the sustainable distribution of agricultural supply chain, Danloup et al. [16] designed a strategy of collaborative distribution, which could improve greenhouse gas emission reduction in transportation. Bortolini et al. [17] developed a tri-objective linear programming mode of the fresh food distribution network to jointly minimize operational costs and carbon emissions. Accorsi et al. [18] formulated a mixed-integer linear programming model to design the storage and distribution network of the perishable supply chain and considered the impact of weather to reduce carbon emissions. Huang et al. [19] proved that vertical cooperation could promote carbon emission reduction in a food supply chain.

(2) Social cross economic sustainability of agricultural supply chain.

Indicators of social sustainability vary in a wide range, which includes the following subbranches. First, in the aspect of social welfare, Sunar et al. [20] designed an allocation rule of socially optimal choice, which could reduce emission costs and increase social welfare by imposing taxes on primary products. Ye et al. [21] found that the decentralized decisions in agricultural supply chain may harm social welfare because consumers had to buy fewer products at higher price, and offered a coordinating mechanism to avoid such a negative effect. Wen et al. [22] showed that if the straw power plant cooperates with brokers, the governmental subsidies may enhance social benefits. Song et al. [23] leveraged evolutionary game theory to analyze how the adoption of blockchain technologies promotes social welfare in the agricultural supply chain. Second, in the aspect of food quality, Chen et al. [24] developed an analytical model with an exploratory case study of the dairy industry, which supported them in mutually attaining the managerial policy of quality control in the food supply chain. Wang et al. [25] presented a system of forward and diverse traceability to evaluate food quality and thereby enhance customer experience and satisfaction. Pal et al. [26] investigated a perishable logistics model to explore the tradeoff between the delivered quality and carbon footprint. Hsu et al. [27] found that the governmental subsidy sometimes may abate both the dairy product quality and the enterprise's profit. Zhao et al. [28] developed a comprehensive model of the agri-food supply chain to show that securing food quality could achieve better financial performance for processing businesses Third, in the aspect of consumer health, Sazvar et al. [29] applied a multi-objective mathematical model to balance reducing economic costs and environmental degradation while increasing consumer health. Fourth, in the aspect of consumer price fairness, Wang et al. [30] developed a markdown model to evaluate the tradeoff between retailer revenue and consumer utility up to the perceived price fairness, food perishability, and scarcity.

(3) Mingled ternary sustainabilities of agricultural supply chain.

Few probed the economic, environmental, and social dimensions simultaneously in a systematic way. Gonela et al. [31] investigated the hybrid generation bioethanol supply chain and proposed regulations for balancing economic, environmental, and social benefits. Rohmer et al. [32] examined the sustainable food supply chain and minimized environmental damage and economic cost while maintaining a sufficient level of dietary intake. Hoang [33] made a case study of the short food supply chain in Vietnam and found that a short food supply chain would increase the farmer's income, decrease environmental pollution, and improve consumer welfare. Chaabane et al. [34] developed a model integrating the three sustainability dimensions of the cold supply chain with clean energy.

The above exploration in three subbranches yields the findings as follows. First, the previous literature has neglected behavioral preferences such as altruism in the course of paying much attention to the sustainability of the agricultural supply chain. Second, only a few have probed the ternary dimensions of sustainability in a joint way, while many have investigated the economic, environmental, and social sustainability of the agricultural supply chain in a separate way. Third, the previous literature widely used the approach of mathematical programming, such as multi-objective decision-making in Allaoui et al. [35], and only a few adopted the approach of game theory y. Therefore, this paper leverages game theory to investigate the impact of altruism on each sustainability dimension of the agricultural supply chain. To the best of our knowledge, this paper is the first to model the effects of altruism on all three dimensions, including economic, environmental, and social sustainability, of the agricultural supply chain using the approach of game theory.

2.2. Altruism in Agricultural Supply Chain

Evidence from behavioral studies has shown that supply chain enterprises, such as the manufacturer, do not purely behave in the self-interested way of traditional economics, and that behavioral factors such as altruism have a significant impact on supply chain performance [36]. Although altruism has hardly been taken into the agricultural supply chain, it has been heavily discussed in other areas such as: (1) low-carbon supply chain; (2) green supply chain; (3) service supply chain; (4) touristic supply chain; and (5) generic supply chain, and has been reviewed respectively in the following subbranches.

(1) Altruism in low-carbon supply chain.

Fan et al. [37] examined the complex dynamics of a low-carbon supply chain and illustrated that the altruism of the retailer may narrow the stable domain of the supply chain system while accelerating carbon emission reduction. Wang et al. [38] investigated the recycling decisions of a low-carbon closed-loop supply chain, and found that the altruistic preference improves the operational efficiency and promotes the recycling of waste products in the supply chain. Ma et al. [39] considered a low-carbon tourist online-to-offline supply chain empowered by big data and showed that the altruistic preference between the tourist spot and the online travel agency strengthens cooperation and achieves the sustainable development of the low-carbon touristic supply chain. Wang et al. [10] studied the decision-making on coordinating a low-carbon supply chain with a dominant retailer and found that the altruistic preference of the dominant retailer enhances the profit of the small and medium-sized manufacturers as well as the system efficiency of the supply chain. Liu et al. [40] developed the model of a low-carbon e-commerce supply chain and concluded that the altruism of the E-platform stabilizes the long-term development of the supply chain system. Zhang et al. [11] examined the decision-making on joint emission reduction in a low-carbon supply chain and found that altruism accelerates carbon emission reduction and leads to more social surplus. Wang et al. [41] investigated the emission reduction of low carbon supply chains with network externalities and showed that altruistic preference incentives the manufacturer to reduce carbon emissions.

(2) Altruism in green supply chain.

Huang et al. [42] investigated the product greenness and pricing decisions of a green supply chain and illustrated that altruistic preference increases the overall profit and enhances the product greenness of the supply chain. Wei et al. [43] probed a green supply chain with asymmetric information and found that the retailer-oriented altruism of the manufacturer could improve the product greenness and the supply chain profitability. Rong et al. [44] examined a multinational green supply chain with a dynamic tariff and showed that the altruistic preference of the manufacturer improves the green level of the supply chain. Liu et al. [45] addressed the innovative strategies for a green supply chain and concluded that both the altruistic preference of the manufacturer and that of the retailer enhance the product greenness and the overall profit of the green supply chain.

(3) Altruism in service supply chain.

Liu et al. [46] examined a logistics service supply chain and showed that both the altruism of the logistics service integrator and that of a functional logistics service provider could enhance the supply chain profit. Qin et al. [47] took a bilateral evolutionary approach to investigate an online shopping service supply chain and illustrated that the bilateral altruism decreases the retail price and service price while increasing the service level. Ma et al. [48] analyzed a product-service supply chain in the online-to-offline environment, and found that bilateral altruism between the manufacturer and the retailer is useful for developing higher quality products, better service, and greater goodwill. Wang et al. [49] investigated a service supply chain with data-driven demand and supply, and concluded that altruism obtains higher-level value-added service at a lower price.

(4) Altruism in touristic supply chain.

Wan et al. [50] examined low-carbon touristic supply chains consisting of providers of low-carbon tourist products and services and online travel agencies, showing that in the case of information symmetry, the altruism of products and services providers increases the overall supply chain profit while the altruism of online travel agencies decreases, but in the case of information asymmetry, both of that decrease the overall supply chain profit. Wan et al. [51] investigated a dual-channel hotel supply chain consisting of upstream hotels and downstream online travel agency platforms, and showed that the altruism of the hotels promotes cooperation among hotels under both merchant mode and agency mode.

(5) Altruism in generic supply chain without specific area or topic.

Xu et al. [52] addressed the cooperative strategy for dual-channel supply chains and found that altruistic reciprocity propels supply chain cooperation and improves channel efficiency. Lin [53] analyzed the pricing and locating decisions in a supply chain with multiple retailers, and showed that the horizontal altruism among retailers improves coordination in the supply chain. Wiedmer et al. [54] conducted a role playing experiment, where respondents were considered as the purchasing managers, and illustrated that the buyer's altruism towards the seller was disadvantageous to supply chain collaboration in the case of resource scarcity. Zhai et al. [55] probed a perishable product supply chain with a capital-constrained retailer under uncertain market demand and found that altruism attains higher supply chain efficiency.

The above exploration of altruism in five different types of supply chains yields the findings as follows. First, previous literature has hardly discussed altruism in the agricultural supply chain, although altruism plays a great role in the operational performance of the green supply chain. Second, previous literature has focused on enterprise-oriented altruism, which means that one supply chain enterprise may try to increase the profit of the other enterprise. For example, the dominant retailer is altruistic towards small and medium-sized manufacturers in retailer-led low-carbon supply chains [10], or the E-platform may interact with the manufacturer altruistically in the low-carbon e-commerce supply chain [40]. Third, previous literature has hardly touched on consumer-oriented altruism, which means that supply chain enterprises actually take the consumers' welfare into account because consumers would buy more products at a higher price when the altruistic manufacturer invests in low-carbon technologies [11]. Therefore, in order to solve the limitations in previous literature, this paper incorporates consumer-oriented altruism into the green agricultural supply chain, which has never been touched before.

Summarily, in the branch of sustainability, although a few researchers have begun to investigate the economic, environmental, and social dimensions of agricultural supply chains in a joint way, none have analyzed the impact of altruism on each dimension of sustainability systematically. Meanwhile, in the branch of altruism, a few researchers have begun to explore how enterprise-oriented altruism affects economic sustainability, such as overall profit, environmental sustainability, such as carbon emission reduction, and social sustainability, such as consumer surplus. However, such exploration has neither occurred in the agricultural supply chain nor adopted consumer-oriented altruism. Therefore, this paper will concurrently explore the economic, environmental, and social sustainability of the green agricultural supply chain, incorporating consumer-oriented altruism in a systematic approach and thereby expanding the intersection of the above two branches. To the best of our knowledge, this paper is the first effort that focuses on the impact of consumer-oriented altruism instead of the widely adopted enterprise-oriented altruism on all three instead of the usually paid one or two sustainability dimensions of the green agricultural supply chain in a systematic formulation.

3. Problem Description

3.1. Assumptions

The green agricultural supply chain consists of a manufacturer and a retailer. The manufacturer refers to any agribusiness corporation that produces green agricultural products. Examples of such corporations are Wens Foodstuff Group Co., Ltd. (Yunfu, China), Muyuan Foods Co., Ltd. (Nanyang, China), and Inner Mongolia Yili Industrial Group Ltd. (Hohhot, China), while the retailer distributes and sells green agricultural products to consumers. The manufacturer invests in environmentally friendly technologies to produce green agricultural products at unit production cost c, and sells the products to consumers via the retailer at the wholesale price w, while consumers pay the retail price p to the retailer with the constraint $p > w > c > 0$. Such a decision model is widely adopted in the agricultural supply chain literature, such as in Hu et al. [56] and Perlman et al. [57]. According to the customary rules in the previous literature, the assumptions of market demand, green investment, consumer-oriented altruism, and operational decisions are formulated as follows, while that of sustainability is discussed and described in Section 5.

3.1.1. Assumption of Market Demand

The demand function is assumed to be linear $q = a - \beta p + \delta g$, which is widely adopted in the previous literature, such as Sinayi et al. [58]. The variable p captures the retail price decided by the retailer with price sensitivity denoted as $\beta > 0$, the variable $g > 0$ measures the green level decided by the manufacturer with green preference denoted as $\delta > 0$, and $a > 0$ represents the potentially maximum demand, which are subject to $a - \beta p > 0$ and $a - \beta c > 0$. As the green preference of consumers can expand the market demand, the supply chain stakeholders will attempt to improve the green level of agricultural products through green investment.

3.1.2. Assumption of Green Investment

In order to meet the green preference of consumers, the manufacturer burdens the investment on environmentally friendly technologies, which can decrease the use of pesticides, chemical fertilizers, herbicides, additives, and other chemical substances. The reduction is followed by increasing the use of degradable, decomposable, and recyclable materials. Therefore, the emissions of pollutants such as methane, carbon dioxide, wastewater, and waste residue are reduced. According to Yalabik et al. [59], Swami et al. [60], and so on, the investment cost of environmentally friendly technologies can be given by $\frac{1}{2}\theta g^2$. The unit pollutant emission reduction, or the green level, is denoted as g, and the marginal coefficient is described by θ, which is usually assumed to be sufficiently large relative to other parameters [60,61].

3.1.3. Assumption of Consumer-Oriented Altruism

Both the manufacturer and retailer are altruistic towards consumers by paying attention to the consumer surplus, which is denoted as $c_s = \frac{(a-\beta p+\delta g)^2}{2\beta}$ under the market demand $q = a - \beta p + \delta g$ [58]. In pursuing the profit $\pi_m = (w - c)(a - \beta p + \delta g) - \frac{1}{2}\theta g^2$, the manufacturer integrates the consumer surplus with the goal of maximizing the utility $u_m = \pi_m + \eta_m c_s$. Similarly, the retailer also takes care the consumer surplus by maximizing the utility $u_r = \pi_r + \eta_r c_s$ instead of the profit $\pi_r = (p - w)(a - \beta p + \delta g)$. The altruistic strength η_m represents how much the manufacturer pays attention to consumer surplus in comparison with self-profit. The bigger altruistic strength is, the more the manufacturer cares about consumer surplus when making decisions. Especially, $\eta_m = 0$ denotes the traditional purely self-interested case assumed in classical economics, where the manufacturer only takes self-profit into account without considering others. Usually, as widely adopted in previous literature such as Wei et al. [43], altruistic strength η_m is subject to the constraint $0 < \eta_m < 1$, which means that the manufacturer pays more attention to self-profit despite being altruistic to consumers. The parameter η_r, similar to η_m, measures the altruistic strength of the retailer. It is subject to $0 < \eta_r < 1$ and constraint $0 < \eta_r + \eta_m < 1$ together with η_m, as used in previous literature such as Wei et al. [43].

3.1.4. Assumption of Operational Decision

The timing of the operational decision within the green agricultural supply chain is formulated as follows. Firstly, the manufacturer produces the green agricultural products at the unit production cost c and a green level g that requires an investment cost $\frac{1}{2}\theta g^2$. Secondly, the manufacturer sells the green agricultural products to the retailer at the wholesale price w. Finally, the retailer sells the agricultural products to consumers at the retail price p with constraint $p > w > c$.

With regards to the supply chain's operational management, the upstream manufacturer with consumer-oriented altruism chooses the wholesale price w and the green level g of the agricultural products to maximize utility $u_m = \pi_m + \eta_m c_s$ instead of profit $\pi_m = (w - c)(a - \beta p + \delta g) - \frac{1}{2}\theta g^2$. Further, the downstream retailer with consumer-oriented altruism chooses the retail price p for the agricultural products to maximize the utility $u_r = \pi_r + \eta_r c_s$ instead of the profit $\pi_r = (p - w)(a - \beta p + \delta g)$. Their decisions and altruism towards consumers jointly determine the operational performance of the green agricultural supply chain.

3.2. Notations

The parameters, decision variables, and symbols in the model of the green agricultural supply chain, are listed as follows, respectively.

3.2.1. Parameters

q: market demand
a: potentially maximum demand
β: price sensitivity
δ: green preference, sensitivity to green level
θ: marginal cost of green investment
c: unit production cost

3.2.2. Decision Variables

g: green level, unit pollutant emission reduction, decided by the manufacturer
w: wholesale price, decided by the manufacturer
p: retail price, decided by the retailer

3.2.3. Symbols

m: agricultural manufacturer, denoted as he or his
r: agricultural retailer, denoted as she or her
π_m: profit of the manufacturer
π_r: profit of the retailer
c_s: consumer surplus
η_m: altruistic strength of the manufacturer
η_r: altruistic strength of the retailer
u_m: utility of the manufacturer
u_r: utility of the retailer

4. Operational Decision of Green Agricultural Supply Chain

4.1. Optimization Model

The approach of reverse reduction is adopted to develop the optimization model of the green agricultural supply chain, incorporating consumer-oriented altruism.

On the side of the agricultural retailer, given the wholesale price w and green level g, the retailer with consumer-oriented altruism takes care both of her self-profit and the consumer surplus to maximize the utility $u_r = \pi_r + \eta_r c_s$ by deciding the retail price p. Her optimization model is given by

$$\max_p u_r = (p-w)(a-\beta p+\delta g)+\eta_r \frac{(a-\beta p+\delta g)^2}{2\beta}$$

On the side of the agricultural manufacturer, given the optimal retail price embedded in the above optimization model of the retailer, the manufacturer with consumer-oriented altruism also takes care of both his self-profit and the consumer surplus to maximize the utility $u_m = \pi_m + \eta_m c_s$ by deciding the wholesale price w and green level g simultaneously. His optimization model is stated as:

$$\max_{w,g} u_m = (w-c)(a-\beta p+\delta g)-\frac{1}{2}\theta g^2+\eta_m \frac{(a-\beta p+\delta g)^2}{2\beta}$$

$$s.t.\max_p u_r = (p-w)(a-\beta p+\delta g)+\eta_r \frac{(a-\beta p+\delta g)^2}{2\beta}$$

4.2. Green Level and Wholesale Pricing Decision

The approach of reverse reduction is adopted to deduce the optimal operational decision of the green agricultural supply chain.

From the first order condition $\frac{\partial u_r}{\partial p} = -\beta(p-w)+(1-\eta_r)(a-\beta p+\delta g) = 0$ of the retailer's optimization model, the reaction function of the retail price is given by $\overline{p}(w,g) = \frac{(1-\eta_r)a+(1-\eta_r)\delta g+\beta w}{\beta(2-\eta_r)}$. Substituting $\overline{p}(w,g) = \frac{(1-\eta_r)a+(1-\eta_r)\delta g+\beta w}{\beta(2-\eta_r)}$ into the optimization model of the manufacturer, yield

$$\begin{aligned}\max_{w,g} u_m = (w-c)\left[a-\frac{(1-\eta_r)a+(1-\eta_r)\delta g+\beta w}{2-\eta_r}+\delta g\right]-\tfrac{1}{2}\theta g^2 \\ +\eta_m \frac{\left[a-\frac{(1-\eta_r)a+(1-\eta_r)\delta g+\beta w}{2-\eta_r}+\delta g\right]^2}{2\beta}\end{aligned}$$

Solving the above optimization model yields the optimal wholesale price and the optimal green level stated in the following Proposition. All the proofs are listed in Appendix A.

Proposition 1. *As the manufacturer's operational decision, the optimal green level of the green agricultural supply chain is* $g^* = \frac{\delta(a-\beta c)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$, *and the optimal wholesale price is* $w^* = c+\frac{\theta(2-\eta_r-\eta_m)(a-\beta c)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$, *where* $\Delta_m = \frac{\theta(2-\eta_r-\eta_m)(a-\beta c)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2} > 0$ *denotes the marginal profit of the manufacturer.*

From Proposition 1, it can be found that the optimal green level, the optimal wholesale price, and the manufacturer's marginal profit in the green agricultural supply chain are determined by both the consumer-oriented altruism of the manufacturer and that of the retailer, except the usually considered green preference. Especially, how consumer-oriented altruism affects the operational decision of the green level is illustrated in the following Corollary.

Corollary 1. *Both the consumer-oriented altruism of the manufacturer and that of the retailer can enhance the green level of agricultural products, namely,* $\frac{\partial g^*}{\partial \eta_m} > 0$ *and* $\frac{\partial g^*}{\partial \eta_r} > 0$.

Previous literature has examined the effect of enterprise-oriented altruism on the green level of products. For instance, Wei et al. [43] showed that the manufacturer's altruism towards the retailer improves the green level of the supply chain. Liu et al. [45] verified that a retailer's altruism towards the manufacturer enhances the product's greenness. The above Corollary 1 demonstrated that consumer-oriented altruism also promotes the green level of agricultural products, although consumers change randomly outside the supply chain, whereas upstream and downstream enterprises interact with each other specifically within the supply chain.

4.3. Retail Pricing Decision

Given the optimal green level and wholesale price determined by the manufacturer, the retailer decides the retail price to maximize her utility. The optimal retail price is formulated in Proposition as follows.

Proposition 2. *As the retailer's operational decisions interact with consumers directly, the optimal retail price of the green agricultural supply chain is* $p^* = w^* + \frac{\theta(a-\beta c)(1-\eta_r)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$*, where* $\Delta_r = \frac{\theta(a-\beta c)(1-\eta_r)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2} > 0$ *denotes the marginal profit of the retailer.*

From Proposition 2, it can be found that the optimal retail price of the green agricultural supply chain is up to both the consumer-oriented altruism of the manufacturer and that of the retailer, except for the usually considered green preference. Integrating the manufacturer's marginal profit Δ_m in Proposition 1 and the retailer's marginal profit Δ_r in Proposition 2, we yield the following corollary.

Corollary 2. *Both the manufacturer and the retailer show their altruism to consumers by cutting down on their own unit marginal profits, namely,* $\frac{\partial \Delta_m}{\partial \eta_m} < 0$, $\frac{\partial \Delta_r}{\partial \eta_r} < 0$.

It is consistent with the original definition of altruism to help others by sacrificing oneself. Integrating the optimal wholesale price in Proposition 1 and the optimal retail price in Proposition 2, how consumer-oriented altruism affects the optimal pricing decision is highlighted in the following corollary.

Corollary 3. *The manufacturer' consumer-oriented altruism decreases his wholesale pricing decision, namely,* $\frac{\partial w^*}{\partial \eta_m} < 0$*, whereas the retailer's consumer-oriented altruism also decreases her retail pricing decision, namely,* $\frac{\partial p^*}{\partial \eta_r} < 0$.

Additionally, substituting $g^* = \frac{\delta(a-\beta c)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$, $w^* = c + \frac{\theta(2-\eta_r-\eta_m)(a-\beta c)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$, and $p^* = w^* + \frac{\theta(a-\beta c)(1-\eta_r)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$, respectively, into $\pi_m = (w-c)(a-\beta p+\delta g) - \frac{1}{2}\theta g^2$ and $\pi_r = (p-w)(a-\beta p+\delta g)$ yields the optimal profit of the manufacturer and that of the retailer. Then, respectively substituting them into $u_m = \pi_m + \eta_m \frac{(a-\beta p+\delta g)^2}{2\beta}$ and $u_r = \pi_r + \eta_r \frac{(a-\beta p+\delta g)^2}{2\beta}$ yields the optimal utility for the manufacturer and that for the retailer. Integrating those two outcomes yields the following corollary.

Corollary 4. *Showing altruisms to consumers, the manufacturer and the retailer attain less profits, denoted as* $\frac{\partial \pi_m^*}{\partial \eta_m} < 0$ *and* $\frac{\partial \pi_r^*}{\partial \eta_r} < 0$*, but more utilities, because of* $\frac{\partial u_m^*}{\partial \eta_m} > 0$ *and* $\frac{\partial u_r^*}{\partial \eta_r} > 0$.

Previous literature has proven that enterprise-oriented altruism would decrease one's own profit. For example, Wei et al. [43] showed that the manufacturer's altruism towards the retailer reduces the profit of the manufacturer. The above Corollary 4 illustrates that the supply chain enterprise's altruism orienting consumers would decrease individual profit but increase self-utility. Although reducing individual profit, consumer-oriented altruism can lead to internally positive intentions, enhancing overall performance and sustainability, which is the reason why this paper incorporates consumer-oriented altruism into the green agricultural supply chain.

5. Sustainability of Green Agricultural Supply Chain

According to the approach of triple bottom [5,6], sustainability can be divided into the economic, environmental, and social dimensions.

5.1. Economic Sustainability

Economic sustainability is described by the total profits of the green agricultural supply chain consistently. The more total profits, the stronger economic sustainability. The total profits equal the sum of the profits of the agricultural manufacturer and that of the agricultural retailer. Thus, the economic sustainability of the green agricultural supply chain is denoted as

$$S_{ec} = \pi_m + \pi_c = (p - c)(a - \beta p + \delta g) - \frac{1}{2}\theta g^2 \tag{1}$$

Substituting $g^* = \frac{\delta(a-\beta c)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$ and $p^* = w^* + \frac{\theta(a-\beta c)(1-\eta_r)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$ into the above (1) yields the economic sustainability of the green agricultural supply chain stated as

$$S_{ec}^* = \frac{\theta(a-\beta c)^2(2\beta\theta(3-2\eta_r-\eta_m)-\delta^2)}{2(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2} \tag{2}$$

5.2. Environmental Sustainability

In the green agricultural supply chain, the manufacturer uses environmentally friendly technologies. Such a green, proactive manufacturer decreases the use of pesticides, chemical fertilizers, herbicides, additives, and other chemical substances, and increases the use of degradable, decomposable, and recyclable materials, and thereby reduces the emission of pollutants such as methane, carbon dioxide, wastewater, and waste residue. Actually, greenhouse gas emissions, carbon footprint, and soil erosion are used to describe the environmental sustainability of the agricultural supply chain in the previous literature. As Miranda-Ackerman et al. [62], Qu et al. [63], and so on, the following takes the total pollutant emission reduction to describe the environmental sustainability of the green agricultural supply chain, given by:

$$S_{en} = \xi g q = \xi g(a - \beta p + \delta g) \tag{3}$$

where g denotes the unit pollutant emission reduction, and q denotes the quantity of production equaling the market demand at equilibrium, while ξ represents the environmental damage stemmed from unit pollutant emission.

Substituting $g^* = \frac{\delta(a-\beta c)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$ and $p^* = w^* + \frac{\theta(a-\beta c)(1-\eta_r)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$ into the above (3) yields the environmental sustainability of the green agricultural supply chain, denoted as

$$S_{en}^* = \frac{\beta\delta\theta\xi(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2} \tag{4}$$

5.3. Social Sustainability

The previous literature has modelled the social sustainability of the supply chain with different indicators such as consumer surplus [58,64], social welfare [20,23], food quality [27], consumer health [29], and consumer price fairness [30]. Those indicators all correlate with consumer surplus, which is the measurement used in this paper, and can be covered by consumer surplus at least to some extent because everyone actually is not only a consumer of agricultural products but also an individual member of society. Actually, in Sinayi et al. [58], Bubicz et al. [64], and so on, consumer surplus is used to describe the social sustainability of the green agricultural supply chain. Consumers with environmental awareness prefer to buy agricultural products with a higher green level, even if they must pay more. Although paying more is unfavorable, the consumption increases to the green level, and consumers can gain more utilities from agricultural products with a higher green level. the more consumption and the higher green level improve the consumer surplus. As the tradeoff of the above two sides, it is rational to take consumer surplus as the representative of the social sustainability of the green agricultural supply chain, denoted as

$$S_{so} = \lambda c_s = \frac{\lambda (a - \beta p + \delta g)^2}{2\beta} \tag{5}$$

where c_s denotes the consumer surplus defined in economics, λ represents how much is paid to consumer welfare when considering sustainable development.

Substituting $g^* = \frac{\delta(a-\beta c)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$ and $p^* = w^* + \frac{\theta(a-\beta c)(1-\eta_r)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$ into the above (5) yields the social sustainability of the green agricultural supply chain given by

$$S_{so}^* = \frac{\beta\lambda\theta^2(a-\beta c)^2}{2(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2} \tag{6}$$

By the above (2), (4), and (6), it is clear that each dimension of sustainability is up to the green investment, the green preference, the price sensitivity, the consumer-oriented altruism of the manufacturer, and that of the retailer simultaneously, although they are individually defined as the economic sustainability, environmental sustainability, and social sustainability of the green agricultural supply chain, respectively.

6. Impact of Consumer-Oriented Altruism on Sustainability

6.1. Impact of Retailer's Consumer-Oriented Altruism

The retailer sells the green agricultural products to consumers directly. Her altruism orienting consumers may result in reciprocally more consumptions responsively. Such direct interaction will influence each sustainability dimension of the green agricultural supply chain.

6.1.1. On Economic Sustainability

Theorem 1. *The retailer's consumer-oriented altruism can improve the economic sustainability of the green agricultural supply chain, which increases with the altruistic strength of the retailer, namely,* $\frac{\partial S_{ec}^*}{\partial \eta_r} > 0$.

The more altruistic the retailer is towards consumers, the stronger the economic sustainability of the green agricultural supply chain is, and the higher becomes the overall profits of the supply chain. At the individual level, a higher degree of consumer-oriented altruism implies less profits but more utilities, as shown in Corollary 4. From the perspective of the supply chain system, the more the retailer is altruistic, the stronger economic sustainability is, and the more system profits for the green agricultural supply chain gains.

6.1.2. On Environmental Sustainability

Theorem 2. *The retailer's consumer-oriented altruism can improve the environmental sustainability of the green agricultural supply chain, which increases with the altruistic strength of the retailer, namely,* $\frac{\partial S_{en}^*}{\partial \eta_r} > 0$.

The more altruistic the retailer is towards consumers, the stronger the environmental sustainability of the green agricultural supply chain becomes, and the more pollutant emission reductions implemented by green investment. At the individual level, more altruistic actions lead to a higher green level and more pollutant emission reductions, as shown in Corollary 1. From the perspective of the supply chain system, the increase in altruistic initiative towards consumers results in higher environmental sustainability and a more systematic reduction of pollutant emission throughout the entire green agricultural supply chain.

6.1.3. On Social Sustainability

Theorem 3. *The retailer's consumer-oriented altruism can improve social sustainability of the green agricultural supply chain, which increases with the altruistic strength of the retailer, namely,* $\frac{\partial S_{so}^*}{\partial \eta_r} > 0$.

The more altruism the retailer shows towards consumers indicates the stronger social sustainability of the green agricultural supply chain, and it leads to an increase in consumers' welfare. At the individual level, as shown in Corollary 1, the more the retailer is altruistic towards consumers, the higher the green level of agricultural products, which can enhance consumer surplus on two sides. On one side, more utilities from unit agricultural product with a higher green level. On the other side, more total quantities because a higher green level may result in more market demand. From the perspective of the supply chain system, the more the retailer is altruistic towards consumers, the higher consumer welfare the green agricultural supply chain achieves.

6.1.4. Systematic Impacts

In the systematic approach, the retailer's consumer-oriented altruism affects each sustainability dimension in the same direction. However, the suffered degrees in each dimension are different. Comparing the impacts of retailers' consumer-oriented altruism on economic, environmental, and social sustainability yields the following proposition.

Proposition 3. *Comparatively, in the green agricultural supply chain, the retailer's consumer-oriented altruism enhances each dimension of sustainability to different degrees. Economic sustainability is promoted the most dramatically, while environmental sustainability is improved the least, namely,* $\frac{\partial S_{ec}^*}{\partial \eta_r} > \frac{\partial S_{so}^*}{\partial \eta_r} > \frac{\partial S_{en}^*}{\partial \eta_r}$.

Although the retailer's consumer-oriented altruism can simultaneously improve economic, environmental, and social sustainability of the green agricultural supply chain simultaneously, as shown in Theorems 1, 2, and 3, respectively, the suffered degrees are different from each other. Economic sustainability gains the greatest improvement, while environmental sustainability attains the least. The greatest improvement of economic sustainability, that is, the system profits of the green agricultural supply chain, is the primary reason why the retailer behaves in an altruistic way orienting consumers. It is interesting that it is environmental sustainability instead of social sustainability that acquires the least improvement from the retailer's consumer-oriented altruism, but more attention has been paid to environmental sustainability instead of social sustainability in previous literature.

6.2. Impact of Manufacturer's Consumer-Oriented Altruism

Although the manufacturer does not face consumers directly, his altruism orienting consumers also may result in more reciprocal consumptions via the retailer. Each sustainability dimension of the green agricultural supply chain also will be influenced by the manufacturer's consumer-oriented altruism significantly.

6.2.1. On Economic Sustainability

Theorem 4. *The manufacturer's consumer-oriented altruism can improve the economic sustainability of the green agricultural supply chain, which increases with the altruistic strength of the manufacturer, namely,* $\frac{\partial S_{ec}^*}{\partial \eta_m} > 0$.

The more altruistic the manufacturer is towards consumers, the stronger the economic sustainability of the green agricultural supply chain becomes, and the more system profits the supply chain acquires. At the individual level, the more the manufacturer is altruistic towards consumers indirectly, the less profits but the more utilities he attains, which is shown in Corollary 4. From the perspective of the supply chain system, the more the manufacturer is altruistic towards consumers indirectly, the higher economic sustainability, and the more system profits of the green agricultural supply chain.

6.2.2. On Environmental Sustainability

Theorem 5. *The manufacturer's consumer-oriented altruism can improve the environmental sustainability of the green agricultural supply chain, which increases with the altruistic strength of the manufacturer, namely* $\frac{\partial S_{en}^*}{\partial \eta_m} > 0$.

The more the manufacturer behaves altruistically to consumers, the stronger environmental sustainability of the green agricultural supply chain is, and the more pollutant emission reductions his green investment achieves. At the individual level, the more the manufacturer is altruistic towards consumers indirectly, the more he will make green investment to reduce pollutant emission, and the higher the green level of agricultural products is, which is shown in Corollary 1. At the perspective of the supply chain system, the more the manufacturer is altruistic towards consumers indirectly, the higher environmental sustainability of the green agricultural supply chain achieves because there is an increased pollutant emission reduction resulting from the more investment in green technologies.

6.2.3. On Social Sustainability

Theorem 6. *The manufacturer's consumer-oriented altruism can improve social sustainability of the green agricultural supply chain, which increases with the altruistic strength of the manufacturer, namely,* $\frac{\partial S_{so}^*}{\partial \eta_m} > 0$.

The more altruistic the manufacturer is towards consumers, the more welfare consumers attain, and the stronger social sustainability of the green agricultural supply chain achieves. At the individual level, as shown in Corollary 1, the more the manufacturer is altruistic towards consumers, the higher the green level of agricultural products is, which can enhance consumer surplus in two aspects. On the one side, the higher green level may result in more utility stemming from the unit product. On the other side, the higher green level may lead to more market demand, which enhances consumer surplus by increasing consumption. From the perspective of the supply chain system, the more the manufacturer is altruistic towards consumers, the more the green agricultural supply chain endows consumers' welfare.

6.2.4. Systematic Impacts

In the systematic approach, the degrees the manufacturer's consumer-oriented altruism affects each sustainability dimension differently, although each dimension changes in the same direction. However, the extents of the impacts on each dimension differ. Comparing the impacts of manufacturer's consumer-oriented altruism on the economic, environmental, and social sustainability yields the following proposition.

Proposition 4. *Comparatively, in the green agricultural supply chain, the manufacturer's consumer-oriented altruism improves each dimension of sustainability in different degrees. The economic sustainability is raised the most dramatically, while the environmental sustainability is enhanced the most slightly, namely,* $\frac{\partial S_{ec}^*}{\partial \eta_m} > \frac{\partial S_{so}^*}{\partial \eta_m} > \frac{\partial S_{en}^*}{\partial \eta_m}$.

Although the manufacturer's consumer-oriented altruism improves the economic, environmental, and social sustainability of green agricultural supply, as shown in Theorem 4, 5, and 6, respectively, the degrees are different from each other. The economic sustainability achieves the greatest improvement, while the environmental sustainability is enhanced the least. The greatest improvement of economic sustainability, that is, the system profits of the green agricultural supply chain, is the reason why the manufacturer behaves in an altruistic way orienting consumers. The improvement of the system profits can lay the financial foundation of green investment, which will promote environmental sustainability directly. Additionally, although less attention has been paid to social sustainability than to environmental sustainability in the previous literature, social sustainability gains greater improvement from manufacturers' consumer-oriented altruism than the environmental sustainability.

6.3. Comparing Impacts of Retailer's and Manufacturer's Consumer-Oriented Altruism

Although both consumer-oriented altruism of the retailer and that of the manufacturer can enhance each sustainability dimension of the green agricultural supply chain, the acquired degrees are different from each other, which are illustrated one by one in detail as follows.

6.3.1. Comparing Impacts on Economic Sustainability

Theorem 7. *The retailer's consumer-oriented altruism improves the economic sustainability of the green agricultural supply chain more than the manufacturer's does, namely,* $\frac{\partial S_{ec}^*}{\partial \eta_r} > \frac{\partial S_{ec}^*}{\partial \eta_m}$.

Although the consumer-oriented altruism of both the retailer and the manufacturer can improve the economic sustainability of the green agricultural supply chain as shown in Theorems 1 and 4, respectively, the impact degrees are different from each other. The consumer-oriented altruism of the retailer can enhance the economic sustainability more than that of the manufacturer in that the retailer is closer to consumers.

6.3.2. Comparing Impacts on Environmental Sustainability

Theorem 8. *The retailer's consumer-oriented altruism enhances the environmental sustainability of the green agricultural supply chain more than the manufacturer's does, namely,* $\frac{\partial S_{en}^*}{\partial \eta_r} > \frac{\partial S_{en}^*}{\partial \eta_m}$.

Consumer-oriented altruism of both the retailer and the manufacturer can improve the environmental sustainability of the green agricultural supply chain as shown in Theorems 2 and 5, respectively. It is interesting that although it is the manufacturer who adopts environmentally friendly technologies to decrease the use of pesticides, chemical fertilizers, herbicides, additives, and other chemical substances, increases the use of degradable, decomposable and recyclable materials, and thereby reduces the emission of pollutants such as methane, carbon dioxide, wastewater, and waste residue. Consumer-oriented altruism of the retailer enhances the environmental sustainability more than that of the manufacturer. The retailer interacts with consumers directly, while the manufacturer's impact weakens gradually along the supply chain.

6.3.3. Comparing Impacts on Social Sustainability

Theorem 9. *The retailer's consumer-oriented altruism promotes social sustainability of the green agricultural supply chain more than the manufacturer's does, namely,* $\frac{\partial S_{so}^*}{\partial \eta_r} > \frac{\partial S_{so}^*}{\partial \eta_m}$.

Although consumer-oriented altruism of both the retailer and the manufacturer can improve the social sustainability of the green agricultural supply chain as shown in Theorems 3 and 6, respectively, the degrees of the impacts are different from each other. The consumer-oriented altruism of the retailer can enhance more than that from the manufacturer. The retailer is closer to consumers, her consumer-oriented altruism can lead to tighter reciprocal altruism. However, at the side of the manufacturer's consumer-oriented altruism, the indirect gradual transmission along the supply chain weakens the impact.

6.3.4. Systematic Comparisons

In the systematic approach, the retailer's consumer-oriented altruism enhances each sustainability dimension of green agriculture more than the manufacturer's does. However, the advantages in each dimension are different. By comparing the differences between the impacts that the retailer's consumer-oriented altruism affects the economic, environmental, and social sustainability, and those the manufacturer's does one by one, we yield the following proposition.

Proposition 5. *The advantages that the retailer's consumer-oriented altruism improves the sustainability of the green agricultural supply chain more than the manufacturer's does are different in each dimension. That in the economic sustainability is the largest, whereas that in environmental sustainability is the smallest, namely,* $\frac{\partial S_{ec}^*}{\partial \eta_r} - \frac{\partial S_{ec}^*}{\partial \eta_m} > \frac{\partial S_{so}^*}{\partial \eta_r} - \frac{\partial S_{so}^*}{\partial \eta_m} > \frac{\partial S_{en}^*}{\partial \eta_r} - \frac{\partial S_{en}^*}{\partial \eta_m}$.

Although the retailer's consumer-oriented altruism always improves each sustainability dimension of the green agricultural supply chain more than the manufacturer's does, as shown in Theorems 7–9, the advantages in economic, environmental, and social sustainability are different. The largest advantage in economic sustainability lays the financial foundation of consumer-oriented altruism. The smallest advantage in environmental sustainability results from the fact that it is the manufacturer who implements green investment to reduce pollutant emission. The relatively bigger advantage in the social dimension stems from the fact that the retailer is closer to consumers than the manufacturer is. However, previous literature has paid more attention to environmental sustainability than to social sustainability. Therefore, it is necessary and reasonable for this paper to investigate each dimension of sustainability by incorporating consumer-oriented altruism into the green agricultural supply chain.

7. Case Study

7.1. Green Strategy of DFF Supply Chain

DFF, Du Family Farm, located in the Jiangsu Province of China, is engaged in agricultural business including the introduction of new rice varieties and the promotion of new planting techniques. Since 2015, it has been cultivating green rice, with a trademark registered as Du Naturally Delicious Rice. It achieved Jiangsu Province's Good Rice Gold Award and the National Organic Expo Gold Award. Mr. Du, the leader of DFF, as a new professional farmer, was rated as National Leader of Rural Bellwether in 2018. At the 19th National Congress of the Communist Party of China in 2017, the Rural Revitalization Strategy was proposed. Four years later, the policy on comprehensively promoting rural revitalization and accelerating agricultural and rural modernization was issued by the Central Committee of the Communist Party of China and the State Council in January 2021. The key work regarding comprehensively promoting rural revitalization in 2022 was regulated in January 2022. Such governmental policy offers significant support to corporations such as the Du Family Farm to achieve rapid development.

DFF has initiated altruistic actions towards consumers by deploying green strategy. To cater for the growing needs of green consumption of consumers, DFF adopted a new technique of dry rice-nursery in cement field. The seedling plates, nutrient soil, and rice seeds, are added to the seedling seeder successively. With the movement of self-propelled seedling seeder, each seeding plate finishes automatically. Such green planting technique ensures the quality of seedlings. DFF has never sprayed any pesticides, never used any chemical fertilizers, and never overused lands. By planting and breeding bio-diversely, the ecological cycle is balanced comprehensively, which offers a way of sustainable coexistence with the land. Some special techniques have been granted national patents, such as a planting method of organic rice, a highly effective method of planting insect resistant organic rice.

In 2022, DFF tends to improve consumer surplus furtherly by implementing a new strategy denoted as 811, which enables excellent rice of 800,000 Mus, green rice of 100,000 Mus, and organic rice of 10,000 Mus. Mu is the unit of measurement of area adopted widely in China. The 811 strategy emphasizes the consumer-oriented altruism in the entire course of order production, brand leadership, and technical services. There is no doubt that the 811 strategy promotes the development of high-quality rice supply chain.

As the result of the green strategy and consumer-oriented altruism during the exploration of new techniques of cultivating rice, Du Naturally Delicious Rice is well acknowledged by consumers willing to pay more in acquiring green products. For instance, the price is CNY 256 per kilogram [65], while the average price of normal rice is CNY 7 per kilogram. The downstream retailer actively distributes Du Naturally Delicious Rice to large cities such as Shanghai and Beijing. The DFF's consumer-oriented altruism in green strategy has advanced the development of its whole supply chain significantly.

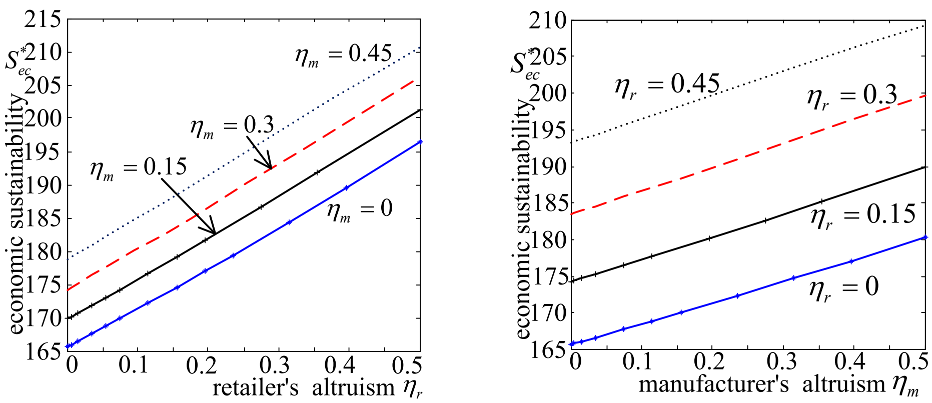
In accordance with the above theoretic assumptions, the real data collected about DFF are standardized, which is similar to Du et al. [66]. The potential maximum demand $a = 50$, price sensitivity $\beta = 2$, green preference $\delta = 1$, marginal cost of green investment $\theta = 100$, unit production cost $c = 4$, environmental damage from unit emission $\xi = 100$, social coefficient $\lambda = 3$, both the altruistic strength of the manufacturer and that of the retailer η_m and η_r change in the domain [0, 0.5] freely. In this case study, DFF, as the manufacturer, produces Du Naturally Delicious Rice in the direction of green strategy, and the retailer distributes and sells Du Naturally Delicious Rice to consumers in large cities such as Shanghai and Beijing.

7.2. Sustainability of DFF Supply Chain

7.2.1. Economic Sustainability

From Equation (2), the economic sustainability of DFF supply chain with the above numerical values is denoted as $S_{ec}^* = \frac{88{,}200(1199-800\eta_r-400\eta_m)}{(799-400\eta_r-200\eta_m)^2}$.

Then, how the economic sustainability S_{ec}^* changes with the retailer's consumer-oriented altruism η_r is illustrated in Figure 1a, which includes four cases of the manufacturer's altruism $\eta_m = 0$, $\eta_m = 0.15$, $\eta_m = 0.3$ and $\eta_m = 0.45$. That with the manufacturer's is illustrated in Figure 1b, also including four cases $\eta_r = 0$, $\eta_r = 0.15$, $\eta_r = 0.3$, and $\eta_r = 0.45$.



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

Figure 1. Impact of consumer-oriented altruism on economic sustainability. (**a**) Retailer's consumer-oriented altruism. (**b**) Manufacture's consumer-oriented altruism.

The numerical analysis illustrated on Figure 1 is interpreted as follows. First, the retailer's consumer-oriented altruism improves the economic sustainability of the green agricultural supply chain, which verifies the above Theorem 1. Second, the manufacturer's consumer-oriented altruism also heightens the economic sustainability of the green agricultural supply chain, which verifies the above Theorem 4. Third, the retailer's consumer-oriented altruism improves economic sustainability in a more dramatic way than the manufacturer's does, which verifies the above Theorem 7. The slope of the latter case is always smaller. The impact of the retailer's consumer-oriented altruism is stronger than that of the manufacturer's altruism.

Furthermore, a new observation from Figure 1 can be found as follows.

Observation 1. *Both consumer-oriented altruism-of the retailer and that of the manufacturer improve the economic sustainability of the green agricultural supply chain in a nearly linear way.*

7.2.2. Environmental Sustainability

From Equation (4), the environmental sustainability of DFF supply chain with the above numerical values is denoted as $S_{en}^* = \frac{35{,}280{,}000}{(400\eta_r + 200\eta_m - 799)^2}$.

Then, how the environmental sustainability S_{en}^* changes with the retailer's consumer-oriented altruism η_r is illustrated in Figure 2a, while that with the manufacturer's is in Figure 2b.

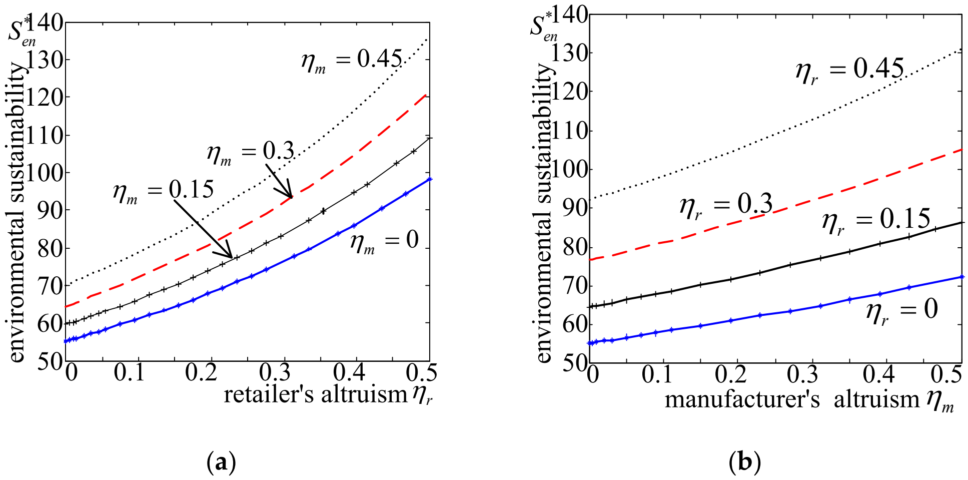


Figure 2. Impact of consumer-oriented altruism on environmental sustainability. (**a**) Retailer's consumer-oriented altruism. (**b**) Manufacture's consumer-oriented altruism.

The numerical analysis illustrated in Figure 2 is interpreted as follows. First, the retailer's consumer-oriented altruism enhances the environmental sustainability of the green agricultural supply chain, which verifies Theorem 2. Second, the manufacturer's consumer-oriented altruism also improves the environmental sustainability of the green agricultural supply chain, which verifies Theorem 5. Third, the retailer's consumer-oriented altruism improves the environmental sustainability in a more dramatic way than the manufacturer's does, which verifies Theorem 8. The slope of the latter case is always smaller, which means that the impact of the retailer's consumer-oriented altruism is stronger than that of the manufacturer's altruism.

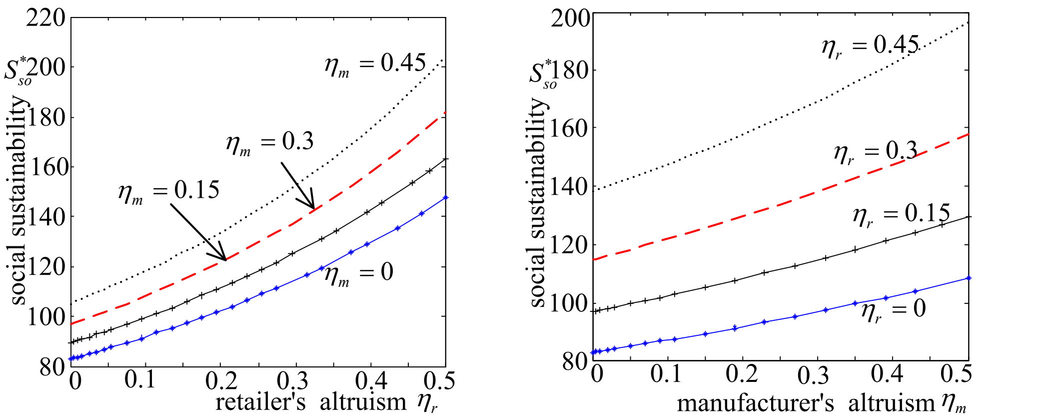
Furthermore, a new observation from Figure 2 can be found as follows.

Observation 2. *The retailer's consumer-oriented altruism improves the environmental sustainability of the green agricultural supply chain in a nearly quadratic way, while the manufacturer's consumer-oriented altruism enhances in a nearly linear way.*

7.2.3. Social Sustainability

From Equation (6), social sustainability of the DFF supply chain with the above numerical values is denoted as $S_{so}^* = \frac{52920000}{(400\eta_r + 200\eta_m - 799)^2}$.

Then, the impact of the retailer's consumer-oriented altruism η_r on social sustainability S^*_{en} is illustrated in Figure 3a, while that of the manufacturer's altruism is illustrated in Figure 3b.



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

Figure 3. Impact of consumer-oriented altruism on social sustainability. (**a**) Retailer's consumer-oriented altruism. (**b**) Manufacture's consumer-oriented altruism.

The numerical analysis illustrated in Figure 3 is interpreted as follows. First, the retailer's consumer-oriented altruism can increase the social sustainability of the green agricultural supply chain, which verifies the above Theorem 3. Second, the manufacturer's consumer-oriented altruism can also heighten the social sustainability of the green agricultural supply chain, which verifies the above Theorem 6. Third, the retailer's consumer-oriented altruism improves social sustainability in a more dramatic way than the manufacturer's does, which verifies the above Theorem 9. The slope of the latter case is always smaller, which means that the impact of the retailer's consumer-oriented altruism is stronger than that of the manufacturer's altruism.

Furthermore, a new observation from Figure 3 can be found as follows.

Observation 3. *The retailer's consumer-oriented altruism improves social sustainability of the green agricultural supply chain in a nearly quadratic way, but the manufacturer's consumer-oriented altruism improves in a nearly linear way.*

8. Conclusions

8.1. Main Findings

This paper investigates the optimal operational decision of the green agricultural supply chain incorporating consumer-oriented altruism, and explores the impacts of the consumer-oriented altruism on the economic, environmental, and social sustainability in a systematic way. The main findings are summarized as follows.

Firstly, in regard to the operational decision of the green agricultural supply chain, consumer-oriented altruism enhances the green level, whereas deceases pricing decisions of agricultural products, which cuts down the marginal profit of each supply chain enterprise.

Nevertheless, previous literature has only considered enterprise-oriented altruism and found that although enterprise-oriented altruism could definitely promote product greenness, it has a divergent effect on the marginal profit of each supply chain enterprise. For example, when the dominant retailer is altruistic towards small and medium-sized manufacturers, the marginal profit of the manufacturer is increased but that of the retailer is decreased [10]. Thus, this paper achieves the expansion and correction of the usual conclusion in previous literature by distinguishing different objects of altruism, orienting enterprises within supply chain or consumers outside supply chain, where the former has been discussed heavily and the latter never be touched before.

Secondly, in regard to the sustainability of the green agricultural supply chain, consumer-oriented altruism facilitates each dimension of sustainability simultaneously, and economic sustainability is improved the most prominently, while environmental sustainability is the least.

Such a systematic approach illustrates the relationship among all three dimensions of sustainability and shows that social sustainability is actually advanced by consumer-oriented altruism more than the popularly considered environmental sustainability, and thereby consumer-oriented altruism cannot be neglected any more. However, previous literature has focused on environmental sustainability while paying little attention to social sustainability [7,8]. So, this paper expands the popular conclusions in previous literature with findings on comprehensive impacts on all three sustainability dimensions of the green agricultural supply chain in a systematic approach.

Thirdly, in regard to the consumer-oriented altruism within the green agricultural supply chain, the retailer's consumer-oriented altruism always improves each dimension of sustainability more than the manufacturer's altruism does, and the advantage in economic sustainability is the largest, whereas that in environmental sustainability is the smallest.

However, previous literature has hardly touched on consumer-oriented altruism, thereby neither exploring the impact of consumer-oriented altruism on sustainability, nor comparing the impacts of retailer's consumer-oriented altruism and manufacturer's altruism. Due to the above, this paper achieves some new discoveries that help decision makers understand the impacts of different origins of consumer-oriented altruism, which has never occurred in previous literature.

8.2. Managerial Implications

From the findings of this paper, some managerial implications for green agricultural supply chain managers can be concluded as follows.

Firstly, supply chain managers should be altruistic towards consumers by taking consumer surplus into operational decisions to facilitate each sustainability dimension of the green agricultural supply chain. Especially, the improvement of social sustainability is greater than that of environmental sustainability, while that of economic sustainability lays the financial foundation of comprehensive sustainable development. Therefore, altruistic behaviors towards consumers are not only capable of enhancing emission reduction but also promoting the consumer welfare of the supply chain.

Secondly, supply chain managers should implement a green strategy by investing in environmentally friendly technologies, which can raise the green level of the agricultural supply chain. By decreasing chemical substances such as pesticides, fertilizers, herbicides, and additives and increasing the use of decomposable, degradable, and recyclable materials, many environmental issues are expected to be alleviated, including greenhouse gas emissions, land erosion, deforestation, and the like. More revenue can be earned because consumers with green preferences prefer to buy more green agricultural products at a higher price.

Finally, supply chain managers should adopt smart information management, which plays the part of signaling their altruistic intentions and green strategies publicly, promptly, and accurately. When interacting with altruistic enterprises, consumers could respond with more reciprocal consumption. Knowing the green level precisely, consumers could efficiently decide the quantity and price they could accept. By applying smart information management, information modification can be prevented, and it is able to diminish information misreport, whose potential earnings are large in the long term.

8.3. Future Directions

There is a pressing need to explore the two points in the future. First, the interaction of power structures with consumer-oriented altruism. This paper has only investigated the green agricultural supply chain with a dominant manufacturer. Scenarios with a dominant retailer and Nash vertical power structure should be explored and compared. Second, the competition among multiple retailers within the green agricultural supply chain. This paper only examines the green agricultural supply chain with a monopolistic retailer, but in practice there are usually multiple retailers competing for upstream manufacturers and downstream consumers.

Author Contributions: Conceptualization, G.W.; Writing—original draft, G.W. and L.Z.; Writing—review and editing, B.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Social Science Foundation of China under Grant No. 20FGLB031.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

Appendix A

Proof of Proposition 1. By u_m, yield the Hessian matrix denoted as $H = \begin{bmatrix} -\frac{\beta(4-2\eta_r-\eta_m)}{(2-\eta_r)^2} & \frac{\delta(2-\eta_r-\eta_m)}{(2-\eta_r)^2} \\ \frac{\delta(2-\eta_r-\eta_m)}{(2-\eta_r)^2} & -\left[\theta - \frac{\eta_m\delta^2}{\beta(2-\eta_r)^2}\right] \end{bmatrix}$. According to $0 \le \eta_m < 1$, $0 \le \eta_r < 1$, $0 \le \eta_m + \eta_r < 1$, and sufficiently large θ, there must be $-\frac{\beta(4-2\eta_r-\eta_m)}{(2-\eta_r)^2} < 0$, $\frac{\delta(2-\eta_r-\eta_m)}{(2-\eta_r)^2} > 0$, and $-\left[\theta - \frac{\eta_m\delta^2}{\beta(2-\eta_r)^2}\right] < 0$. Then, H is a negative matrix that ensures the uniqueness of the optimal solution. Therefore, with the first order conditions $\frac{\partial u_m}{\partial g} = 0$ and $\frac{\partial u_m}{\partial w} = 0$, yield the optimal $g^* = \frac{\delta(a-\beta c)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$ and $w^* = c + \frac{\theta(2-\eta_r-\eta_m)(a-\beta c)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$. □

Proof of Proposition 2. Substituting the above optimal $g^* = \frac{\delta(a-\beta c)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$ and $w^* = c + \frac{\theta(2-\eta_r-\eta_m)(a-\beta c)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$ into $\overline{p}(w,g) = \frac{(1-\eta_r)a+(1-\eta_r)\delta g+\beta w}{\beta(2-\eta_r)}$, we yield the optimal retail price $p^* = w^* + \frac{\theta(a-\beta c)(1-\eta_r)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$. □

Proof of Corollary 1. From the optimal $g^* = \frac{\delta(a-\beta c)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$, yield that $\frac{\partial g^*}{\partial \eta_r} = \frac{2\beta\theta\delta(a-\beta c)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2} > 0$ and $\frac{\partial g^*}{\partial \eta_m} = \frac{2\theta\delta(a-\beta c)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2} > 0$ because of $a - \beta c > 0$, $0 \le \eta_m < 1$, $0 \le \eta_r < 1$, $0 \le \eta_m + \eta_r < 1$, and sufficiently large θ. □

Proof of Corollary 2. From the above $\Delta_m = \frac{\theta(2-\eta_r-\eta_m)(a-\beta c)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$, yield $\frac{\partial \Delta_m}{\partial \eta_m} = -\frac{\theta(a-\beta c)(\beta\theta(2-\eta_r)-\delta^2)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2} < 0$ because of $a - \beta c > 0$, $0 \le \eta_m < 1$, $0 \le \eta_r < 1$, $0 \le \eta_m + \eta_r < 1$, and sufficiently large θ. Similarly, from $\Delta_r = \frac{\theta(a-\beta c)(1-\eta_r)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$, yield $\frac{\partial \Delta_r}{\partial \eta_r} = -\frac{\theta(a-\beta c)(\beta\theta(2-\eta_m)-\delta^2)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2} < 0$. □

Proof of Corollary 3. From the above $w^* = c + \frac{\theta(2-\eta_r-\eta_m)(a-\beta c)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$, yield $\frac{\partial w^*}{\partial \eta_m} = -\frac{\theta(a-\beta c)(\beta\theta(2-\eta_r)-\delta^2)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2} < 0$ because of $a - \beta c > 0$, $0 \le \eta_m < 1$, $0 \le \eta_r < 1$, and sufficiently large θ. Similarly, from $p^* = w^* + \frac{\theta(a-\beta c)(1-\eta_r)}{\beta\theta(4-2\eta_r-\eta_m)-\delta^2}$, it is easy to deduct $\frac{\partial p^*}{\partial \eta_r} = \frac{\beta\theta^2(a-\beta c)^2(\beta\theta(\eta_m-2\eta_r)+\delta^2)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3} < 0$. □

Proof of Corollary 4. Firstly, by $\pi_m^* = \frac{\theta(a-\beta c)^2(2\theta\beta(2-\eta_r-\eta_m)-\delta^2)}{2(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2}$, yield $\frac{\partial\pi_m^*}{\partial\eta_m} = \frac{\eta_m\beta^2\theta^3(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3} < 0$ because of $0 \le \eta_m < 1$, $0 \le \eta_r < 1$, $0 \le \eta_m + \eta_r < 1$, and sufficiently large θ. Similarly, from $\pi_r^* = \frac{\beta\theta^2(a-\beta c)^2(1-\eta_r)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2}$, it is easy to yield $\frac{\partial\pi_r^*}{\partial\eta_r} = \frac{\beta\theta^2(a-\beta c)^2(\beta\theta(\eta_m-2\eta_r)+\delta^2)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3} < 0$ because of $0 \le \eta_m < 1$, $0 \le \eta_r < 1$, $0 \le \eta_m + \eta_r < 1$, $\eta_m < \eta_r$, and sufficiently large θ. Secondly, from $u_m^* = \frac{\theta(a-\beta c)^2}{2(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)}$, yield $\frac{\partial u_m^*}{\partial\eta_m} = \frac{\beta\theta^2(a-\beta c)^2}{2(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2} > 0$. Similarly, from $u_r^* = \frac{\beta\theta^2(a-\beta c)^2(2-\eta_r)}{2(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2}$, yield $\frac{\partial u_r^*}{\partial\eta_r} = \frac{\beta\theta^2(a-\beta c)^2(\beta\theta(4+2\eta_r-\eta_m)-\delta^2)}{2(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3} > 0$ because of $0 \le \eta_m < 1$, $0 \le \eta_r < 1$, $0 \le \eta_m + \eta_r < 1$, and sufficiently large θ. □

Proof of Theorem 1. By $S_{ec}^* = \frac{\theta(a-\beta c)^2(2\beta\theta(3-2\eta_r-\eta_m)-\delta^2)}{2(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2}$, yield $\frac{\partial S_{ec}^*}{\partial\eta_r} = \frac{2\beta^2\theta^3(a-\beta c)^2(2-2\eta_r-\eta_m)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$. From $0 \le \eta_m < 1$, $0 \le \eta_r < 1$, $0 \le \eta_m + \eta_r < 1$, and sufficiently large θ, yield $\frac{\partial S_{ec}^*}{\partial\eta_r} > 0$. □

Proof of Theorem 2. By $S_{en}^* = \frac{\beta\delta\theta\xi(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2}$, get $\frac{\partial S_{en}^*}{\partial\eta_r} = \frac{4\delta\xi\beta^2\theta^2(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$. From $0 \le \eta_m < 1$, $0 \le \eta_r < 1$, $0 \le \eta_m + \eta_r < 1$, and sufficiently large θ, yield $\frac{\partial S_{en}^*}{\partial\eta_r} > 0$. □

Proof of Theorem 3. By $S_{so}^* = \frac{\beta\lambda\theta^2(a-\beta c)^2}{2(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2}$, get $\frac{\partial S_{so}^*}{\partial\eta_r} = \frac{2\lambda\beta^2\theta^3(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$. From $0 \le \eta_m < 1$, $0 \le \eta_r < 1$, $0 \le \eta_m + \eta_r < 1$, and sufficiently large θ, yield $\frac{\partial S_{so}^*}{\partial\eta_r} > 0$. □

Proof of Proposition 3. Firstly, from $\frac{\partial S_{ec}^*}{\partial\eta_r} = \frac{2\beta^2\theta^3(a-\beta c)^2(2-2\eta_r-\eta_m)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$ and $\frac{\partial S_{en}^*}{\partial\eta_r} = \frac{4\delta\xi\beta^2\theta^2(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$, yield $\frac{\partial S_{ec}^*}{\partial\eta_r} - \frac{\partial S_{en}^*}{\partial\eta_r} = \frac{2\beta^2\theta^2(a-\beta c)^2(\theta(2-2\eta_r-\eta_m)+\delta\xi)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$. From $0 \le \eta_m < 1$, $0 \le \eta_r < 1$, $0 \le \eta_m + \eta_r < 1$, and sufficiently large θ, yield $\frac{\partial S_{ec}^*}{\partial\eta_r} - \frac{\partial S_{en}^*}{\partial\eta_r} > 0$. Secondly, from $\frac{\partial S_{so}^*}{\partial\eta_r} = \frac{2\lambda\beta^2\theta^3(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$ and $\frac{\partial S_{en}^*}{\partial\eta_r} = \frac{4\delta\xi\beta^2\theta^2(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$, yield $\frac{\partial S_{so}^*}{\partial\eta_r} - \frac{\partial S_{en}^*}{\partial\eta_r} = \frac{2\beta^2\theta^2(a-\beta c)^2(\theta\lambda-2\delta\xi)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$. From $0 \le \eta_m < 1$, $0 \le \eta_r < 1$, $0 \le \eta_m + \eta_r < 1$ and sufficiently large θ, yield $\frac{\partial S_{so}^*}{\partial\eta_r} - \frac{\partial S_{en}^*}{\partial\eta_r} > 0$. □

Proof of Theorem 4. From $S_{ec}^* = \frac{\theta(a-\beta c)^2(2\beta\theta(3-2\eta_r-\eta_m)-\delta^2)}{2(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2}$, yield $\frac{\partial S_{ec}^*}{\partial\eta_m} = \frac{\beta^2\theta^3(a-\beta c)^2(2-2\eta_r-\eta_m)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$. From $0 \le \eta_m < 1$, $0 \le \eta_r < 1$, $0 \le \eta_m + \eta_r < 1$, and sufficiently large θ, yield $\frac{\partial S_{ec}^*}{\partial\eta_m} > 0$. □

Proof of Theorem 5. By $S_{en}^* = \frac{\beta\delta\theta\xi(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2}$, get $\frac{\partial S_{en}^*}{\partial\eta_m} = \frac{2\delta\xi\beta^2\theta^2(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$. From $0 \le \eta_m < 1$, $0 \le \eta_r < 1$, $0 \le \eta_m + \eta_r < 1$, and sufficiently large θ, yield $\frac{\partial S_{en}^*}{\partial\eta_m} > 0$. □

Proof of Theorem 6. By $S_{so}^* = \frac{\beta\theta^2(a-\beta c)^2}{2(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2}$, get $\frac{\partial S_{so}^*}{\partial\eta_m} = \frac{\beta^2\theta^3(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$. From $0 \le \eta_m < 1$, $0 \le \eta_r < 1$, $0 \le \eta_m + \eta_r < 1$, and sufficiently large θ, yield $\frac{\partial S_{so}^*}{\partial\eta_m} > 0$. □

Proof of Proposition 4. Firstly, by $\frac{\partial S_{ec}^*}{\partial\eta_m} = \frac{\beta^2\theta^3(a-\beta c)^2(2-2\eta_r-\eta_m)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$ and $\frac{\partial S_{en}^*}{\partial\eta_m} = \frac{2\delta\xi\beta^2\theta^2(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$, yield $\frac{\partial S_{ec}^*}{\partial\eta_m} - \frac{\partial S_{en}^*}{\partial\eta_m} = \frac{\beta^2\theta^2(a-\beta c)^2(\theta(2-2\eta_r-\eta_m)+\delta\xi)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$. From $0 \le \eta_m < 1$, $0 \le \eta_r < 1$, $0 \le \eta_m + \eta_r < 1$, and sufficiently large θ, yield $\frac{\partial S_{ec}^*}{\partial\eta_m} - \frac{\partial S_{en}^*}{\partial\eta_m} > 0$. Secondly, from $\frac{\partial S_{so}^*}{\partial\eta_m} = \frac{\lambda\beta^2\theta^3(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$

and $\frac{\partial S_{en}^*}{\partial \eta_m} = \frac{2\delta\xi\beta^2\theta^2(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$, yield $\frac{\partial S_{so}^*}{\partial \eta_m} - \frac{\partial S_{en}^*}{\partial \eta_m} = \frac{\beta^2\theta^2(a-\beta c)^2(\theta\lambda-2\delta\xi)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$. From $0 \leq \eta_m < 1$, $0 \leq \eta_r < 1$, $0 \leq \eta_m + \eta_r < 1$, and sufficiently large θ, yield $\frac{\partial S_{so}^*}{\partial \eta_m} - \frac{\partial S_{en}^*}{\partial \eta_m} > 0$. □

Proof of Theorem 7. By $S_{ec}^* = \frac{\theta(a-\beta c)^2(2\beta\theta(3-2\eta_r-\eta_m)-\delta^2)}{2(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2}$, yield $\frac{\partial S_{ec}^*}{\partial \eta_r} - \frac{\partial S_{ec}^*}{\partial \eta_m} = \frac{\beta^2\theta^3(a-\beta c)^2(2-2\eta_r-\eta_m)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$. By $0 \leq \eta_m < 1$, $0 \leq \eta_r < 1$, $0 \leq \eta_m + \eta_r < 1$, and sufficiently large θ, yield $\frac{\partial S_{ec}^*}{\partial \eta_r} - \frac{\partial S_{ec}^*}{\partial \eta_m} > 0$. □

Proof of Theorem 8. From the above $S_{en}^* = \frac{\beta\delta\theta\xi(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2}$, yield $\frac{\partial S_{en}^*}{\partial \eta_r} - \frac{\partial S_{en}^*}{\partial \eta_m} = \frac{2\delta\xi\beta^2\theta^2(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$. From $0 \leq \eta_m < 1$, $0 \leq \eta_r < 1$, $0 \leq \eta_m + \eta_r < 1$, and sufficiently large θ, yield $\frac{\partial S_{en}^*}{\partial \eta_r} - \frac{\partial S_{en}^*}{\partial \eta_m} > 0$. □

Proof of Theorem 9. From the above $S_{so}^* = \frac{\beta\lambda\theta^2(a-\beta c)^2}{2(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^2}$, attain $\frac{\partial S_{so}^*}{\partial \eta_r} - \frac{\partial S_{so}^*}{\partial \eta_m} = \frac{\lambda\beta^2\theta^3(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$. From $0 \leq \eta_m < 1$, $0 \leq \eta_r < 1$, $0 \leq \eta_m + \eta_r < 1$, and sufficiently large θ, yield $\frac{\partial S_{so}^*}{\partial \eta_r} - \frac{\partial S_{so}^*}{\partial \eta_m} > 0$. □

Proof of Proposition 5. Firstly, from the above $\frac{\partial S_{ec}^*}{\partial \eta_r} - \frac{\partial S_{ec}^*}{\partial \eta_m} = \frac{\beta^2\theta^3(a-\beta c)^2(2-2\eta_r-\eta_m)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$ and $\frac{\partial S_{en}^*}{\partial \eta_r} - \frac{\partial S_{en}^*}{\partial \eta_m} = \frac{2\delta\xi\beta^2\theta^2(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$, yield $\left(\frac{\partial S_{ec}^*}{\partial \eta_r} - \frac{\partial S_{ec}^*}{\partial \eta_m}\right) - \left(\frac{\partial S_{en}^*}{\partial \eta_r} - \frac{\partial S_{en}^*}{\partial \eta_m}\right) = \frac{\beta^2\theta^2(a-\beta c)^2(\theta(2-2\eta_r-\eta_m)+\delta\xi)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$. From $0 \leq \eta_m < 1$, $0 \leq \eta_r < 1$, $0 \leq \eta_m + \eta_r < 1$, and sufficiently large θ, yield $\left(\frac{\partial S_{ec}^*}{\partial \eta_r} - \frac{\partial S_{ec}^*}{\partial \eta_m}\right) - \left(\frac{\partial S_{en}^*}{\partial \eta_r} - \frac{\partial S_{en}^*}{\partial \eta_m}\right) > 0$. Secondly, from $\frac{\partial S_{so}^*}{\partial \eta_r} - \frac{\partial S_{so}^*}{\partial \eta_m} = \frac{\lambda\beta^2\theta^3(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$ and $\frac{\partial S_{en}^*}{\partial \eta_r} - \frac{\partial S_{en}^*}{\partial \eta_m} = \frac{2\delta\xi\beta^2\theta^2(a-\beta c)^2}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$, yield $\left(\frac{\partial S_{so}^*}{\partial \eta_r} - \frac{\partial S_{so}^*}{\partial \eta_m}\right) - \left(\frac{\partial S_{en}^*}{\partial \eta_r} - \frac{\partial S_{so}^*}{\partial \eta_m}\right) = \frac{\beta^2\theta^2(a-\beta c)^2(\theta-2\delta)}{(\beta\theta(4-2\eta_r-\eta_m)-\delta^2)^3}$. From $0 \leq \eta_m < 1$, $0 \leq \eta_r < 1$, $0 \leq \eta_m + \eta_r < 1$, and sufficiently large θ, yield $\left(\frac{\partial S_{so}^*}{\partial \eta_r} - \frac{\partial S_{so}^*}{\partial \eta_m}\right) - \left(\frac{\partial S_{en}^*}{\partial \eta_r} - \frac{\partial S_{so}^*}{\partial \eta_m}\right) > 0$. □

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