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Optimization of the Green Agricultural Supply Chain Under Governmental Intervention Policies

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Abstract:

With economic development, green agricultural products have gained increasing attention in society. Consumers have a preference for green agricultural products and are willing to pay a premium for them. However, this premium comes with uncertainty and can affect the production of green agricultural products. This paper proposes an information provision program where the government predicts premium information and shares it with farmers, comparing it with the traditional production subsidy program. To do so, this paper constructs a supply chain model where some farmers choose the direct sales channel while others opt for the contract farming channel. Nash and Stackelberg games are used to analyze farmers' production decisions. The study finds that (1) The production subsidy program can effectively promote the production of green agricultural products, but excessive subsidies can reduce farmers' income. (2) The information provision program does not directly affect the production of green agricultural products but can promote farmers' income. Moreover, the more accurate the forecast information and the greater the premium volatility, the more significant the increase in farmers' income. (3) When the production cost of green agricultural products is low or the unit area yield is high, the information provision program can better help farmers achieve higher income. However, when the production cost of green agricultural products is high or the unit area yield is low, the production subsidy program is more effective.

Keywords: Green agricultural products, Consumer preferences, Government intervention

1. INTRODUCTION

In recent years, the issues of quality and safety concerning agricultural products have risen to the forefront of societal concern[1]. Green agricultural products, through their cultivation, diminish the application of pesticides and fertilizers, showcasing superior standards of safety and quality compared to conventional agricultural produce. Consequently, they are increasingly garnering favor among consumers[2]. Numerous research endeavors have elucidated that consumers are amenable to paying a premium for green agricultural products, particularly in emerging nations such as China[3-4]. Furthermore, the premium associated with green agricultural products, as it serves to incentivize agricultural producers to embrace more sustainable production practices, whilst affording them augmented income, an imperative facet for the economic development of rural sectors in emerging economies[5]. However, it is noteworthy that the premium associated with green agricultural products is subject to dynamic fluctuations and fraught with uncertainty, rendering it challenging for ordinary farmers to access information regarding such premiums[6].

In the face of information asymmetry prevalent in the green agricultural products market, the government plays a pivotal role[7]. Government agencies can proactively forecast price information for agricultural products by analyzing market trends, monitoring supply and demand dynamics, and investigating consumer preferences. A plethora of research indicates that the information provision program (IPP) can effectively assist farmers in increasing both production and income. For example, Chen et al. (2015) found that information provision has a significant positive impact on the income of farmers in emerging economies[6]. However, their study is confined to conventional agricultural products and does not juxtapose the information provision program with other policy programs for comparison. Against the backdrop of the escalating significance of the green economy, researching the impact of the information provision program on the production decisions of green agricultural products holds significant theoretical and practical significance. Furthermore, the production subsidy program (PSP), as a traditional form of government intervention measure, can effectively assist farmers in increasing production and income[8-10]. So, what distinguishes government-provided information from government-provided green subsidies? Under what circumstances does the information provision program become a more suitable option for green agricultural products? These questions remain subjects of intense interest and pressing concern for both the industry and the academic community.

Simultaneously, we also observe that contract farming holds significant importance in developing nations[11-12]. Contract farming entails a farmer entering into a legally binding forward contract with a company prior to the cultivation of green agricultural products. The contracting parties mutually establish the wholesale price and transaction timeframe. The farmer conducts production activities in accordance with the contractual terms, and upon the conclusion of the production season, the company procures the green agricultural products[13]. Given that contract farming can provide farmers with a stable sales channel, it has gradually gained acceptance among them[14]. Consequently, in many rural areas, some farmers opt for direct sales, while others choose contract farming. Our study combines the dual-channel production approach of green agricultural products with various government intervention programs. Accordingly, our work addresses the following questions:

(1) How does PSP affect the yield and income of farmers in different channels?

(2) What impact does IPP have on the yield and income of farmers in different channels?

(3) Does PSP invariably excel over IPP in fostering the enhancement of green agricultural product yields? Under what conditions should the government advocate for the implementation of IPP intervention programs?

To address the aforementioned questions, we consider a dual-channel supply chain model in which some farmers opt for the direct sales channel while others choose the contract farming channel. Simultaneously, the government implements an information provision program and a production subsidy program for these farmers. Furthermore, we proceed by delineating the production decision functions of farmers under different government intervention programs. Subsequently, we employ a game theory framework to analyze farmers' planting strategies and calibrate our model using data from the cassava supply chain in China, thereby offering decision-makers a more comprehensive understanding.

The remainder of this paper is organized as follows. Section 2 reviews the literature and positions this study. the model preliminaries are described in Section 3. We carry out the equilibrium analysis in Sections 4. We calibrate our model with data in Section 5. Conclusions and implications are provided in Section 6. All proofs are given in the online supplemental materials.

2. LITERATURE REVIEW

The research is related to three streams of the literature: the consumer green preference, the agricultural supply chain, and government intervention programs.

2.1 Consumer Green Preference

As consumers increasingly prioritize product quality, they tend to prefer and are willing to pay a premium for greener alternatives when faced with similar products or services. Therefore, considering consumer green preferences will become even more essential in future markets. Cheung et al. (2015) investigated the influence of consumer's perception of the green value and trustworthiness of green agricultural products on their willingness to purchase such products[15]. The results indicated that enhancing consumer trust in green attributes contributes to attracting consumers towards purchasing green agricultural products. Furthermore, Ghosh et al. (2017)conducted a study to investigate the influence of consumer green preference coefficients on decision outcomes under different leadership scenarios[16]. Xiao et al. (2023) considered consumers' low-carbon awareness and explored the role of greenness-based subsidy and dual credit policy in promoting new energy vehicles[17]. Zhang et al. (2017) investigated the influence of product greenness in a three-tier supply chain and derived optimal pricing strategies for retailers under three different decentralized decision models[18]. Meng et al. (2021) examined collaborative pricing strategies for products in a dual-channel green supply chain and observed that higher consumer green preferences or a lower preference for offline channels corresponded to greater demand for green products[19]. Zhou and Duan (2022) studied consumer reference greenness effect and environmental awareness in their choice of selling formats (reselling or agency selling) in an e-commerce supply chain[20]. Yi et al. (2022) formulated a supply chain model where manufacturers are responsible for green technology investment and retailers handle marketing to consumers with green preferences[21]. They found that consumer green preferences can lead to reduced marginal costs for green technology investment. Xu et al. (2017) studied the impact of technological spillovers and environmental awareness on reducing carbon emissions[22]. Ran et al. (2024) designed a dual low-carbon incentive strategy based on a government-led digital platform to encourage corporate alliances to adopt low-carbon distribution model[23]. Different from the aforementioned literature, this paper integrates PSP and IPP with the green supply chain, analyzing the impact of different government intervention initiatives on the dual-channel distribution of green agricultural products.

2.2 Agricultural Supply Chain

Agriculture serves as a cornerstone of a nation's economic development, prompting numerous scholars to engage in research on agricultural supply chains. Some of these scholars have delved into cooperative contracts within agricultural supply chains.

Scholars like Niu et al. (2016) have considered the benefits and costs of farmers' efforts and explored the coordination of agricultural cooperation through two contract farming models: "farmer + company" and "farmer + cooperative + company" [24]. Feng et al. (2021) developed contract models, including cost-sharing contracts, cost-sharing and revenue-sharing contracts, and cost-sharing and balance strategies, to investigate production decision issues within agricultural supply chains[25]. Yan et al. (2021) conducted research on optimal ordering strategies and coordination in agricultural supply chains based on two-period prices, wholesale prices, and option contracts[26]. Wang et al. (2020) addressed a green fresh produce supply chain problem and established decentralized models, traditional cost-sharing models, and a Nash bargaining model with cost sharing for coordination[27]. Li et al. (2024) studied the weather risk hedging mechanism of contract farming supply chain under the Newsvendor setting[28]. Some scholars have also analyzed the randomness in agricultural product output. For instance, Golmohammadi et al. (2018) examined joint ordering and pricing issues for agricultural products in the context of dual randomness in output and demand[29]. Zhang et al. (2020) considered the uncertainty of rainfall in the African continent, proposed a new planting plan to increase local farmers' income and improve their livelihoods[30]. Their study found that if the production cost of high-value agricultural products is low, farmers with lower output can effectively increase their income by choosing contract farming. Several scholars have also focused on dual-channel agricultural products. For example, Agbo et al. (2015) constructed a dual-channel agricultural product supply chain where farmers engage in direct sales and sell through cooperatives[31]. Their study found that cooperative game in the cooperative channel can influence the non-cooperative game of farmers in the direct sales market. Their research indicated that when a fixed pricing strategy is employed between the company and farmers, risk-averse farmers offer the same quantity of agricultural products in both channels. There are also scholars who have studied blockchain technology for agricultural supply chains during the COVID-19 pandemic and identified the benefits and solutions of using blockchain to smoothly carry out agricultural supply chains during COVID-19[32]. Hu et al. (2022) studied the impact mechanism of blockchain certification traceability model and blockchain-based e-commerce model on dual-channel organic agricultural supply chain[33]. In addition, Handayati and Widyanata (2024) examined the current status of the agricultural food supply chain, pointed out that a large portion of food is wasted in the agricultural supply chain, and discussed the various challenges and complexities involved in managing food waste[34]. Khalili et al. (2024) systematically investigated Iranian farmers' intention to choose contract farming[35].

The aforementioned studies have provided valuable insights into agricultural supply chains. However, they have overlooked consumer demand for green agricultural products and the impact of government interventions on agricultural supply chains.

2.3 Government Intervention Programs

The development of agriculture relies on government support, and countries worldwide have implemented various support policies for agriculture. This has also attracted numerous scholars to conduct research on government intervention programs. Tang et al. (2015) found that unless the upfront investment in agricultural production is sufficiently low, providing planting advice to farmers by the government does not always improve farmers' welfare[36]. Akkaya et al. (2017) explored the effectiveness of government taxation, subsidies, and mixed policies in organic agriculture and analyzed government intervention programs in developing countries in the forms of price support, cost support, or income enhancement[37]. Guda et al. (2018) studied government-supported price schemes in developing countries, where governments purchase crops at specific prices to support impoverished populations, and analyzed the impact of such subsidy policies on farmers, consumers, and the government[38]. Alizamir et al. (2018) found that when subsidy policies create economic and policy frictions, subsidies that benefit both consumers and farmers may lead to a decrease in overall societal welfare[39]. Peng et al. (2019) discovered that as government subsidies increase, both suppliers and distributors see increased profits, while the impact of government subsidies on farmer income depends on the farmers' risk aversion[40]. Hsu et al. (2019) studied innovative agricultural partnerships in the dairy industry, and their model showed that government subsidies based on product quality can sometimes reduce the quality of dairy products[41].They found that subsidizing sellers can maximize societal welfare when farmers have large planting areas and the government budget is relatively high."

What sets this study apart from the aforementioned research is that it explores and compares PSP and IPP in the context of consumer preferences for green agricultural products. This enriches the research landscape of government intervention programs.

3. PROBLEM DESCRIPTION AND MODEL HYPOTHESIS

This paper assumes that in a rural area, there are n homogeneous farmers. m farmers choose the direct sales channel, where they individually produce green agricultural products and sell them directly in the retail market. The remaining $n-m$ farmers opt for the contract farming channel. Under the contract farming channel, farmers enter into production and sales contracts with the company. When the agricultural products are mature, the company purchases all the green agricultural products and then releases them to the market for sale. Farmers in both channels independently decide on the production quantity.

Before modeling, the following assumptions are made:

(1) In the dual-channel agricultural product supply chain, the planting area for an individual farmer in the direct sales channel is denoted as q_i, and for an individual farmer in the contract farming channel, it is denoted as q_j. Hence, the total planting area for farmers in the direct sales channel is denoted as $Q_{DS} = \sum_{i=1}^{m} q_i$ $(i = 1,2, \dots, m)$, the total planting area in the contract farming channel is denoted as $Q_{CF} = \sum_{j=m+1}^{n} q_j (m+1, m+2, \dots, n)$. Due to the influence of factors such as weather, crop yield is subject to uncertainty and the yield per unit area $u \sim N(\mu, \sigma^2)$, $\gamma = \mu^2 + \sigma^2$. Therefore, $Q = u(Q_{DS} + Q_{CF})$ represents the total yield of green agricultural products.

(2) The market price of green agricultural products is denoted as $p = a - bu(Q_d + Q_e) + \varepsilon$, where $a\ (a > 0)$ represents the consumers' baseline willingness to pay for the agricultural product, b is the price elasticity coefficient, and ε represents the premium consumers are willing to pay for green products due to their preference. To account for the uncertainty in consumers' willingness to pay a premium for green agricultural products, we assume $\varepsilon \sim N(\mu_\varepsilon, \sigma_\varepsilon^2)$. $a + \varepsilon$ represents the willingness of consumers to pay.

(3) In the contract farming channel, the company purchases all the green agricultural products produced by farmers at a contract price, denoted as $\max(w_0, w)$, where w represents the company's decision on the purchase price, and w_0 is the minimum price that farmers are willing to accept when signing the contract, known as the guaranteed price. If the company's optimal purchase price w is lower than the guaranteed price w_0, farmers and the company will comply with the guaranteed price w_0 to fulfill the agricultural contract.

(4) Due to the scale inefficiencies associated with agricultural cultivation, the cost function for the agricultural product differs from that of typical products. Drawing from the work of Ye et al. (2021) and similar studies, we assume the cost function for agricultural cultivation is given by $\frac{1}{2}cq^2$, where c represents the cultivation cost coefficient.

(5) To promote the development of green agricultural products, the government intervenes by implementing two intervention programs. The first measure is PSP, where the government provides subsidies to farmers based on the quantity of green agricultural products. The subsidy amount per unit of production is denoted as s. The second intervention measure is IPP, where the government has the ability to accurately predict market prices and obtain information about the preference levels for green agricultural products. The government can provide information I about the degree of preference for green agricultural products, which follows a normal distribution $I \sim N(\mu_I, \sigma_I^2)$ and $E[\varepsilon|I] = \mu_\varepsilon + \rho\frac{\mu_\varepsilon}{\mu_I}(I - \mu_\varepsilon)$, $Var[\varepsilon|I] = \sigma_\varepsilon^2(I - \rho^2)$.

(6) In this supply chain, only one type of agricultural product is sold, all decision-makers are risk-neutral. Farmers need to decide on the planting area q for the green agricultural product, and the company needs to determine the agricultural products' purchase price w in the contract farming channel. The structure of the green agricultural supply chain is depicted in the Figure 1.

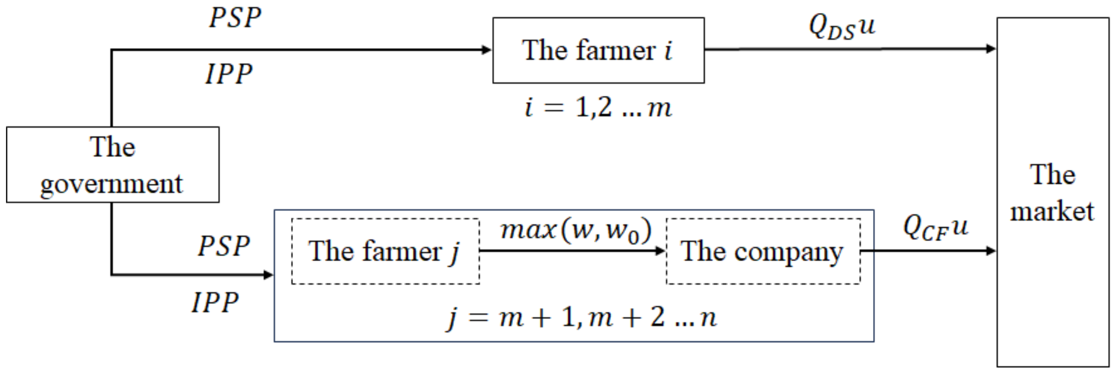


Figure 1 Structure of the Green Agricultural Supply Chain

In the subsequent analysis, the superscripts PSP represent the government providing the product subsidy program, and IPP represents the government providing the information provision program. π_i and π_j respectively denote the expected profits of farmers in the direct sales channel and the contract farming channel, while π_m represents the expected profit of the agricultural company.

4. MODEL AND SOLUTIONS

In the context of a dual-channel green agricultural product supply chain, there are m individual farmers operate independently, not participating in contract farming, $n-m$ farmers who engage in contract farming, establishing cooperative relationships with the agricultural company. The decision sequence within the model involves two types of farmers and the company:

(1) Under direct sales channel, individual farmers autonomously determine the scale of cultivation for green agricultural products with the objective of maximizing their individual profits.

(2) Under contract farming channel, the agricultural company, with the aim of profit maximization, make decisions regarding the purchase price. Subsequently, farmers, motivated by the objective of maximizing their individual benefits, make decisions regarding the scale of cultivation for green agricultural products.

Due to the independent decision-making regarding the cultivation scale between different channels, individual farmers and contract-farming farmers engage in a non-cooperative game, known as Nash game. Meanwhile, a vertical cooperative relationship is formed between contract-farming farmers and the company, representing a Stackelberg game.

4.1 Production Subsidy Program

Under PSP, the government provides subsidies based on the green agricultural product yield of farmers. Both farmers in the direct sales channel and those in the contract farming channel can receive government subsidies per unit of production s. That is, the farmer i in the direct sales channel can receive subsidies sq_iu and the farmer j in the direct sales channel can receive subsidies sq_ju.

The expected revenue of farmers in the direct sales channel is expressed as follows:

$$\pi_i{}^{PSP}(q_i) = E[(a - bQu + \varepsilon)q_iu - \frac{1}{2}cq_i^2 + sq_iu] \quad (1)$$

The expected revenue of farmers in the contract farming channel is expressed as follows:

$$\pi_j{}^{PSP}(q_j) = E[wq_ju - \frac{1}{2}cq_j^2 + sq_ju] \quad (2)$$

The expected revenue of the company is expressed as follows:

$$\pi_m^{PSP}(w) = E[(a - bQu - w + \varepsilon)Q_{CF}u] \quad (3)$$

In which $Q_{CF} = \sum_{j=m+1}^{n} q_j$.

Farmers in different channels make simultaneous decisions on the planting area. By taking the first-order derivative of the planting area q_i for the farmer's expected revenue in direct sales channels $\pi_i{}^{PSP}$, we can obtain

$$q_i = \frac{b(m-n)q_j\gamma + (a+s)\mu + \mu\mu_\varepsilon}{c + 2bm\gamma} \quad (4)$$

Similarly, taking the first derivative of the farmer's revenue in the contract farming channel $\pi_j{}^{PSP}$ with respect to the planting area q_j can be obtained.

$$q_j = \mu\frac{w+s}{c} \quad (5)$$

where w is the contract price set by the company. As farmers and the company engage in a Stackelberg game in contract farming, reverse reasoning can be applied to analyze the pricing decision of the company, so the company's contract price can be expressed as

$$\max\left(\frac{(a+\mu_\varepsilon-s)c\mu - 2b(n-m)s\gamma\mu - bcmq_i\gamma}{2(c+b(n-m)\gamma)\mu}, w_0\right) \quad (6)$$

By combining equations (1), (2), and (3), we can obtain the Nash equilibrium solution for farmers in both the direct sales channel and the contract farming channel, as well as the contract price of the agricultural enterprise.

Theorem 1. Under PSP, the optimal planting areas for agricultural products under the direct sales channel q_i^{PSP}, the contract farming channel q_j^{PSP}, and the optimal contract price for agricultural products w^{PSP} are respectively:

$$w^{PSP} = \max(w_1, w_0) \tag{7}$$

$$q_i^{PSP} = \begin{cases} \frac{\mu(b(m-n)(s+w_0)\gamma+cM)}{c(c+2bm\gamma)} & \text{if } w_1 < w_0 \\ \frac{(2c+b(n-m)\gamma)\mu M}{2c^2+2bc(m+n)\gamma+3b^2m(n-m)\gamma^2} & \text{if } w_1 > w_0 \end{cases} \tag{8}$$

$$q_j^{PSP} = \begin{cases} \frac{(s+w_0)\mu}{c} & \text{if } w_1 < w_0 \\ \frac{(c+bm\gamma)\mu M}{2c^2+2bc(m+n)\gamma+3b^2m(n-m)\gamma^2} & \text{if } w_1 > w_0 \end{cases} \tag{9}$$

where $w_1 = \frac{c(c+bm\gamma)(a+s+\mu_\varepsilon)}{2c^2+2bc(m+n)\gamma+3b^2m(n-m)\gamma^2} - s$, $M = a + s + \mu_\varepsilon$.

Proposition 1. Under PSP, if $w_1 < w_0$, then (1) q_i^{PSP} is a decreasing function with respect to b, n, w_0 and σ, and an increasing function with respect to a, μ_ε and s.

(2) q_j^{PSP} is an increasing function with respect to μ, w_0 and s, and a decreasing function with respect to c.

Proposition 1 (1) indicates that when the government provides production subsidies, the expected planting area q_i^{PSP} in the direct sales channel is negatively correlated with the price elasticity coefficient b, the number of farmers n, the contract farming guarantee price w_0, and the planting risk σ, and positively correlated with the consumer's basic willingness to pay a, consumer preference for green agricultural products μ_ε, and production subsidy s. This is because a larger price elasticity coefficient b indicates that the market sale price of green agricultural products is more sensitive to changes in agricultural production. Therefore, a larger price elasticity coefficient b will suppress farmers' planting enthusiasm, leading to a reduction in the planting area. Additionally, a higher number of farmers n implies more intense production competition, which also discourages farmers from expanding their planting area. An increase in the safeguard price w_0 promotes the production of green agricultural products in the contract farming channel, thereby squeezing the consumption share of green agricultural products in the direct sales channel and having an adverse effect on the planting area q_i^{PSP} in the direct sales channel. Moreover, a higher planting risk σ leads farmers to reduce the planting area to mitigate risk. Conversely, an increase in the basic willingness to pay a and consumer preference for green agricultural products μ_ε indicates an expanded sales market for green agricultural products, which encourages farmers to expand their planting area. An increase in the production subsidy s helps farmers reduce planting costs, which has a favorable impact on expanding the planting area.

Proposition 2. Under PSP, if $w_1 \geq w_0$, then (1) The parameter w_1 is a decreasing function with respect to b, s, n and μ and an increasing function with respect to c. When $m < n < 3m(2 + \frac{bm\gamma}{c})$, it is an increasing function with respect to m; when $n > 3m(2 + \frac{bm\gamma}{c})$, it is a decreasing function with respect to m. (2) The quantities q_i^{PSP} and q_j^{PSP} are decreasing functions with respect to b and n, and increasing functions with respect to a, s, and μ_ε.

Proposition 2(1) explains that the contract price w_1 in the contract farming is inversely proportional to the price elasticity coefficient b, the number of farmers n, the production subsidy s, and the unit area yield μ. This is because a larger price elasticity coefficient b implies that the market price of green agricultural products is more susceptible to supply changes, leading agricultural enterprises to lower the contract price w_1 to control the planting quantity. An increase in production subsidy s, the number of farmers n, and unit area yield μ tends to intensify production competition between different channels. In this situation, agricultural enterprises also tend to lower the contract price to avoid increased production competition. Agricultural enterprises, in order to secure a stable supply of green agricultural products, are willing to offer higher contract prices to encourage farmers with higher planting cost coefficients c to expand their production areas. In particular, when the total number of farmers n is relatively small (i.e., $m < n < 3m(2 + \frac{bm\gamma}{c})$), the contract price w_1 is directly proportional to the number of farmers in the direct sales channel m. However, when the total number of farmers n is relatively large (i.e., $n > 3m(2 + \frac{bm\gamma}{c})$), the contract price w_1 becomes inversely proportional to the number of farmers in the direct sales channel m. This is because when the total number of farmers n is relatively small, there is not intense competition for production between different channels. Agricultural enterprises can increase the contract price w_1 to cover the increased number of farmers m in the direct sales channel and benefit from the increased production. However, when the total number of farmers n is relatively large, intense production competition exists between different channels, and agricultural enterprises cannot cover the increased number of farmers m in the direct sales channel by raising the contract price w_1 to offset the impact on their profits. In this case, the agricultural enterprise chooses to lower the contract price w_1 to reduce losses.

An increase in the price elasticity coefficient b and the number of farmers n intensify the production competition between different channels for green agricultural products, negatively impacting farmers' income. Therefore, facing the rising price elasticity coefficient b and the number of farmers n, farmers in different channels choose to reduce their planting quantities to minimize losses. Conversely, an increase in consumers' basic willingness to pay a and their preference for green agricultural products μ_ε leads to higher prices for green agricultural products in the market, thereby encouraging farmers to expand their cultivation areas. Additionally, an increase in production subsidies s helps farmers reduce production costs and is beneficial for increasing their planting quantities.

Correspondingly, the optimal revenue for farmers in the direct sales channel π_i^{PSP}, and the optimal revenue for farmers in the contract farming channel π_j^{PSP}, are given by:

$$\pi_i^{PSP}=\begin{cases}\frac{\mu^2(cM+b(m-n)(s+w_0)\gamma)^2}{2c^2(c+2bm\gamma)} & \text{if } w_1<w_0\\ \frac{(c+2bm\gamma)(2c+b(-m+n)\gamma)^2\mu^2M^2}{2(2c^2+2bc(m+n)\gamma+3b^2m(n-m)\gamma^2)^2} & \text{if } w_1>w_0\end{cases} \tag{10}$$

$$\pi_j^{PSP}=\begin{cases}\frac{(s+w_0)^2\mu^2}{2c} & \text{if } w_1<w_0\\ \frac{c(c+bm\gamma)^2\mu^2M^2}{2(2c^2+2bc(m+n)\gamma+b^2m(-3m+3n)\gamma^2)^2} & \text{if } w_1>w_0\end{cases} \tag{11}$$

Similarly, the optimal expected revenue for the agricultural enterprise π_m can be expressed as:

$$\pi_m^{PSP}=\begin{cases}\frac{M_1(c^2w_0+bc(ns+(m+n)w_0)\gamma+M_2-(a+\mu_\varepsilon)c(c+bm\gamma))}{c^2(c+2bm\gamma)} & \text{if } w_1<w_0\\ \frac{(n-m)(c+bm\gamma)^2(c+b(n-m)\gamma)\mu^2M^2}{(2c^2+2bc(m+n)\gamma+3b^2m(n-m)\gamma^2)^2} & \text{if } w_1>w_0\end{cases} \tag{12}$$

where $M_1=(m-n)(s+w_0)\mu^2$, $M_2=b^2m(n-m)(s+w_0)\gamma^2$

Proposition 3. Under PSP, if $w_1<w_0$, then (1) $q_i^{PSP}\ge q_j^{PSP}$ when $0<s<\frac{c(a+\mu_\varepsilon)}{b(m+n)\gamma}$, $w_1<w_0\le\frac{c(a+\mu_\varepsilon)-b(m+n)s\gamma}{c+b(m+n)\gamma}$ (2) $q_i^{PSP}<q_j^{PSP}$ when $s\ge\frac{c(a+\mu_\varepsilon)}{b(m+n)\gamma}$ or $0<s<\frac{c(a+\mu_\varepsilon)}{b(m+n)\gamma}$)、$w_0>\frac{c(a+\mu_\varepsilon)-b(m+n)s\gamma}{c+b(m+n)\gamma}$.

Proposition 3(1) indicates that when the government subsidy s and contract price w_0 are both at a lower level, the planting area of farmers in the contract farming channel is lower than that in the direct sales channel.

On the other hand, if the government subsidy s is sufficiently large (i.e., $s\ge\frac{c(a+\mu_\varepsilon)}{b(m+n)\gamma}$) or the contract price w_0 is sufficiently high (i.e., $w_0>\frac{c(a+\mu_\varepsilon)-b(m+n)s\gamma}{c+b(m+n)\gamma}$), then the planting area of agricultural products in the contract farming channel will be greater than that in the direct sales channel. This illustrates that government subsidy s and contract price w_0 are key factors affecting the planting area in different channels. When the government can only provide a limited subsidy s due to budget constraints, the level of the contract price w_0 directly influences the planting area of agricultural products in different channels. A higher contract price w_0 directly stimulates an increase in the planting area in the contract farming channel.

Proposition 4. Under PSP, when $w_1\ge w_0$, then if $0<m\le\frac{n}{2}$ or $\frac{n}{2}<m<n$ and $c\ge b(2m-n)\gamma$, $q_i^{PSP}\ge q_j^{PSP}$; if $\frac{n}{2}<m<n$ and $0<c<b(2m-n)\gamma$, $q_i^{PSP}<q_j^{PSP}$.

Proposition 4 indicates that when farmers in the contract farming channel trade with agricultural enterprises at the contract price w_1, if the number of farmers in the direct sales channel m is small (i.e., $0<m\le\frac{n}{2}$), or if the number of farmers in the direct sales channel m is large but the planting cost coefficient c is high, then the planting area q_i^{PSP} of agricultural products in the contract farming channel will be less than the planting area q_j^{PSP} of agricultural products in the direct sales channel. However,

when the number of farmers in the direct sales channel m is large but the planting cost coefficient c is low, the planting area q_i^{PSP} of agricultural products in the contract farming channel is at a higher level. This is because when the number of farmers in the direct sales channel m is large, the competition among farmers has intensified, and if the planting cost coefficient c decreases to a lower level, farmers can more easily produce more agricultural products. This obviously intensifies the competition in the direct sales channel among farmers, and the decrease in planting cost cannot cover the income loss caused by intensified competition in production.

Proposition 5. (1) π_i^{PSP} and π_j^{PSP} are increasing functions with respect to a and μ_ε. π_j^{PSP} is also an increasing function with respect to s. (2) When $w_0 > w_1$, if $0 < b < \frac{c}{(n-m)\gamma}$ and $s \geq w_0(\frac{c}{c+b(m-n)\gamma} - 1)$, π_i^{PSP} is a decreasing function with respect to s. When $w_0 \leq w_1$, π_i^{PSP} is an increasing function with respect to s.

Proposition 5 (1) indicates that an increase in consumers' willingness to pay a and their preference for green agricultural products μ_ε can enhance the income of farmers. The income of farmers in the contract farming channel π_j^{PSP} is an increasing function with respect to production subsidy s. When $w_0 \leq w_1$, the income of farmers in the direct sales channel π_i^{PSP} is an increasing function with respect to production subsidy s. However, when $w_0 > w_1$ and production subsidy s is relatively high, the income of farmers in the direct sales channel π_i^{PSP} becomes a decreasing function with respect to production subsidy s. This is because when $w_0 > w_1$, an increase in production subsidy s, while leading to higher agricultural product output in the contract farming channel, does not result in increased income for farmers in the direct sales channel. This is because in the contract farming channel, transactions occur at the contract price w_1, and the company can control the planting area of farmers by adjusting w_1 to avoid overproduction and competition between channels. However, when $w_0 > w_1$, in the contract farming channel, transactions occur at the guaranteed price w_0, and an increase in production subsidy s leads to a rapid increase in agricultural product output. At this point, the agricultural company cannot control the planting area of farmers by adjusting w_1. As a result, the increase in production subsidy s does not offset the income loss caused by intensified competition in the direct sales channel. This leads to a negative correlation between production subsidy s and the income of farmers in the direct sales channel π_i^{PSP}.

Proposition 5(2) illustrates that an increase in production subsidies does not necessarily lead to an increase in farmer income. Sometimes, excessive production subsidies can result in overproduction by farmers, causing a decline in market prices for agricultural products, which in turn leads to a decrease in farmer income.

4.2 Information Povision Program (IPP)

The government possesses a commendable capability for market price forecasting and technological acquisition, enabling it to furnish the agricultural company and farmers with pertinent information. The government provides information on the preference for green agricultural products I, which follows a normal distribution $I \sim N(\mu_I, \sigma_I^2)$, in which $E[\varepsilon|I] = \mu_\varepsilon + \rho\frac{\mu_\varepsilon}{\mu_I}(I - \mu_\varepsilon)$, $Var[\varepsilon|I] = \sigma_\varepsilon^2(I - \rho^2)$.

Under IPP, the decision sequence of companies and farmers is similar to that Under PSP. The government provides information on the preference for green agricultural products I, as an exogenous variable that does not participate in the decision-making process.

The expected revenue of farmers in the direct sales channel is expressed as follows:

$$\pi_i(q_i|I) = E[(a - bQu + \varepsilon)q_i u - \frac{1}{2}cq_i^2|I] \tag{13}$$

The expected revenue of farmers in the contract farming channel is expressed as follows:

$$\pi_j(q_j|I) = E[wq_j u - \frac{1}{2}cq_j^2|I] \tag{14}$$

The expected revenue of the company is expressed as follows:

$$\pi(w|I) = E[(a - bQu - w + \varepsilon)Q_{CF}u|I] \tag{15}$$

Lemma 1. Under IPP, the equilibrium planting quantities of farmers in different channels satisfy the following relationship:

$$q_i|I=\begin{cases}\frac{(c(a+M_3)+b(m-n)w_0\gamma)\mu}{c(c+2bm\gamma)} & \text{if } w_I<w_0\\ \frac{(a+M_3)(2c+b(n-m)\gamma)\mu}{2c^2+2bc(m+n)\gamma+3b^2m(n-m)\gamma^2} & \text{if } w_I>w_0\end{cases} \tag{16}$$

$$q_j|I=\begin{cases}\frac{w_0\mu}{c} & \text{if } w_I<w_0\\ \frac{(a+M_3)(c+bm\gamma)\mu}{2c^2+2bc(m+n)\gamma+3b^2m(n-m)\gamma^2} & \text{if } w_I>w_0\end{cases} \tag{17}$$

where $w_I=\frac{c(a+M)(c+bm\gamma)}{2c^2+2bc(m+n)\gamma+3b^2m(n-m)\gamma^2}$, $M_3=\mu_\varepsilon+\rho\frac{\sigma_\varepsilon}{\sigma_I}(I-\mu_I)$

To calculate the expected value of the relationship presented in the lemma, we arrive at the following theorem.

Theorem 2. Under IPP, the optimal planting areas for agricultural products under the direct sales channel q_i^{IPP}, the contract farming channel q_j^{IPP}, and the optimal contract price for agricultural products w^{IPP} are respectively:

$$w^{ISP}=\max(w_2,w_0) \tag{18}$$

$$q_i^{IPP}=\begin{cases}\frac{(c(a+\mu_\varepsilon)+b(m-n)w_0\gamma)\mu}{c(c+2bm\gamma)} & \text{if } w_2<w_0\\ \frac{(a+\mu_\varepsilon)(2c+b(-m+n)\gamma)\mu}{2c^2+2bc(m+n)\gamma+3b^2m(-m+n)\gamma^2} & \text{if } w_2>w_0\end{cases} \tag{19}$$

$$q_j^{IPP}=\begin{cases}\frac{w_0\mu}{c} & \text{if } w_2<w_0\\ \frac{(a+\mu_\varepsilon)(c+bm\gamma)\mu}{2c^2+2bc(m+n)\gamma+3b^2m(-m+n)\gamma^2} & \text{if } w_2>w_0\end{cases} \tag{20}$$

where $w_2=\frac{c(a+\mu_\varepsilon)(c+bm\gamma)}{2c^2+2bc(m+n)\gamma+3b^2m(n-m)\gamma^2}$.

Proposition 6. Under IPP, if $w_2<w_0$, (1) q_i^{IPP} increases with respect to a and μ_ε but decreases with respect to n, b and w_0. (2) q_j^{IPP} is independent of n, b, a and μ_ε. It increases with respect to w_0 and μ but decreases with respect to c.

Proposition 6(1) indicates that the planting area q_i^{IPP} in the direct sales channel is positively correlated with consumer basic willingness to pay a and consumer preference for green products μ_ε. However, it is negatively correlated with the number of farmers n, price sensitivity coefficient b, and the safeguard price w_0. This is because an increase in consumer basic willingness to pay a and consumer preference for green products μ_ε can lead to higher selling prices for green agricultural products, thus stimulating farmers' planting enthusiasm. Additionally, an increase in the number of farmers n and the price sensitivity coefficient b intensifies the competition in the production of green agricultural products, thereby suppressing the increase in the planting area. An increase in the safeguard price w_0 implies an increase in the production of agricultural products in the contract farming channel, which has a negative impact on the production of agricultural products in the direct sales channel. Therefore, q_i^{IPP} is negatively correlated with w_0.

Proposition 6 (2) indicates that when the safeguard price w_0 is relatively high, farmers and agricultural enterprises in the contract farming channel settle based on the safeguard price w_0. This means that the planting area q_j^{IPP} is only related to the safeguard price w_0, unit area yield μ, and planting cost coefficient c.

Proposition 7. Under IPP, if $w_2\geq w_0$, q_i^{IPP} and q_j^{IPP} increase with respect to a and μ_ε but decreases with respect to n, b and σ.

Similar to proposition 6, proposition 7 indicates that an increase in the number of farmers n and the price sensitivity coefficient b can lead to intensified competition for agricultural product production, which has adverse effects on the expansion of agricultural product planting scale. The increase in output risk σ makes agricultural product production more uncertain, thus farmers often choose to reduce planting area to avoid risk. However, an increase in consumer willingness to pay a and consumer green preference μ_ε can boost farmers' planting enthusiasm and promote farmers to expand planting area.

Proposition 8. Under IPP, if $w_2<w_0$, then $q_i^{IPP}>q_j^{IPP}$ when $a+\mu_\varepsilon>w_0+\frac{b(m+n)w_0\gamma}{c}$; $q_i^{IPP}\leq q_j^{IPP}$ when $a+\mu_\varepsilon<w_0+\frac{b(m+n)w_0\gamma}{c}$.

When agricultural enterprises and farmers in contract farming channel at the guaranteed price w_0, the agricultural product planting area in the contract farming channel is independent of the consumers' willingness to pay $a+\mu_\varepsilon$ for green agricultural products. This means that farmers in contract farming cannot enjoy the boosting effect brought by the increase in consumers' willingness to pay $a+\mu_\varepsilon$. Therefore, when consumers' willingness to pay $a+\mu_\varepsilon$ is at a high level, the agricultural product planting area in the direct sales channel is higher than that in the contract farming channel (i.e., $q_i^{IPP} > q_j^{IPP}$).

Proposition 9. Under IPP, if $w_2 \geq w_0$, then $q_i^{IPP} > q_j^{IPP}$ when $bm\gamma \leq c$ or $bm\gamma > c$ and $n > \frac{2bm\gamma - c}{b\gamma}$; $q_i^{IPP} \leq q_j^{IPP}$ when $bm\gamma > c$ and $m < n < \frac{2bm\gamma - c}{b\gamma}$.

Proposition 9 indicates that when the planting cost coefficient is large (i.e., $bm\gamma \leq c$) or when the planting cost coefficient is small and the number of farmers is relatively high (i.e., $bm\gamma > c$ and $n > \frac{2bm\gamma - c}{b\gamma}$), the agricultural product planting area in the direct sales channel is larger than that in the contract farming channel. However, when both the planting cost coefficient and the number of farmers are relatively small (i.e., $bm\gamma > c$ and $m < n < \frac{2bm\gamma - c}{b\gamma}\gamma$), the agricultural product planting area in the direct sales channel is smaller than that in the contract farming channel. Since a larger planting cost coefficient indicates that the farmer's planting technology is more backward, proposition 9 reveals that when the planting technology of farmers in a certain area is relatively backward or when the number of farmers participating in agricultural planting is large, farmers may choose the direct sales channel to produce more agricultural products. Conversely, when the planting technology in the area is relatively advanced and the number of farmers is not high, the contract farming channel can effectively promote the increase of green agricultural product production.

Correspondingly, the optimal revenue for farmers in the direct sales channel π_i^{IPP}, the optimal revenue for farmers in the contract farming channel π_j^{IPP}, and the optimal expected revenue for the agricultural enterprise π_m^{IPP}, are given by:

$$\pi_i^{IPP} = \begin{cases} \frac{((b(m-n)w_0\gamma + c(a+\mu_\varepsilon))^2 + (c\rho\mu_\varepsilon)^2)\mu^2}{2c^2(c+2bm\gamma)} & \text{if } w_2 < w_0 \\ \frac{(c+2bm\gamma)(2c+b(-m+n)\gamma)^2\mu^2 M_4}{2(2c^2+2bc(m+n)\gamma+3b^2m(-m+n)\gamma^2)^2} & \text{if } w_2 > w_0 \end{cases} \tag{21}$$

$$\pi_j^{IPP} = \begin{cases} \frac{{w_0}^2\mu^2}{2c} & \text{if } w_2 < w_0 \\ \frac{c(c+bm\gamma)^2\mu^2 M_4}{2(2c^2+2bc(m+n)\gamma+3b^2m(-m+n)\gamma^2)^2} & \text{if } w_2 > w_0 \end{cases} \tag{22}$$

$$\pi_m^{IPP} = \begin{cases} \frac{(n-m)w_0(M_5+b^2m(m-n)w_0\gamma^2)\mu^2}{c^2(c+2bmy)} & \text{if } w_2 < w_0 \\ \frac{M_4(n-m)(c+bm\gamma)^2(c+b(n-m)\gamma)\mu^2}{(2c^2+2bc(m+n)\gamma+3b^2m(n-m)\gamma^2)^2} & \text{if } w_2 > w_0 \end{cases} \tag{23}$$

where $M_4 = (a+\mu_\varepsilon)^2 + (\rho\sigma_a)^2$, $M_5 = c^2(a+\mu_a - w_0) + bc(m(a+\mu_\varepsilon) - (m+n)w_0)\gamma$.

Proposition 10. Under IPP, (1) when $w_2 < w_0$, π_j^{IPP} remains independent of ρ and σ_ε, while π_i^{IPP} becomes a monotonically increasing function with respect to ρ and σ_ε. (2) when $w_2 \geq w_0$, both π_i^{IPP} and π_j^{IPP} exhibit monotonic increases concerning ρ and σ_ε.

Due to the fact that when $w_2 < w_0$, the farmers' profit π_j^{IPP} in the contract farming channel is solely related to the guaranteed price w_0, the unit area yield μ, and the cultivation cost coefficient c, and remains unaffected by the correlation coefficient ρ and the volatility of consumer preferences σ_ε related to market and government forecasts. However, proposition 10 also indicates that, in most cases, the income of farmers in different channels will be positively influenced by the correlation coefficient ρ and the fluctuation in consumer preferences σ_ε related to market and government forecasts. This is because government forecasting of market information can mitigate the losses caused by fluctuations in consumer preferences for farmers, and the greater the preference fluctuation, the more apparent the benefits of forecasting information for farmers' income enhancement become.

Analyzing the contrasting cultivation areas of agricultural products under different government intervention programs can elucidate the differential effects of various government programs on agricultural production. As $w_2 > w_1$, analysts need to categorically examine and discuss the relationship between cultivation areas of agricultural products under different intervention programs.

Proposition 11. (1) When $w_0 < w_1$, $q_i^{PSP} > q_i^{IPP}$, $q_j^{PSP} > q_j^{IPP}$.

(2) When $w_1 < w_0 < w_2$, if $c > b(n-m)\gamma$, $q_i^{PSP} > q_i^{IPP}$; if $c < b(n-m)\gamma$,there is $M_6 < 0$, so when $s < -\frac{M_7}{M_6}$, $q_i^{PSP} > q_i^{IPP}$; when $s > -\frac{M_7}{M_6}$, $q_i^{PSP} < q_i^{IPP}$.

(3) When $w_0 > w_2$, if $c > b(n-m)\gamma$, $q_i^{PSP} > q_i^{IPP}$; if $c < b(n-m)\gamma$, $q_i^{PSP} < q_i^{IPP}$. When $w_0 > w_2$, $q_j^{PSP} > q_j^{IPP}$.

where $M_6 = \frac{(c+b(m-n)\gamma)\mu}{c(c+2bm\gamma)}$,

$$M_7 = \left(\frac{c(a+\mu_\varepsilon)+b(n-m)w_0\gamma}{c(c+2bm\gamma)} + \frac{(a+g)(2c+b(n-m)\gamma)}{2c^2+2bc(m+n)\gamma+3b^2m(n-m)\gamma^2}\right)\mu > 0.$$

Proposition 11(1) indicates that when the guaranteed price w_0 in contract farming is low, the agricultural product production under PSP in both the direct sales channel and the contract farming channel is higher than that under IPP. This is because when the guaranteed price is low, agricultural enterprises in the contract farming channel trade agricultural products at the contract price w_1 and w_2. Since PSP directly affects the farming stage and can effectively reduce farmers' planting costs, the agricultural product production under the yield subsidy program in each channel is greater than that under IPP.

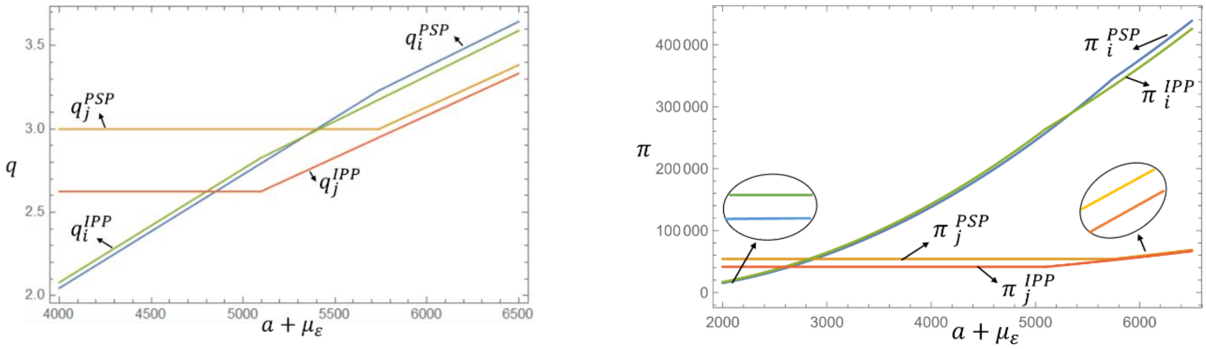
When $w_1 < w_0 < w_2$, agricultural enterprises under the yield subsidy program trade at the contract price w_0, while agricultural enterprises under IPP trade at the contract price w_2, which makes the agricultural product planting area under different government programs relatively complicated. As shown in proposition 10(2), when the planting cost coefficient is large (i.e., $c > b(n-m)\gamma$), the yield subsidy program can help farmers in the direct sales channel obtain higher agricultural product yields. However, when the planting cost coefficient is small (i.e., $c < b(n-m)\gamma$) and the yield subsidy is small (i.e., $s < -\frac{M_7}{M_6}$), the yield subsidy program has higher agricultural product yields in the direct sales channel, and vice versa. This is because when the planting cost coefficient is small, the yield of green agricultural products is already at a high level. If the government provides additional subsidies at this time, yield competition will further intensify, which will reduce the yield of agricultural products in the direct sales channel under the yield subsidy program.

When $w_0 > w_2$, agricultural enterprises in the contract farming channel trade agricultural products at the contract price w_0. In the case of the same contract purchase price, for farmers in the contract farming channel, the yield subsidy program can directly reduce planting costs, which makes the yield of agricultural products under the yield subsidy program higher in the contract farming channel. For farmers in the direct sales channel, if the planting cost coefficient of agricultural products is relatively large (i.e., $c > b(n-m)\gamma$), farmers face higher planting costs, and the yield subsidy program can better help farmers reduce planting costs. This also results in a higher yield of agricultural products under the yield subsidy program in the direct sales channel when the planting cost coefficient is large.

5. NUMERICAL ANALYSIS

The Chinese government values the development of the cassava bioenergy industry and has stopped subsidies for corn-based ethanol since 2016, instead supporting the production of bioethanol from cassava, a non-edible feedstock[42]. In the numerical analysis section, the cassava bioenergy industry in China is used as a case study to explore the impact of the planting cost and other parameters on the participants in the bioenergy supply chain. Based on the research by Ye et al. (2020), taking cassava as a green agricultural product as a numerical example, the following parameters were obtained: $a = 3500$, $\mu = 3500$, $\sigma = 35$, $c = 12000$, $b = 0.01$. In addition, through actual research on some farms in Guangzhou, Guangdong Province, the following parameters were set according to the actual situation: $n = 2000$, $m = 1500$, $\mu_\varepsilon = 100$, $\sigma_\varepsilon = 100$, $\rho = 0.2$, $s = 100$, $w_0 = 800$.

5.1 Effect of the Willingness to Pay on Supply Chain



(a) (b)

Figure 2 Effect of willingness to pay $a + \mu_\varepsilon$ on planting area and farmers' profit

Because w_1 and w_2 increase with the consumers' willingness to pay a higher base price for agricultural products, this leads to varying patterns in the planting scale as the consumers' willingness to pay $a + \mu_\varepsilon$ changes. As depicted in Figure 2(a), when the consumers' willingness to pay $a + \mu_\varepsilon$ is relatively low, farmers and agricultural enterprises in the contract farming channel engage in agricultural product transactions at the guaranteed price w_0. At this point, q_j^{PSP} and q_j^{IPP} remain unaffected by the consumers' willingness to pay $a + \mu_\varepsilon$, hence in Figure 2(a), q_j^{PSP} and q_j^{IPP} do not vary with an increase in the consumers' willingness to pay a when it is low. Conversely, when the consumers' willingness to pay $a + \mu_\varepsilon$ is relatively high, in this scenario, farmers and agricultural enterprises in the contract farming channel trade agricultural products at the prices w_1 and w_2, respectively. In this case, q_j^{PSP} and q_j^{IPP} increase with an increase in the consumers' willingness to pay $a + \mu_\varepsilon$. The changes in q_i^{PSP} and q_i^{IPP} also exhibit a similar pattern with an increase in the consumers' willingness to pay $a + \mu_\varepsilon$.

From Figure 2(a), it is evident that the cultivation area of agricultural products in the contract farming channel under PSP, q_j^{PSP}, consistently exceeds that of IPP, q_j^{IPP}. This underscores that, in terms of encouraging farmers to expand their cultivation area, PSP exerts a more robust influence on promoting agricultural product cultivation by directly subsidizing farmers' production.

Interestingly, the cultivation area of agricultural products in the direct sales channel under PSP, q_i^{PSP}, is not always higher than that of IPP, q_i^{IPP}. When the consumers' willingness to pay a is low, $q_i^{PSP} < q_i^{IPP}$, and when the consumers' willingness to pay $a + \mu_\varepsilon$ is high, $q_i^{PSP} > q_i^{IPP}$. This implies that for agricultural products with lower consumer base payment willingness, such as rice and wheat, the government can implement an IPP to stimulate an increase in agricultural product production. On the other hand, for agricultural products with higher consumer base payment willingness, like grapes and durian, PSP can more effectively promote increased agricultural product production.

Figure 2(b) represents the variation in farmers' income as the consumers' willingness to pay $a + \mu_\varepsilon$ increases. The change in farmers' income follows a pattern similar to the cultivation area. When the consumers' willingness to pay $a + \mu_\varepsilon$ increases to a certain extent, the contract prices for farmers and agricultural enterprises in the contract farming channel shift from w_0 to w_1 and w_2. This results in the income change curve for farmers not being smooth but rather exhibiting a change at a certain point. For farmers in the contract farming channel, the income of farmers under PSP, π_j^{PSP}, is always greater than that under IPP, π_j^{IPP}. Interestingly, when the consumers' willingness to pay $a + \mu_\varepsilon$ increases to a certain extent, the income gap between different subsidy programs in the contract farming channel narrows. For farmers in the direct sales channel, when the consumers' willingness to pay $a + \mu_\varepsilon$ is low (high), the income of farmers under PSP π_i^{PSP}, is lower (higher) than that under IPP, π_i^{IPP}. This is also because when the consumers' willingness to pay $a + \mu_\varepsilon$ is low, $q_i^{PSP} < q_i^{IPP}$, and when the consumers' willingness to pay a is high, $q_i^{PSP} > q_i^{IPP}$. Moreover, as observed in Figure 1(a), when the consumers' willingness to pay $a + \mu_\varepsilon$ increases to a certain extent, the cultivation area q_j^{IPP} under IPP under the contract farming channel experiences a rapid increase. This to some extent intensifies competition between different channels, leading to a slower increase in income for farmers in the direct sales channel, π_i^{IPP}.

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5.2 Effect of the Planting Cost on Supply Chain

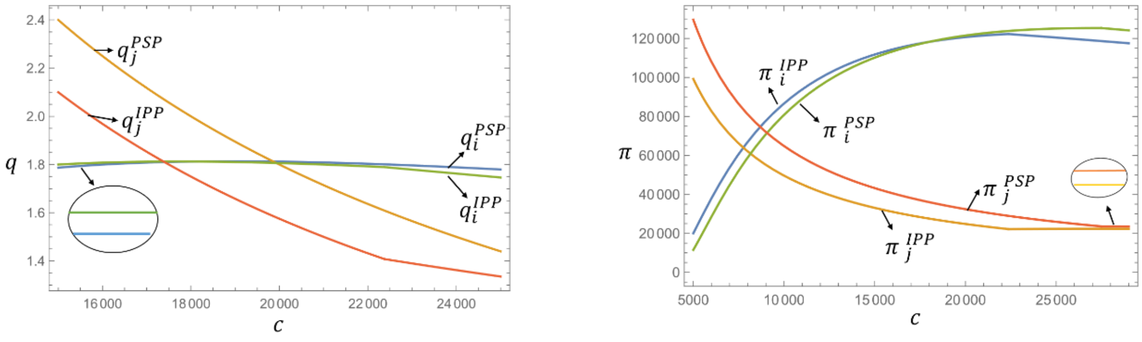

Figure 3 Effect of planting cost coefficients c on planting area and farmers' profit

Figure 3 illustrates the relationship between cultivation area q and farmers' income π concerning the cultivation cost coefficient c. A higher cultivation cost coefficient c implies that the farmers in that region have less advanced cultivation techniques. Therefore, Figure 3 helps assess how government intervention methods and sales channels affect the production decisions of the green agricultural product supply chain in regions with varying degrees of cultivation technology.

From Figure 3(a), it can be deduced that for farmers in the contract farming channel, government-provided PSP can better incentivize farmers to expand their cultivation areas and achieve higher agricultural product yields. However, for farmers in the direct sales channel with more advanced production techniques (i.e., lower cultivation cost coefficient c), IPP can promote the expansion of cultivation areas and result in higher yields. Conversely, when farmers have less advanced production techniques (i.e., higher cultivation cost coefficient c), the government should offer PSP to reduce cultivation costs, thereby increasing farmers' motivation to expand their cultivation areas. Figure 3(a) aligns with reality, as IPP is often more suitable for regions with advanced production technologies, as they can assist farmers in selling their agricultural products more efficiently. In contrast, regions with less advanced production techniques, where higher cultivation costs constrain production, require PSP to reduce costs and stimulate production.

The patterns of curve changes in Figure 3(b) are similar to those in Figure 3(a). As the cultivation cost coefficient c increases, the income of farmers in the contract farming channel decreases. After reaching a certain threshold of the cultivation cost coefficient c, the rate of income reduction for farmers slows down because, at this point, farmers and agricultural enterprises in the contract farming channel engage in transactions at the guaranteed price w_0, which to some extent protects farmers' income. Additionally, Figure 3(b) reveals that PSP can assist farmers in the contract farming channel in achieving higher income.

For farmers in the direct sales channel, as the cultivation cost coefficient c increases, their income first increases and then decreases. This phenomenon occurs because when the cultivation cost coefficient c is low, the market is relatively saturated with agricultural product yield, resulting in oversupply and lower income for farmers. If the cultivation cost coefficient c increases at this point, it somewhat restricts the increase in agricultural product yield, bringing the market price back to a reasonable range, which, in turn, allows farmers to earn higher income. However, as the cultivation cost coefficient c continues to rise into a larger range, the production cost of agricultural products becomes prohibitively high, and farmers can no longer earn higher income. Furthermore, if farmers have advanced (less advanced) production techniques, IPP (PSP) can help them achieve higher income.

5.3 Effect of Unit Area Yield

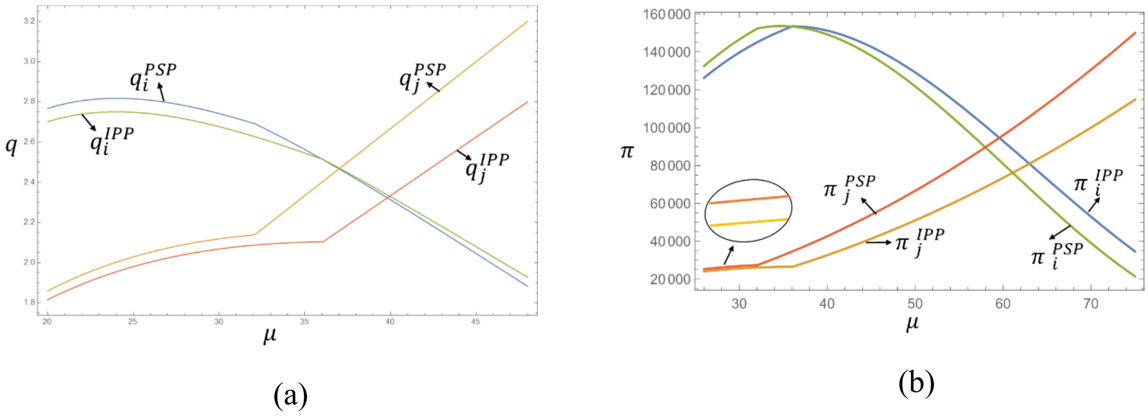

Figure 4 Effect of unit area yield μ on planting area and farmers' profit.

Figure 4 depicts the relationship between cultivation area q and farmers' income π concerning the unit area yield μ of agricultural products. Interestingly, for farmers in the direct sales channel, a higher unit area yield μ does not necessarily lead to an increase in the cultivation area q. As evident from Figure 4(a) and (b), the cultivation area q and farmers' income π in the direct sales channel follow a trend of initially increasing and then decreasing as the unit area yield μ increases. This is because a higher unit area yield μ results in higher agricultural product yield, which, to some extent, can boost farmers' motivation to expand cultivation areas and increase yields. However, when the unit area yield μ increases to a certain extent, there is an oversupply of agricultural products, leading to a situation where excessive supply depresses prices and, consequently, damages farmers' interests. This causes a decline in farmers' motivation to plant, resulting in a reduction in cultivation area. In contrast, in the contract farming channel, the cultivation area of agricultural products increases with an increase in the unit area yield μ. This is primarily because when the unit area yield μ increases to a certain extent, farmers and agricultural enterprises engage in transactions at the guaranteed price w_0, which protects farmers' motivation to cultivate and promotes higher farmers' income. This also means that when the unit area yield μ is relatively high, the cultivation area and farmers' income in the contract farming channel will be greater than those in the direct sales channel.

6. CONCLUSION

Consumers have a preference for green agricultural products and are willing to pay a higher price for them. However, this premium that consumers are willing to pay for green agricultural products can be volatile, leading to information gaps between farmers and the green agricultural product sales market. This information gap is detrimental to the development of green agricultural products. To address this issue, this paper constructs a dual-channel agricultural product supply chain, with some farmers participating in the direct sales channel and others in the contract farming channel. The paper then analyzes the impact of IPP and PSP on the production decisions of subsidized channel farmers.

This study has found the following key insights:

(1) When the government implements production subsidies, such subsidies can effectively promote an increase in the production of green agricultural products. This conclusion aligns with the research outcomes of Ye et al. (2021) and Cai et al. (2021). However, unlike their studies, which only considered contract farming, our investigation encompasses both contract farming and direct sales, pointing out the varying performances of production subsidy policies in these distinct channels. Our research finds that the impact of the same subsidy amount on the promotion of green agricultural product production varies within the subsidized channel. If the guaranteed price in the contract farming channel is low, then when there are relatively larger farms and lower cultivation costs in the direct sales channel, the agricultural product production in the contract farming channel is greater than in the direct sales channel. However, when the guaranteed price in the contract farming channel is high, the agricultural product production in the direct sales channel is higher when production subsidies are low, while the agricultural product production in the contract farming channel is higher when production subsidies are high.

(2) While it might be intuitive to think that higher production subsidies lead to higher farmer income, the model analysis has revealed that excessive production can saturate the market with agricultural products, resulting in lower prices and, consequently,

reduced farmer income. Therefore, the relationship between production subsidies and farmer income is not straightforward. This conclusion has been similarly confirmed in the research conducted by Ye et al. (2021) and Cai et al. (2021).

(3) An increase in farmers' willingness to produce green agricultural products directly promotes an increase in production. IPP may not directly increase production but can enhance farmers' income. Importantly, the higher the relevance of predictive information and the stronger the fluctuation in consumer preferences, the more effective IPP is in increasing farmers' income. Furthermore, it should be noted that the PSP falls under Amber Policies, while the IPP is categorized within Green Box Policies. In the context of WTO rules, governments worldwide are progressively reducing the deployment of Amber Box policies in agriculture, shifting focus towards enhancing the impact of Green Box policies. From this perspective, IPP not only enables farmers to achieve higher earnings amidst the uncertainty of consumer preferences but also complies with the direction of policy evolution, deserving adoption and broad promotion by governments across the globe. This managerial insight is an aspect not mentioned in other academic studies.

(4) Similarly, the effectiveness of IPP in promoting green agricultural product production varies across different channels. When the guaranteed purchase price is low in the contract farming channel and consumers have a strong willingness to pay for green agricultural products, the production of green agricultural products in the direct sales channel is higher than in the contract farming channel, and vice versa when the guaranteed purchase price in the contract farming channel is high. Additionally, the cultivation cost and the number of farmers in the contract farming channel have an impact on the effectiveness of IPP. This management inspiration can provide useful reference for the government in promoting IPP.

(5) The study conducted model calibration using real-world data and found that when the cultivation cost coefficient c is low or the unit area yield μ is high, IPP consistently help farmers achieve higher income compared to PSP, and the corresponding supply chain overall income remains at a higher level. Lower cultivation cost coefficients c or higher unit area yields μ also indicate that the agricultural region can produce more agricultural products, emphasizing the advantages of IPP in assisting with agricultural product sales and mitigating oversupply issues. However, when the cultivation cost coefficient c is high or the unit area yield μ is low, the agricultural region may be in a relatively less advanced state. In such cases, the government should provide PSP to help farmers reduce production costs, address production challenges, and enable farmers to achieve higher income.

This study assumed that all farmers have the same production cost coefficient and only produce one type of agricultural product. In reality, farmers' production costs are heterogeneous, and they may cultivate multiple types of agricultural products. Secondly, we assumed that farmers do not face financial constraints and have access to a sufficient amount of land. However, in many developing countries, farmers do experience financial constraints and limitations on the available cultivation area. Lastly, considering the government's choices in subsidizing policies within a limited policy budget would indeed be a challenging and meaningful direction to explore. Governments often need to make difficult decisions regarding the allocation of resources to various agricultural programs and subsidies, and analyzing the impact of such budget constraints on policy effectiveness could provide valuable insights. These considerations highlight potential areas for further research and model refinement to better align with the complexities of real-world agricultural systems.

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CONTRIBUTIONS

Xie Jun: Conceptualization, Methodology, Software, Writing original draft. Jian Liu: Conceptualization, Visualization, Supervision.

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APPENDIX

Proof of Theorem 1

The expected revenue of farmers in the direct sales channel is expressed as follows:

$$\pi_i{}^{PSP}(q_i) = E[(a - bQu + \varepsilon)q_i u - \frac{1}{2}cq_i^2 + sq_i u] \quad (a1)$$

The expected revenue of farmers in the contract farming channel is expressed as follows:

$$\pi_j{}^{PSP}(q_j) = E[wq_j u - \frac{1}{2}cq_j^2 + sq_j u] \quad (a2)$$

The expected revenue of the company is expressed as follows:

$$\pi_m^{PSP}(w) = E[(a - bQu - w + \varepsilon)Q_{CF}u] \quad (a3)$$

In which $Q_{CF} = \sum_{j=m+1}^{n} q_j$.

We first compute the first-order and second-order derivatives of farmer profits in the direct sales channel.

$\frac{\partial \pi_i{}^{PSP}}{\partial q_i} = -\frac{1}{2}cq_i{}^2 - b(mq_i{}^2 + (-m + n)q_i q_j)\gamma + q_i\mu(a + \mu_\varepsilon)$.

$\frac{\partial^2 \pi_i{}^{PSP}}{\partial^2 q_i} = -c - 2bm\gamma < 0$.

Let $\frac{\partial \pi_i{}^{PSP}}{\partial q_i} = 0$, we can obtain $q_i = \frac{b(m-n)q_j\gamma + (a+s+\mu_\varepsilon)\mu}{c+2bm\gamma}$.

In the context of Stackelberg game analysis between farmers and the company in the contract farming channel, employing a backward induction approach, we first calculate the first-order and second-order derivatives of expected farmer profits.

$\frac{\partial \pi_j{}^{PSP}}{\partial q_j} = (w + s)\mu - cq_j$

$\frac{\partial^2 \pi_j{}^{PSP}}{\partial^2 q_j} = -c$

Let $\frac{\partial \pi_j^{PSP}}{\partial q_j} = 0$, we can obtain $q_j = \mu \frac{w+s}{c}$.

Substituting $q_j = \mu \frac{w+s}{c}$ into equation (a3), and then calculating the first-order and second-order derivatives of expected company profits, we can obtain:

$$\frac{\partial \pi_m^{PSP}}{\partial w} = \frac{(m-n)\mu(c(s+2w-a)\lambda\mu + b\gamma(cmq_i - 2(m-n)(s+w)\mu) - c\mu\mu_\varepsilon)}{c^2}.$$

$$\frac{\partial^2 \pi_m^{PSP}}{\partial^2 w} = \frac{2(m-n)(b(n-m)\gamma + c)\mu^2}{c^2} < 0.$$

Let $\frac{\partial \pi_m^{PSP}}{\partial w} = 0$, we can obtain $w = \frac{(a+\mu_\varepsilon - s)c\mu - 2b(n-m)s\gamma\mu - bcmq_i\gamma}{2(c+b(n-m)\gamma)\mu}$.

If $w > w_0$ at this point, substituting w into q_j, we can find that $q_j = \frac{bmq_i\gamma - (a+s+\mu_\varepsilon)\mu}{2b(m-n)\gamma - 2c}$. As different channel farmers engage in a Nash game, solving for $q_i = \frac{b(m-n)q_j\gamma + (a+s+\mu_\varepsilon)\mu}{c+2bm\gamma}$ and $q_j = \frac{bmq_i\gamma - (a+s+\mu_\varepsilon)\mu}{2b(m-n)\gamma - 2c}$, we obtain:

$$q_i = \frac{(2c+b(n-m)\gamma)\mu M}{2c^2 + 2bc(m+n)\gamma + 3b^2m(n-m)\gamma^2}, \quad q_j = \frac{(c+bm\gamma)\mu M}{2c^2 + 2bc(m+n)\gamma + 3b^2m(n-m)\gamma^2}.$$

Similarly, based on the equation $q_j = \mu \frac{w+s}{c}$, we can derive: $w_1 = \frac{c(c+bm\gamma)(a+s+\mu_\varepsilon)}{2c^2 + 2bc(m+n)\gamma + 3b^2m(n-m)\gamma^2} - s$.

If $w < w_0$ in the case of the contract farming channel, where farmers and the company use the guaranteed price w_0 as the purchase price, substituting w_0 into q_j, we can easily obtain: $q_i = \frac{\mu(b(m-n)(s+w_0)\gamma + cM)}{c(c+2bm\gamma)}$, $q_j = \frac{(s+w_0)\mu}{c}$.

Proof of Proposition 3

Under PSP, when $w_1 < w_0$, $K1 = q_i^{PSP} - q_j^{PSP} = \frac{(c(a+\mu_\varepsilon - w_0) - b(m+n)(s+w_0)\gamma)\mu}{c(c+2bm\gamma)}$. Because $c(c+2bm\gamma) > 0$, we can determine the sign of $K1$ by evaluating the sign of $c(a+\mu_\varepsilon - w_0) - b(m+n)(s+w_0)\gamma$. Furthermore, due to the constraint $0 < w_1 < w_0$, when $0 < s < \frac{c(a+g)}{b(m+n)\gamma}$, we have $w_1 < w_0 \le \frac{c(a+\mu_\varepsilon) - b(m+n)s\gamma}{c+b(m+n)\gamma}$, which implies $K1 \ge 0$. When $0 < s < \frac{c(a+\mu_\varepsilon)}{b(m+n)\gamma}$) and $w_0 > \frac{c(a+g) - b(m+n)s\gamma}{c+b(m+n)\gamma}$, we have $K1 < 0$. It is easy to find that when $s \ge \frac{c(a+\mu_\varepsilon)}{b(m+n)\gamma}$, we have $K1 < 0$.

Proof of Proposition 4

Under PSP, when $w_1 \ge w_0$, let $K2 = q_i^{PSP} - q_j^{PSP} = \frac{(a+s+\mu_\varepsilon)(c+b(n-2m)\gamma)\mu}{2c^2 + 2bc(m+n)\gamma + 3b^2m(n-m)\gamma^2}$.

Because $(a+s+\mu_\varepsilon) > 0$, $2c^2 + 2bc(m+n)\gamma + 3b^2m(n-m)\gamma^2 > 0$,

determining the sign of $(c + b(n-2m)\gamma)$ is all that's needed to ascertain the sign of $K2$. Therefore, it can be easily deduced that $K2 \ge 0$ when $0 < m \le \frac{n}{2}$ or $\frac{n}{2} < m < n$ and $c \ge b(2m-n)\gamma$; $K2 < 0$ when $\frac{n}{2} < m < n$ and $0 < c < b(2m-n)\gamma$.

Proof of Proposition 5

When $w_0 > w_1$, $\frac{\partial \pi_i^{PSP}}{\partial s} = \frac{(c+b(m-n)\gamma)(c(a+\mu_\varepsilon+s) + b(m-n)(s+w_0)\gamma)\mu^2}{c^2(c+2bm\gamma)}$.

If $0 < b < \frac{c}{(n-m)\gamma}$, we obtain $(c + b(m-n)\gamma) > 0$.

If $s \ge w_0(\frac{c}{c+b(m-n)\gamma} - 1)$, we obtain $(c(a+\mu_\varepsilon+s) + b(m-n)(s+w_0)\gamma) < 0$.

Therefore, when $0 < b < \frac{c}{(n-m)\gamma}$ and $s \ge w_0(\frac{c}{c+b(m-n)\gamma} - 1)$, it is easy to find that $\frac{\partial \pi_i^{PSP}}{\partial s} < 0$.

Proof of Lemma 1

The proof process of Lemma 1 is analogous to that of Theorem 1 and will not be reiterated here.

Proof of Proposition 9.

Let $K3 = q_i^{IPP} > q_j^{IPP} = \frac{(a+\mu_\varepsilon)(c+b(n-2m)\gamma)\mu}{2c^2+2bc(m+n)\gamma+3b^2m(-m+n)\gamma^2}$.

Because $2c^2 + 2bc(m+n)\gamma + 3b^2m(-m+n)\gamma^2 > 0$, $(a+\mu_\varepsilon) > 0$, determining the sign of $(c+b(n-2m)\gamma)$ is sufficient to ascertain the sign of $K3$.

It is easy to find that if $bm\gamma \le c$, $K3 \le 0$; if $bm\gamma > c$ and $n > \frac{2bm\gamma - c}{b\gamma}$, $K3 \le 0$; if

$bm\gamma > c$ and $m < n < \frac{2bm\gamma - c}{b\gamma}$, $K3 > 0$.

Proof of Proposition 11

If $w_0 < w_1$, we can find that:

$q_i^{PSP} - q_i^{IPP} = \frac{s(2c+b(n-m)\gamma)\mu}{2c^2+2bc(m+n)\gamma+3b^2m(-m+n)\gamma^2} > 0$

$q_j^{PSP} - q_j^{IPP} = \frac{s(c+bm\gamma)\mu}{2c^2+2bc(m+n)\gamma+3b^2m(n-m)\gamma^2} > 0$

If $w_1 < w_0 < w_2$, we obtain: $q_i^{PSP} - q_i^{IPP} = M_6 + M_7 s$,

where $M_6 = \left(\frac{c(a+\mu_\varepsilon)+b(n-m)w_0\gamma}{c(c+2bm\gamma)} + \frac{(a+\mu_\varepsilon)(2c+b(n-m)\gamma)}{2c^2+2bc(m+n)\gamma+3b^2m(-m+n)\gamma^2}\right)\mu > 0$,

$M_7 = (\frac{\mu}{c+2bm\gamma} + \frac{b(m-n)\gamma\mu}{c(c+2bm\gamma)})$.

When $c > b(n-m)\gamma$, we have $M_7 > 0$,so in this case, $M_6 + M_7 s > 0$.

When $c < b(n-m)\gamma$, we have $M_7 > 0$, then if $s < -\frac{M_7}{M_6}$, $q_i^{PSP} - q_i^{IPP} > 0$;if $s > -\frac{M_7}{M_6}$, $q_i^{PSP} - q_i^{IPP} < 0$.

When $w_0 > w_2$, $q_i^{PSP} - q_i^{IPP} = \frac{s(c+b(m-n)\gamma)\mu}{c(c+2bm\gamma)}$. It is easy to find that $q_i^{PSP} - q_i^{IPP} > 0$ when $c > b(n-m)\gamma$; $q_i^{PSP} - q_i^{IPP} < 0$ when $c < b(n-m)\gamma$.

When $w_0 > w_2$, we obtain $q_j^{PSP} - q_j^{IPP} = \frac{s\mu}{c} > 0$.