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Optimization of the Biofuel Supply Chain With Capital-Constrained Farmers Under Government Subsidies

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ABSTRACT China's biofuel industry faces the problem of insufficient supply of biomass feedstock because farmers lack the funds to carry out their planting plans. Moreover, natural disasters can easily expose farmers to bankruptcy risks, making it difficult for farmers with limited capital to obtain financing from banks. This paper studies the government's subsidy programmes for helping farmers obtain financing: a poverty alleviation programme (PAP) and a social welfare programme (SWP). We construct a biofuel supply chain model including the government, the bank, farmers, and companies, which optimizes the biomass feedstock production and the government subsidy in different subsidy programmes. We find that high planting efficiency leads to a lower subsidy interest rate for farmers in PAP, while in SWP, high planting efficiency can promote the government to set higher subsidy interest rate when the competitive intensity between bioenergy companies is weak. Furthermore, the total biomass feedstock planting area and the optimal subsidy interest rate in SWP are larger (smaller) than those under PAP when the planting efficiency is higher (lower) than a certain threshold. An extension of our model shows that the government's subsidy policy for the farmer with financial constraints will reduce the benefits of the farmer who does not need to borrow from the bank. The government's failure to implement subsidy programmes can sometimes lead to a higher total income for farmers.

INDEX TERMS Supply chain finance, biofuel supply chain, yield uncertainty, government subsidy.

I. INTRODUCTION

With the development of the global economy, the consumption of fossil fuels has increased rapidly. Unfortunately, as a non-renewable energy source, fossil fuels have been consumed on a large scale by humans for the past two hundred years, and they are facing a depletion crisis [1]–[3]. In addition, the massive burning of fossil fuels causes air pollution, releases harmful substances such as sulphur dioxide, and aggravates the greenhouse effect. The energy crisis and environmental pollution have become two major obstacles to sustainable human development. Therefore, it has become a global consensus that it is important to develop a low-carbon economy and new energy sources [4], [5].

Biofuels, produced by energy crops, are regarded as an important direction for renewable energy development and utilization because of its convenient storage and transportation, as well as environmental protection [6], [7]. As a result, biofuels have attracted great attention from countries around the world. The United States and Brazil are the two most important countries in the world in terms of biofuel production. In the past few decades, the United States and Brazil have issued many subsidy policies to the biofuel industry, such as tax incentives for biofuel producers, to support biofuel development [8]. According to the report "Renewables 2018", published by the International Energy Agency (IEA), biofuels account for approximately 50% of the world's total

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renewable energy, and they are expected to be produced more than other renewable energy sources between 2018 and 2023 [9]. There is also great interest in biofuels in China. China's National Development and Reform Commission has also launched a series of policies to support biofuels, which are projected to reach 62 million tonnes in 2020. However, biofuel production is expected to fall far short of the target because of insufficient supply of agricultural feedstock for bioethanol production [10].

Unlike Western countries, China's biomass feedstock is grown by many small-scale farmers scattered throughout the country. A key issue for small farmers in China is that farmers often lack sufficient funds, which prevents them from expanding their production scale or even starting planting plans [11]. In the case of capital shortages, farmers need short-term financing to carry out their operations [12]. However, it is often difficult for farmers to receive loans from the bank due to the lack of collateral [13]. Since agriculture plays an important role in the sustainable development of developing countries' economies, the Chinese government has formulated policies to provide banks with interest rate subsidies to encourage banks to provide loans to farmers. Government financing subsidies help farmers increase their income and eliminate poverty. Furthermore, the government can provide two subsidy programmes for different subsidy purposes. Under a poverty alleviation programme (PAP), the government's purpose is to maximize the income of farmers with financial constraints. For example, the federal government of Nigeria formulates a series of poverty alleviation programs to help farmers get out of poverty [14]. Under a social welfare programme (SWP), the government's purpose is to maximize social welfare. U.S. develops various agricultural subsidy programs to improve social welfare [15]. Government subsidies have been proven to help farmers obtain credit loans and boost farmers' production scale [16].

In view of the increasingly important role of biofuel in solving the energy crisis and environmental pollution problems, and considering that the Chinese government is implementing different subsidy policies to promote the development of the biofuel industry, from a policy perspective, it is very important to understand the impact of different subsidy programmes on different stakeholders in the biofuel supply chain. This will help the government optimize subsidy policies to promote the further development of the biofuel industry. Therefore, we aim to answer the following questions: What is the government's optimal subsidy interest rate? What factors affect the optimal subsidy mechanism? Is the government's subsidy policy always beneficial to farmers?

To answer these questions, we construct a biofuel supply chain that includes the government, the bank, farmers, and companies and use game theory to analyse the interactions among the participants in the supply chain. Farmers and companies cooperate through a contract farming scheme. Such a scheme is widely used in countries around the world and is beneficial to both farmers and companies [17], [18]. Under contract farming, the company signs a contract with the farmer before the growing season, promising to purchase the biomass raw materials harvested by the farmer at the contract price. The farmer, who is subject to capital constraints, needs bank loans for production operations under the condition of yield uncertainty (due to weather or for other reasons). We considered the competitive relationship between the two companies in the supply chain. The more bioenergy that a company 1 produces, the lower is the retail price that bioenergy company 2 receives. To help farmers borrow loans from the bank, the government provides farmers with interest rate subsidies for bank financing. We also investigate the decision-making behaviour of the participants between the biofuel supply chain under different government subsidy targets that involve optimizing farmers' incomes or maximizing social welfare. Furthermore, we extend our analysis to a more realistic scenario where one farmer with capital constraints requires a loan while another farmer does not need a loan.

By doing so, our paper makes three contributions. First, it takes into account the financial constraints of farmers and explores the impact of different government subsidy programmes on farmers' income. Second, the paper discusses the impact of factors such as competitive intensity between companies and farmers' planting efficiency on the performance of government subsidy programmes. Third, the paper generates some counterintuitive results. For example, in areas with high planting levels, the government's failure to implement subsidy programmes may bring higher returns to farmers. In short, this paper provides a theoretical basis for the government to provide financial subsidy policies for the biofuel supply chain, which is beneficial for the government's optimization of subsidy programmes.

The remainder of this paper is organized as follows. Section 2 reviews related studies and positions this study in terms of existing studies. Section 3 describes the model. We analyse the basic setting in section 4 and discuss three extensions in section 5. We conclude in section 6. All proofs are provided in the Appendix.

II. LITERATURE REVIEW

First, our study is also closely related to the biofuel supply chain. Considering energy security, climate change and sustainable economic development, governments around the world are actively reducing their dependence on traditional fossil fuels, such as coal and oil, and they are supporting new energy production, such as biofuel production. The enormous demand for biofuels has attracted the attention of scholars, and many scholars have studied the biofuel supply chain. Some scholars mainly focus on the location, transportation and storage of the biofuel supply chain. For example, [19], [20] studied the optimal location planning problem for biofuel refineries. Reference [21] provided guidance on site selection for the biofuel supply chain based on infrastructure investment and the amount of raw materials grown. Reference [22] determined the optimal scale of biofuel conversion plants with the goal of minimizing energy conversion costs. Reference [23] analysed the relationship between the capacity of biofuel conversion plants and the associated biomass transport costs. Reference [24] found that different storage systems have a significant impact on biomass raw material loss and product quality through field investigations. In recent years, an increasing number of scholars have paid attention to the coordination mechanism of the biofuel supply chain. Reference [25] used game theory to analyse the biomass power generation process, considering three players—distributors, power developers, and farmers—and they solved the problem of power equipment implementation and biofuel raw materials supply. Reference [26] explored the optimal strategy of the agricultural biomass supply chain under management competition. Reference [27] designed a suitable straw acquisition model for China's straw power plants and found that the hybrid collection model can be effectively implemented in practice and that it ensures a lower supply cost of straw. Reference [28] proposed three types of contracts (overproduction risk sharing contracts, underproduction risk sharing contracts and hybrid contracts) to study biofuel supply chain coordination issues. However, our research is different from the current research. We further consider the capital constraints of farmers growing biofuel raw materials and the government financing subsidy, focusing on the decision-making behaviour of farmers given different government subsidy targets.

Second, the literature relevant to our research concerns the interfaces of supply chain operations and financial decisions studies. In supply chain finance, there are two main financing modes to solve short-term capital shortages: bank credit financing and trade credit financing. Under bank credit financing mode, the bank provides short-term financing. Under trade credit financing, loans are provided by members of the supply chain such as core companies [13], [29], [30]. Some scholars have studied the bank credit financing mode. References [31], [32] analysed the financing and operation decisions of the retailer with capital constraints at a given bank loan interest rate. Reference [33] found that appropriate bank interest rates could motivate retailers subject to capital constraints to order more products and increase the capital income of upstream and downstream members of the supply chain. There are also some scholars who have studied the trade credit financing mode. For example, [34] explored the impact of trade credit on the interests of buyers and sellers. Reference [35] analysed the risk-sharing role of trade credit. Reference [36] studied the issue of price competition between upstream producers in the context of trade credit financing. Reference [37] investigated the impact of different credit ddscores on the trade credit financing mode. Furthermore, some scholars compared bank credit financing with commercial credit financing. Reference [38] studied the financing equilibrium problem in which a capital-constrained retailer can obtain a loan from a bank or manufacturer. Reference [30] found that trade credit financing is more conducive to mitigating the bilateral effects than bank credit financing in the case of lower planting cost coefficients. Reference [39] compared trade credit financing and bank credit financing under a revenue sharing contract.

Aiming at the problem of insufficient supply of biomass feedstocks in China's biofuel industry, we construct a biofuel supply chain consisting of the government, the bank, farmers, and agricultural companies, and study how to optimize the biofuel supply chain so that farmers with financial constraints can execute their operation under yield uncertainty. Our research differs from the article mentioned above in two aspects. First, the first stream of biofuel supply chain literature (i.e. Ye et al., 2017, Ye et al., 2018) either does not take into account the financial constraints of farmers, or fail to consider the bankruptcy risks of farmers, as well as the government playing an important role in the cultivation of biomass feedstocks. In fact, in order to promote the development of biomass materials, the government will provide subsidies to farmers to help them develop production. Second, the second stream of supply chain finance literature (i.e. Kouvelis and Zhao 2015, Yang and Birge 2017, Peura et al., 2017) focuses more on the traditional industry. However, agricultural supply chain finance has the remarkable characteristics of yield uncertainty. Unlike traditional manufacturing supply chains, the biofuel supply chain has supply uncertainties, as biofuel feedstocks are often affected by natural disasters such as typhoons and heavy rains during their growth. Moreover, the government often provides subsidy programs to promote biomass feedstocks development. These characteristics are not considered in the second stream literature on supply chain finance mentioned above. Overall, our study comprehensively considers the financial constraints of farmers, the risk of bankruptcy and the yield uncertainty, the government subsidy programs, as well as the competition intensity between companies purchasing biofuel feedstocks. Our study can provide more insights for policy makers to provide an effective subsidy programs and enriches the research of the bioenergy supply chain. Table 1 compares previous studies and this present study.

III. PROBLEM DESCRIPTION

In this paper, we construct a biofuel supply chain including the bank, the government, two companies and two farmers. To ease the computational burden, we assume that the two small-scale farmers are homogenous in terms of the input cost coefficient and yield uncertainty. Farmer 1 (2) determines the planting area of biomass feedstock $q_1(q_2)$ at an input cost $\frac{1}{2}cq_1^2$ ($\frac{1}{2}cq_2^2$), which represents the total cost of obtaining all the resources and exerting the efforts needed to plant $q_1(q_2)$ square metre. The planting cost coefficient c reflects the farmer's planting efficiency. The greater the planting cost coefficient, the lower the planting efficiency. The quadratic input cost functions that capture the increasing marginal cost of input have been used in agricultural models [15], [18], [28]. Agricultural production is very susceptible to weather [40]–[42]. Therefore, we assume that the yield $\varepsilon(\varepsilon \in (A, B))$ is random with a continuous probability density function $f(\varepsilon)$

TABLE 1. **A summary of the main literature.**

	Sun et al. (2013)[26]	Kouvelis and Zhao (2015)[32]	Ye et al. (2017)[11]	Yang and Birge (2017)[35]	Peura et al. (2017)[36]	Ye et al. (2018)[10]	This paper
Capital constraint		√		√	√		√
Bankruptcy risks		√		√	√		√
Yield uncertainty			√			√	√
Government subsidy							√
Competition	√				√		√

and a cumulative distribution function $F(\varepsilon)$ and that ε satisfies IFG. R property [43]. Therefore, for farmer 1 (2), the realized yielded feedstock is $q_1\varepsilon$ ($q_2\varepsilon$), where $E\varepsilon = \bar{\varepsilon}$, $D\varepsilon = \delta^2$.

To encourage the bank to provide loans to the farmer and facilitate the farmer's operations, the government provides government subsidized bank financing (the farmer receives a bank loan where the interest is partly paid by the government). We assume that the small-scale farmer has zero initial capital and that he or she will apply for bank loans with an interest rate r $(1 > r > 0)$ to execute his or her operations, between which the government provides interest subsidies for the loan with a subsidy rate s. Therefore, if farmer 1 (2) is not bankrupt, he or she will repay the loan to the bank $cq_1^2(1+r-s)$ $(cq_2^2(1+r-s))$.

We also assume that the two farmers sign contracts with different biofuel companies. Company 1 (2) purchases all agricultural products of farmer 1 (2) at the purchasing price w_1 (w_2). Without loss of generality, we assume that the conversion rate of biomass feedstock into biofuel is 1. Therefore, the amount of biofuel that company 1(2) puts into the market is $q_1\varepsilon$ ($q_2\varepsilon$), and the biofuel on the market is sold at a retail price $p_1 = a - q_1\varepsilon - bq_2\varepsilon$ ($p_2 = a - q_2\varepsilon - bq_1\varepsilon$), where $a(> 0)$ denotes the maximum possible price for the biofuel and $b(> 0)$ represents the competitive intensity between companies. The more intense the competition between companies, the lower is the market price of biofuel.

The sequence of events for the biofuel supply chain system is shown in Fig. 1.

Throughout the paper, we use the subscripts F1 (C1) and F2 (C2) to indicate the first farmer (company) and the second farmer (company), respectively. Superscript PA (SW) denotes a variable pertaining to the poverty alleviation programme (social welfare programme). Accordingly, π_{F1}^{PA}, π_{F2}^{PA} (π_{F1}^{sw}, π_{F2}^{sw}) represent the expected profit of farmer 1 and farmer 2 in PAP (SWP). π_{C1}^{PA}, π_{C2}^{PA} (π_{C1}^{SW}, π_{C2}^{SW}) represent the expected profit of company 1 and company 2 in PAP (SWP). Π^{PA} (Π^{SW}) represents the social welfare in PAP (SWP).

IV. THE MODELS AND DECISIONS

A. THE OBJECTIVE OF FARMERS AND COMPANIES

After the biomass is harvested, the company acquires all the biomass of farmer 1 at the purchase price w_1. Therefore, the expected profit of farmer 1 is expressed as:

$$\pi_{F1} = [w_1 q_1\varepsilon - c(q_1)^2 (1+r-s)]^+ \quad (1)$$

Equation 1 indicates that when the production of raw biofuel materials encounters a disaster year, that is, when productivity ε is small, farmer 1 will face bankruptcy. Therefore, we first solve the problem that the farmer's bankruptcy threshold $\tilde{\varepsilon}$ satisfies the following equation:

$$\int_{\tilde{\varepsilon}}^{B} \varepsilon f(\varepsilon)\, d\varepsilon = 2\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}) \quad (2)$$

When the actual productivity of crops falls below the bankruptcy threshold, farmers will go bankrupt. Conversely, farmers will not go bankrupt.

Company 1 retails biofuels on the market at a price $a - q_1\varepsilon - bq_2\varepsilon$ and purchases biofuel feedstocks from the farmer at a price w_1. Therefore, the expected profit of company 1 is expressed as:

$$\pi_{C1} = E[(a - q_1\varepsilon - bq_2\varepsilon - w_1)\, q_1\varepsilon] \quad (3)$$

Because the relationship between farmer 1 and company 1 is similar to that between farmer 2 and company 2, solving equations (1) (2) (3), we can obtain the optimal planting area of farmer 1(2) and the optimal purchasing price of company 1(2).

Theorem 1: Under a given subsidy s, the optimal purchasing price of company 1(2) and the optimal planting area of

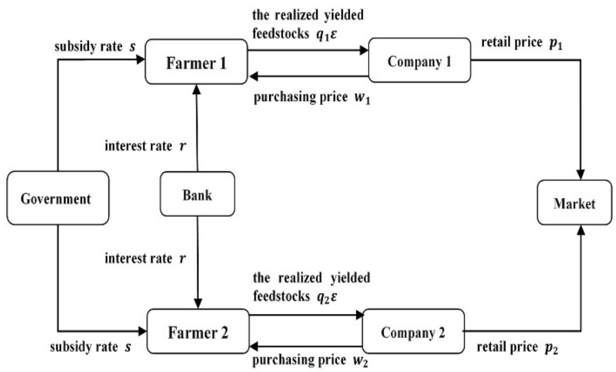


FIGURE 1. **Sequence of events for the biofuel supply chain.**

farmer 1(2) are:

$$w_1^* = w_2^* = \frac{ac(1+(1-s)r)}{(2+b)\,\sigma^2\tilde{\varepsilon} + 2c(1+(1-s)r)} \tag{4}$$

$$q_1^* = q_2^* = \frac{a\tilde{\varepsilon}}{2c(1+r-rs) + (2+b)\tilde{\varepsilon}\sigma^2} \tag{5}$$

We find that market size a, farmers' planting costs can promote the increase of contract prices, and the increase in the government subsidy rates, the yield uncertainty, the bankruptcy threshold, and the competition intensity between companies will make companies set lower contract prices. This is in line with reality. When the government grants large subsidies to farmers, similar to the reduction in farmers' planting costs, companies can purchase products at lower prices. When crops are affected by natural disasters or competition between companies is intensifying, in order to avoid risks, companies will also choose to set lower contract prices to avoid acquisition risks.

At the same time, we find that a larger market size can stimulate farmers to expand production, while increasing government interest rates will also induce farmers to increase investment. When the bankruptcy threshold is relatively large, in order to avoid bankruptcy caused due to too low actual output, farmers will actively expand the production scale, hoping to increase the actual harvest by increasing the planting area. In addition, the increase in planting costs, the intensity of competition between companies, and yield uncertainty risks will reduce yields.

Combining (1)(4)(5), we obtain the expected profit function of the farmers:

$$\pi_{F1}^* = \pi_{F2}^* = \frac{a^2 c\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})(1+r-rs)}{\left(2c(1+r-rs) + (2+b)\tilde{\varepsilon}\sigma^2\right)^2} \tag{6}$$

Combining (3)(4)(5), we obtain the expected profit function of the companies:

$$\pi_{C1}^* = \pi_{C2}^* = \frac{a^2\tilde{\varepsilon}(c(1+r-rs) + \tilde{\varepsilon}\sigma^2)}{\left(2c(1+r-rs) + (2+b)\tilde{\varepsilon}\sigma^2\right)^2} \tag{7}$$

Proposition 1: For a given subsidy s, we find that

(1) $\frac{dw_i}{ds} < 0$, $\frac{dq_i}{ds} > 0$, $\frac{d\pi_{ci}}{ds} > 0$

(2) If $c > \frac{(2+b)\tilde{\varepsilon}\sigma^2}{2}$, then $\frac{d\pi_{Fi}}{ds} > 0$. If $c < \frac{(2+b)\tilde{\varepsilon}\sigma^2}{2}$, then $\frac{d\pi_{Fi}}{ds} > 0$ when $s \in (0, s_1)$; $\frac{d\pi_{Fi}}{ds} < 0$ when $s \in (s_1, 1)$, where $s_1 = \frac{1+r}{r} - \frac{(2+b)\tilde{\varepsilon}\sigma^2}{2cr}$.

The purchasing price of contract farming declined with the increase of government subsidy interest rate, which means that farmers are willing to accept low purchase prices to achieve the cultivation of agricultural products under the stimulation of high subsidy. Our results are similar to literature [15] in which increased government subsidies can promote a reduction in agricultural purchase prices. Interestingly, even if the purchase price is low, farmers may choose to expand production scale under the influence of high subsidy rates; thus, the company can purchase more biomass feedstock at a lower price, and the income increases. For farmers, the income of the farmers shows a trend that first increases and then decreases with the subsidy, which means that an excessive subsidy will damage the income of the farmers.

B. THE GOVERNMENT'S OBJECTIVE

In this section, we first analyse PAP, whereby governments help farmers with financial constraints to earn higher incomes. The optimal subsidy interest rate under PAP is as follows:

$$s^{PA*} = \frac{2c(1+r) - (2+b)\tilde{\varepsilon}\sigma^2}{2cr} \tag{8}$$

Under PAP, the company's income, the farmer's income and the social welfare are respectively

$$\pi_{c1}^{PA*} = \pi_2^{PA*} = \frac{a^2(4+b)}{8(2+b)^2\sigma^2} \tag{9}$$

$$\pi_{F1}^{PA*} = \pi_{F2}^{PA*} = \frac{a^2\tilde{\varepsilon}}{8(2+b)\sigma^2} \tag{10}$$

$$\Pi^{PA*} = \frac{a^2((5+b+2(2+b)(1+\bar{F}(\tilde{\varepsilon}))\tilde{\varepsilon})\sigma^2 - 2c(1+r))}{4(2+b)^2\sigma^4} \tag{11}$$

Proposition 2: Under PAP, the optimal subsidy interest rate $s^{PA*} = 0$ when $c < c_1$, and the optimal subsidy interest rate $s^{PA*} = 1$ when $c > c_2$. Therefore, if $c \in (c_1, c_2)$, the optimal subsidy interest rate $s^{PA*} \in (0, 1)$, where $c_1 = \frac{(2+b)\tilde{\varepsilon}\sigma^2}{(2+2r)}$, $c_2 = \frac{(2+b)\tilde{\varepsilon}\sigma^2}{2}$.

As Proposition 2 suggests, there is no need for the government to implement PAP when the planting cost coefficient is relatively small (i.e., $c < c_1$). This is because for farmers with advanced production methods, the government subsidy may lead to their over-production, thus reducing their income. When the farmer's productivity is very low, that is, $c > c_2$, the government should pay a high subsidy to help farmers achieve optimal returns. This is consistent with the fact that the government has implemented high subsidies in underdeveloped areas to help farmers alleviate poverty.

Proposition 3:

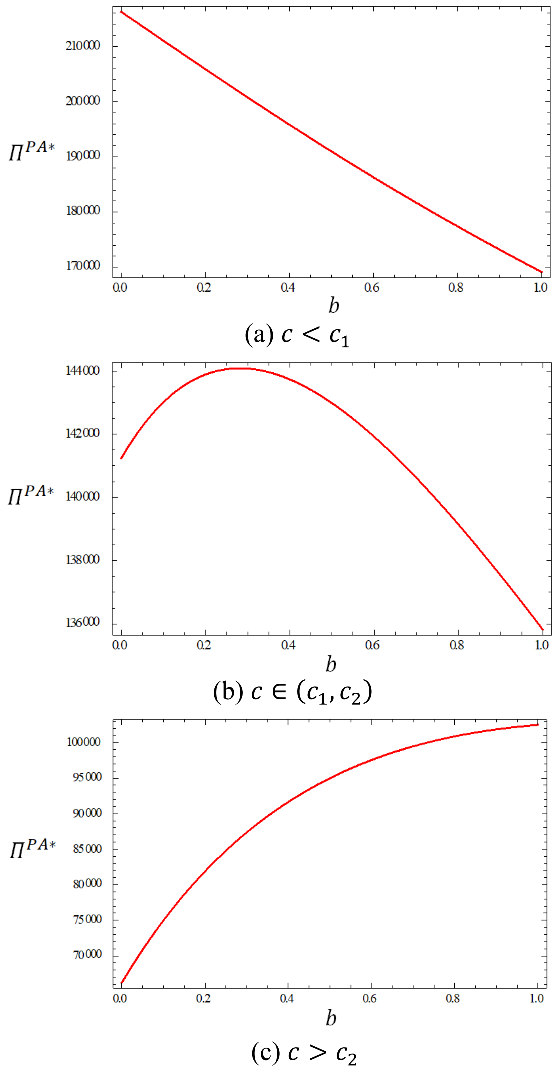
(1) If $c \in (c_1, c_2)$, then $\frac{d\Pi^{PA*}}{db} > 0$ when $b \in (0, b_1)$; then $\frac{d\Pi^{PA*}}{db} < 0$ when $b \in (b_1, 1)$, where $b_1 = \frac{4c(1+r) - 2(4+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}))\sigma^2}{(1+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}))\sigma^2}$, $c_1 = \frac{(4+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}))\sigma^2}{2(1+r)}$, $c_2 = \frac{3(3+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}))\sigma^2}{4(1+r)}$.

(2) If $c < c_1$, $b_1 < 0$ *always hold, then* $\frac{d\Pi^{PA*}}{db} < 0$.

(3) If $c > c_2$, $b_1 > 1$ *always hold, then* $\frac{d\Pi^{PA*}}{db} > 0$.

To intuitively display proposition 3, we created the following figures that show the relationship between competitive intensity b and optimal social welfare in PAA with different planting cost coefficients c. We assume $\varepsilon \sim U(6.53, 7.61)$, $r = 0.2$, $a = 10$.

When the planting efficiency is within a certain range, that is, $c \in (c_1, c_2)$, the social welfare will increase and then decrease with the degree of competition between enterprises in PAP. If the planting cost coefficient is low, that is, $c < c_1$, social welfare decreases in competitive intensity.



(a) $c < c_1$

(b) $c \in (c_1, c_2)$

(c) $c > c_2$

FIGURE 2. The impact of competitive intensity *b* on optimal social welfare in PAP.

However, if the planting cost coefficient is high, that is, $c > c_2$, stronger competitive intensity can make the social welfare larger. This means that in areas where farmers' production methods are backward, the government whose goal is to alleviate poverty can instead obtain higher social welfare when the competition between enterprises is strong.

Under SWP, the government's objective is to determine the optimal subsidy rate s offered to the farmer's bank loan to maximize the social welfare. In this study, social welfare has four parts: the first part is total farmers' profit $\pi_{F1} + \pi_{F2}$. The second part is total companies' profit $\pi_{C1} + \pi_{C2}$. The third part is the consumer surplus $\frac{(q_1\varepsilon)^2}{2} + \frac{(q_2\varepsilon)^2}{2}$. The last part is the government expenditure $\mathrm{cs}(q_1)^2 + \mathrm{cs}(q_2)^2$. Hence, the government's social welfare is:

$$\Pi^{SW} = \pi_{F1} + \pi_{F2} + \pi_{C1} + \pi_{C2} + \frac{(q_1\varepsilon)^2 + (q_2\varepsilon)^2}{2} - cs(q_1)^2 - cs(q_2)^2 \quad (12)$$

Theorem 2: Under SWP, the government subsidy interest rate (13), as shown at the bottom of this page.

We can find that rising planting costs can stimulate the government to set a higher subsidy rate, which also reflects that the government is willing to pay more subsidies to help them produce in order to help the backward production methods, that is, farmers with large production cost coefficients. In addition, higher competition between companies will actually reduce subsidy rates. This is because as the subsidy rate increases, the scale of farmers' planting increases and the output of agricultural products will increase, which will increase competition between companies. Therefore, in order to avoid excessive competition between companies, the government chooses to provide a low subsidy interest rate.

Proposition 4: Under SWP, if $b \in (0, b_2)$, then $\frac{ds^{SW*}}{dc} < 0$; if $b \in (b_2, 1)$, then $\frac{ds^{SW*}}{dc} > 0$. Under PAP, $\frac{ds^{PA*}}{dc} > 0$.

Proposition 4 shows that if the government aims to maximize the income of farmers, then the government subsidy rate will not be related to the degree of competition between enterprises and that it is related to the planting efficiency of farmers. For farmers with backward production methods, the government will increase the subsidy interest rate to support the farmers in their production operations. If the government aims to maximize social welfare, then the government subsidy interest rate will take into account the planting efficiency of farmers and the intensity of competition between enterprises. When the competition between enterprises is strong ($b \in (b_2, 1)$), if the planting cost coefficient of farmers is relatively low, a small subsidy by the government can boost social welfare growth. When competition between enterprises is weak ($b \in (0, b_2)$), regarding farmers with low planting cost coefficients, the government should give a small subsidy interest rate to encourage the farmers to expand production to improve social welfare.

Proposition 5:

(1) $\frac{ds^{PA*}}{db} < 0$, $\frac{dq_i^{PA*}}{db} < 0$, $\frac{d\pi_{ci}^{PA*}}{db} < 0$.

(2) If $b \in (0, b_3)$ then $\frac{d\pi_{Fi}^{sw*}}{db} > 0$. If $b \in (b_3, 1)$ then $\frac{d\pi_{Fi}^{sw*}}{db} < 0$.

(3) If $b \in (0, 1)$ then $\frac{d\pi_{Fi}^{PA*}}{db} < 0$.

Proposition 5 suggests that with the higher level of competition, the farmers under PAP will not only receive less government subsidy but also reduce their planting area. Furthermore, the farmer's profit and the company's profit decrease in the competitive intensity under PAP. Under SWP,

$$s^{SW*} = \frac{2c(1 + \tilde{\varepsilon}(\bar{F}(\tilde{\varepsilon}) - 1))(1 + r) - \tilde{\varepsilon}(b - 4 + (2 + b)\tilde{\varepsilon}(1 + \bar{F}(\tilde{\varepsilon})))\sigma^2}{2c(1 + \tilde{\varepsilon} + \tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}))r} \quad (13)$$

intense competition between companies reduces the company's profit. However, if the level of competitive intensity is relatively small (i.e., $b \in (0, b_3)$), the farmer's profit increases in b due to a relatively high government subsidy under SWP.

Proposition 6:

(1) If $c < c_3$, then $s^{SW*} > s^{PA*}$, $q^{SW*} > q^{AP*}$, $\pi_{C1}^{SW*} > \pi_{C1}^{PA*}$.

(2) If $c > c_3$, then $s^{SW*} < s^{PA*}$, $q^{SW*} < q^{AP*}$, $\pi_{c1}^{SW*} < \pi_{c1}^{PA*}$.

When the planting cost coefficient of farmers is low, excessive subsidies will damage the income of farmers under PAP, so the government chooses to lower the subsidy interest rate, resulting in a low company's income and low farmers' planting area. When the planting cost coefficient of farmers is high, the government needs a larger subsidy to increase the income of farmers under PAP. As the subsidy increases, farmers can accept smaller contract prices, allowing companies to buy more agricultural products at smaller contract prices. At this time, the company's income and the farmer's planting area are higher than the government's consideration of social welfare. When the subsidy increases, companies can obtain more biomass feedstock at a smaller purchasing price. At this time, the company's income and the farmer's planting area under PAP are higher than that under SWP.

The social welfare under SWP is obviously greater than that under PAP. In the same way, the farmer's profit under PAP is obviously greater than that under SWP. Is the farmers' income improvement efficiency (the ratio of the farmer's income to government expenditure) under SWP is definitely higher than that under PAP? To address this question, we define the subsidy efficiency ratio $\tau^i = \frac{\pi_{F1}^{i*}+\pi_{F2}^{i*}-(\pi_{F1}^{NS}+\pi_{F2}^{NS})}{s^i c(q_1^{i*}+q_2^{i*})}$ for $i \in \{PA, SW$, where π_{F1}^{NS}, π_{F2}^{NS}, respectively, indicate the income of farmer 1 and farmer 2 when no subsidies (NS) are offered by the government.

Proposition 7: If $c < \frac{3\sigma^2}{2(1+r)}$, then subsidy efficiency ratio $\tau^{PA} > \tau^{SW}$, otherwise, there is $\tau^{PA} \leq \tau^{SW}$.

When the planting cost coefficient is relatively small, the planting efficiency of the farmers is relatively high. At this time, the government aiming to improve the income of farmers can expand the production scale of farmers with a small subsidy interest rate and help farmers obtain higher returns. When the farmers' production method is backward, the government needs to set a high subsidy rate to increase the income of the farmers, which leads to a decline in the efficiency of government funds. Therefore, when the farmers' planting cost coefficient is high, the government that aims at maximizing social welfare can achieve the optimization of poverty alleviation efficiency.

V. EXTENSION

Based on the previous analysis, we now discuss a more realistic situation in which some farmers need to borrow from banks, while others do not need to borrow. We assume that farmer 1, who borrows from the bank, has government subsidies, and that farmer 2, who does not need to borrow, has not received government subsidies. To distinguish the previous discussions, we use the superscript A-AP and A-SW to represent the poverty alleviation programme and the social welfare programme, respectively. The rest of the settings are the same as in section 4.

A. POVERTY ALLEVIATION PROGRAMME

The expected profit of farmer 1 is expressed as:

$$\pi_{F1} = [w_1 q_1 \varepsilon - c(q_1)^2 (1 + r - s)]^+ \tag{14}$$

The expected profit of farmer 2 is expressed as:

$$\pi_{F2} = w_2 q_2 \varepsilon - c(q_2)^2 \tag{15}$$

The expected profit of company 1 and the company 2 are expressed as:

$$\pi_{C1} = E[(a - q_1\varepsilon - bq_2\varepsilon - w_1)\, q_1\varepsilon] \tag{16}$$

$$\pi_{C2} = E[(a - q_2\varepsilon - bq_1\varepsilon - w_2)\, q_2\varepsilon] \tag{17}$$

The government's goal is to maximize the income of farmer 1 who receives government subsidies. Therefore, the optimal subsidy interest rate is shown in Proposition 8.

Theorem 3: The optimal subsidy interest rate under PAP is expressed as:

$$s^{A-PA*} = \frac{8c^2(1+r) + 4c(1-2\tilde{\varepsilon}+r)\sigma^2 + (b^2-4)\tilde{\varepsilon}\sigma^4}{4cr(2c+\sigma^2)} \tag{18}$$

We find that the government's optimal subsidy interest rate increase with respect to the farmer's planting cost coefficient c, the bank interest rate r, and the intensity of competition between enterprises b.

The optimal farmer's planting area can be expressed as:

$$q_1^{A-PA*} = \frac{a(b-2)\sigma^2 - 4ac}{2(b^2-4)\sigma^4 - 16c\sigma^2} \tag{19}$$

$$q_2^{A-PA*} = \frac{1}{4}a\left(\frac{1}{2c+\sigma^2} + \frac{2\,(b-2)}{-8c + \left(b^2-4\right)\sigma^2}\right) \tag{20}$$

The optimal farmer's profit can be expressed as:

$$\pi_{F1}^{A-PA*} = \frac{\tilde{\varepsilon}\bar{F}\,(\tilde{\varepsilon})\,(4ac + a(2-b)\sigma^2)^2}{16\sigma^2(2c+\sigma^2)(-8c+(b^2-4)\sigma^2)} \tag{21}$$

$$\pi_{F2}^{A-PA*} = \frac{c(4a(-4+b)c + a(b-2)(4+b)\sigma^2)^2}{16(2c+\sigma^2)^2(-8c+(b^2-4)\sigma^2)^2} \tag{22}$$

Proposition 8:

(1) q_1^{A-PA*}, q_2^{A-PA*}, π_{F1}^{A-PA*}, π_{F2}^{A-PA*} decreases in b.

(2) q_1^{A-PA*}, π_{F1}^{A-PA*}, π_{C1}^{A-PA*} increases in c.

(3) $q_1^{A-PA*} + q_2^{A-PA*}$ decreases in c.

Intense competition between companies will lead to a decline in the scale of biomass raw material production and reduce the income of farmers under PAP. However, farmer 1 can obtain higher subsidies under high planting cost coefficients, which makes farmer 1 choose to expand production.

Therefore, the high planting cost coefficient of biomass feedstock will stimulate the income of farmer 1 and company 1's income. However, the planting area of farmer 2 shrinks under the influence of high planting cost coefficients; thus, the total planting area of farmers still decreases as planting cost coefficients increase.

B. SOCIAL WELFARE PROGRAMME

Since farmer 2 does not receive the government subsidy, the social welfare can be expressed as:

$$\Pi^{A-SW} = \pi_{F1}^{A} + \pi_{F1}^{A} + \pi_{C1}^{A} + \pi_{C2}^{A} + \frac{(q_1^A \varepsilon)^2}{2} + \frac{(q_2^A \varepsilon)^2}{2} - sc(q_1^A)^2 \quad (23)$$

Theorem 4: The optimal subsidy interest rate under SWP is expressed as:

$$s^{A-SW*} = \frac{A_1}{B_1} \quad (24)$$

The optimal farmer's planting area can be expressed as:

$$q_1^{A-SW*} = \frac{B_2}{A_3} \quad (25)$$

$$q_2^{A-SW*} = \frac{aA_2}{2(2c+\sigma^2)A_3} \quad (26)$$

The optimal farmer's profit can be expressed as:

$$\pi_{F1}^{A-SW*} = \frac{B_3 A_2}{4(2c+\sigma^2)^2 z^2} \quad (27)$$

$$\pi_{F2}^{A-SW*} = \frac{a^2 c A_2^2}{4(2c+\sigma^2)^2 A_3^2} \quad (28)$$

Details of $A_1, A_2, A_3, B_1, B_2, B_3$ can be seen in the appendix.

C. NUMERICAL EXAMPLES

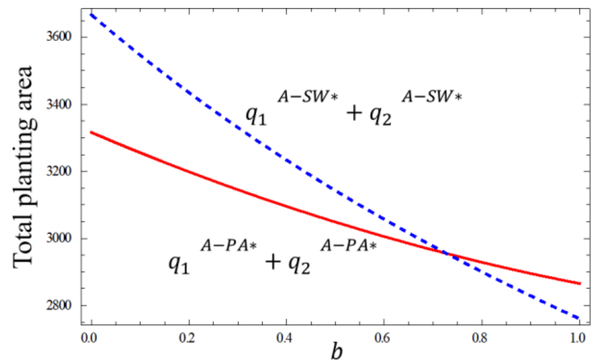
The case where farmer 1 receives the subsidy and farmer 2 does not receive the subsidy is quite complicated. In this subsection, we present numerical examples to further illustrate the impact of different government decision-making objectives, planting costs, and the intensity of competition between companies on supply chain performance. By doing so, we can provide management suggestions on how to design a government subsidy mechanism and improve farmer performance.

Bioethanol based on sugarcane has great market potential in China [44]. Therefore, in this section, we focus on the empirical application of sugarcane bioethanol supply chain in China. According to China's National Bureau of Statistics, we use the statistical software SPSS to analyse the data of sugarcane yield in China from 2007 to 2017 and find that the yield per square metre of sugarcane ε (kg) follows a uniform distribution, with $\varepsilon \sim U(6.53, 7.61)$ (CNBS, [45]). As the China Center of Financial Research (CCFR) reported, the average financing cost of agriculture is higher than 10%, but the annual interest rate of loans generally does not exceed 30% (CCFR, [46]). Therefore, we assume the interest rate $r = 0.2$. Due to the confidentiality of enterprises, the collected survey data related to parameters such as c and a are scattered, and it is difficult to obtain accurate parameter values. We let the maximum possible price for the biofuel $a = 10$ to indicate the customers' purchase intention. In addition, we set the competitive intensity $b = 0.5$, and the planting cost coefficient $c = 1$.

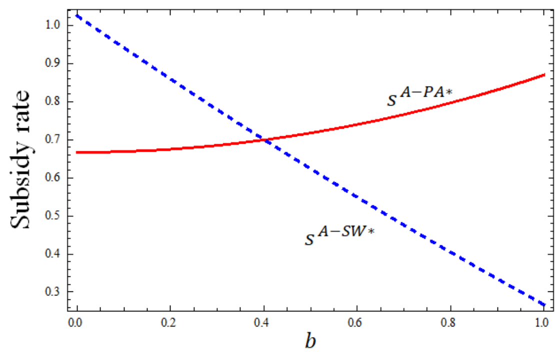
In the following image obtained by numerical analysis, we use the superscript A-NS to represent the benchmark case with no subsidy (NS). Hence, π_{F1}^{A-NS*} indicates the optimal profit of farmer 1 in NS.

1) IMPACT OF COMPETITIVE INTENSITY ON PERFORMANCES

The larger the planting area, the greater the consumer welfare. Therefore, according to Fig.3 (a), we can find that when competitive intensity b is small, consumers benefit is greater under SWP, and when competitive intensity b is large, consumers benefit is greater under PAP.



(a)



(b)

FIGURE 3. Impact of competitive intensity *b* on the planting area and the subsidy rate.

Under SWP, the optimal subsidy interest rate decreases with the competitive intensity b. As shown in Fig.3 (b), when the competition is fierce, excessive subsidies further exacerbate competition between companies and reduce the company's profit. Under PAP, due to the high degree of competition, the farmer's profit is very low. Therefore, the government will give a larger subsidy to protect the farmer's profit.

2) IMPACT OF PLANTING COST COEFFICIENT ON THE PROFIT OF FARMER 1 UNDER THE DIFFERENT INTEREST RATE

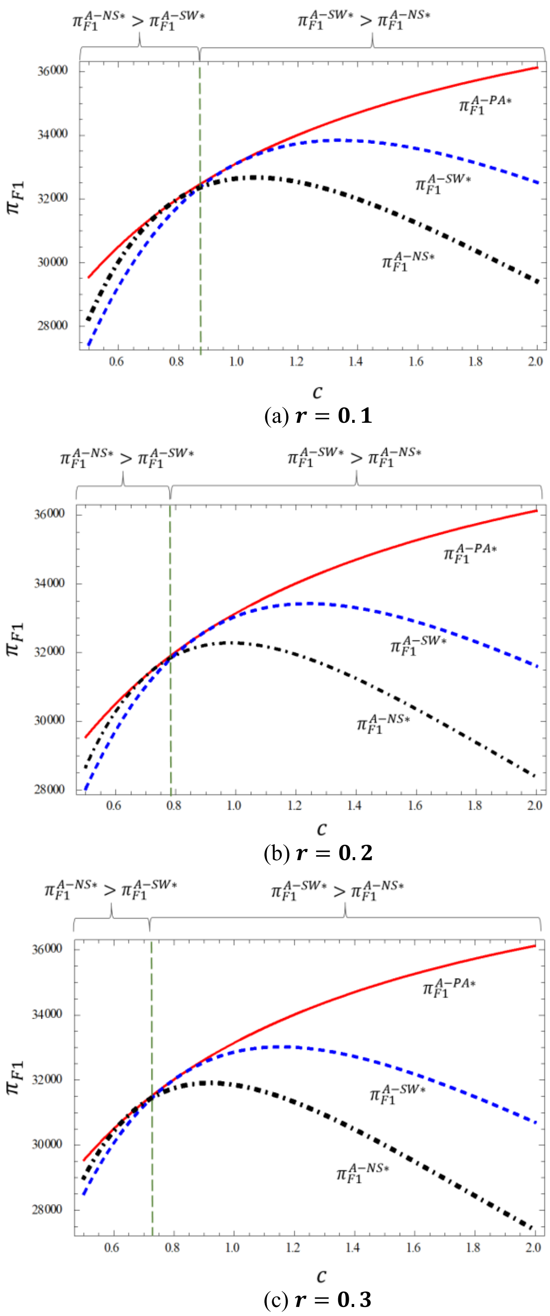


FIGURE 4. **Impact of planting cost coefficient c on the profit of farmer 1 under different interest rate *r*.**

3) IMPACT OF PLANTING COST COEFFICIENT ON THE PROFIT OF FARMER 1 UNDER DIFFERENT COMPETITIVE INTENSITY

As shown in Fig.4 and Fig.5, the income of farmer 1 first rises and then decreases with the increase of planting cost coefficient under SWP or benchmark case with no subsidy (NS). The following explanation may support this finding. When the planting cost coefficient is very small, both farmers

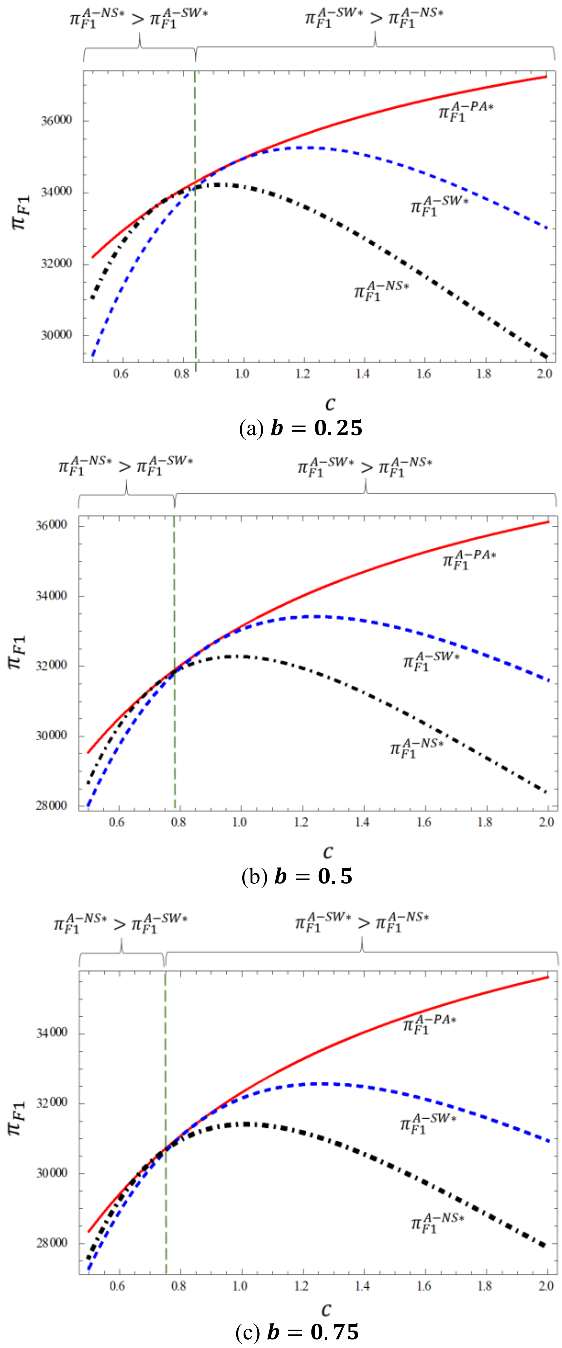


FIGURE 5. **Impact of planting cost coefficient *c* on the profit of farmer 1under different competitive intensity *b*.**

produce a large amount of biomass feedstock, which intensifies competition and leads to lower income for farmers. A certain degree of planting cost coefficient increase slows down the competitive loss. However, when the cost is high, the farmer chooses a small amount of production and the income is reduced. Under poverty alleviation model, the income of poor farmer increases with the increase of cost, as shown by Proposition 6. In Fig.4 and Fig.5, we also find that the profit of farmer 1 under PAP has always been highest. However, when the planting efficiency is high, that is, the planting cost coefficient is relatively small, the profit of farmer 1 in SWP is higher than that in NS. This finding reflects the government's goal of maximizing of social welfare may sometimes harm the profit of farmer 1 because social welfare also includes the benefits of companies. Under different interest rate r or competitive intensity b, the above findings are stable.

4) IMPACT OF PLANTING COST COEFFICIENT ON THE PROFIT OF FARMERS UNDER DIFFERENT INTEREST RATE

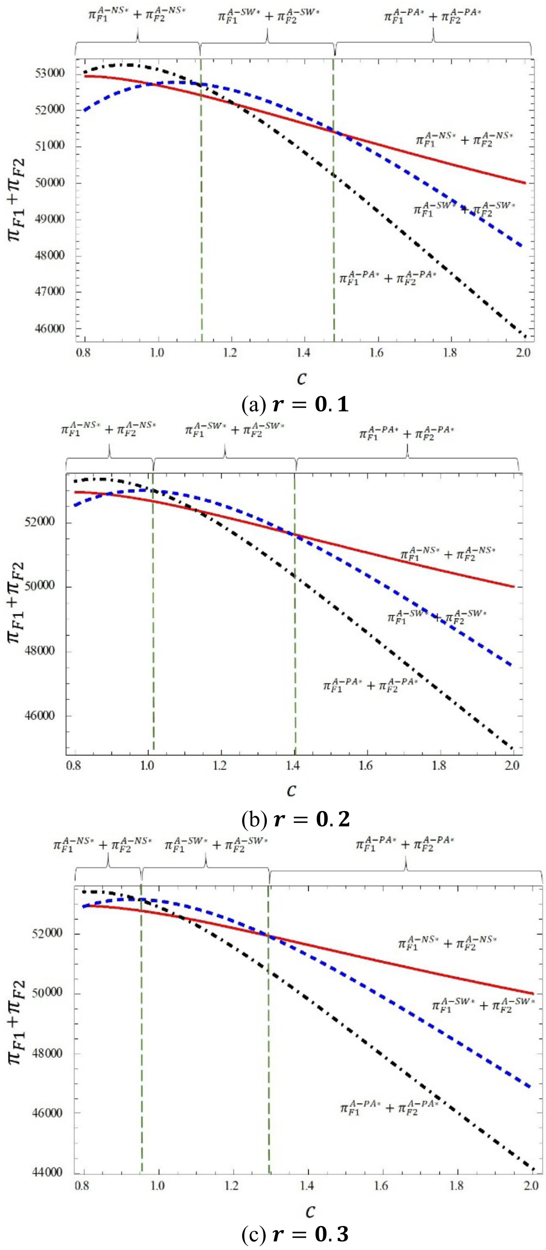


FIGURE 6. Impact of planting cost coefficient c on farmers' profit under different interest rate r.

5) IMPACT OF PLANTING COST COEFFICIENT ON FARMERS' PROFIT UNDER DIFFERENT COMPETITIVE INTENSITY

As shown in Fig.6 and Fig.7, when the planting cost coefficient is relatively low, the total income of the farmers in

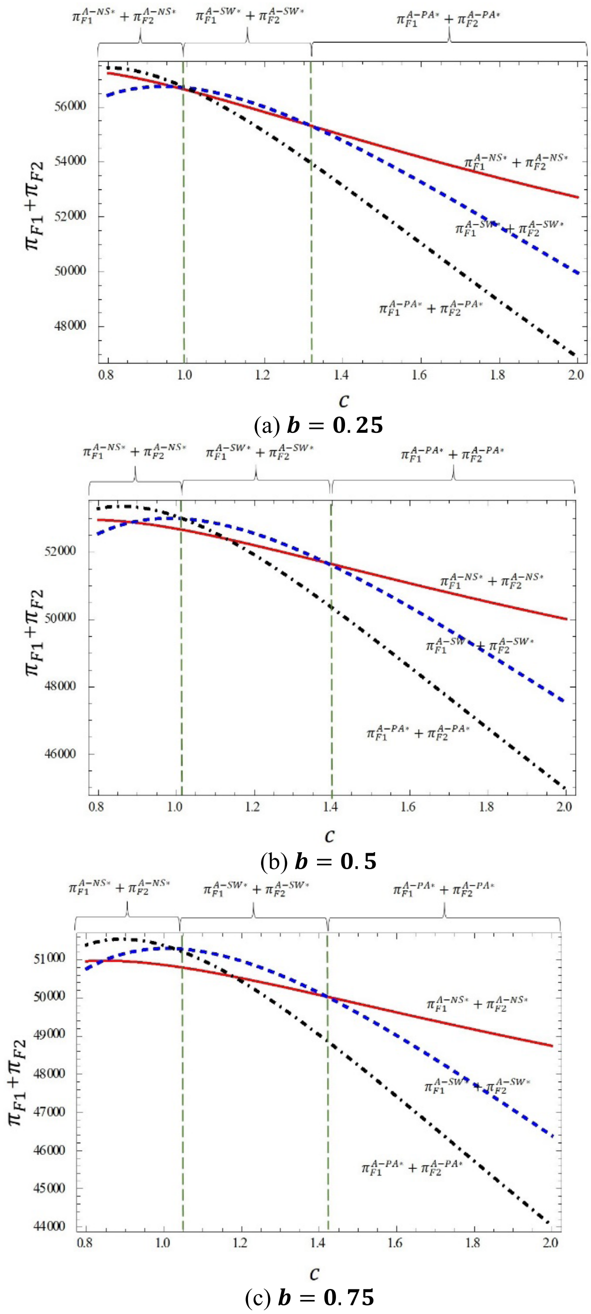


FIGURE 7. Impact of planting cost coefficient c on farmers' profit under different competitive intensity b.

benchmark case is higher than that in PAP or SWP. Although the subsidy can help the farmer 1 to increase his income, the profit of the farmer 2 is damaged, resulting in an increase in the income of the farmer 1 less than the decrease in the income of the farmer 2. When the planting cost coefficient is in the middle area, the total income of the farmers is the highest under SWP. When the planting cost coefficient is sufficiently large, the poverty alleviation program can effectively increase the income of the farmer 1. At the same time, the benefits to the farmer 1 is greater than the damage to the farmer 2, so that the total income of farmers under PAP is larger than that in benchmark case.

Therefore, when the planting cost coefficient of farmers is relatively small, the subsidy policy should be used cautiously to avoid damage to the income of the farmer who do not need loans; and when the cost is high, the government's poverty alleviation program can effectively increase the income of the farmer 1. while the planting cost coefficient is in the middle area, the social welfare program can help the total income of farmers while increasing social welfare. We use different parameters about interest rate r or competitive intensity b for numerical analysis, and find the above conclusion is stable. These findings have certain policy guiding significance.

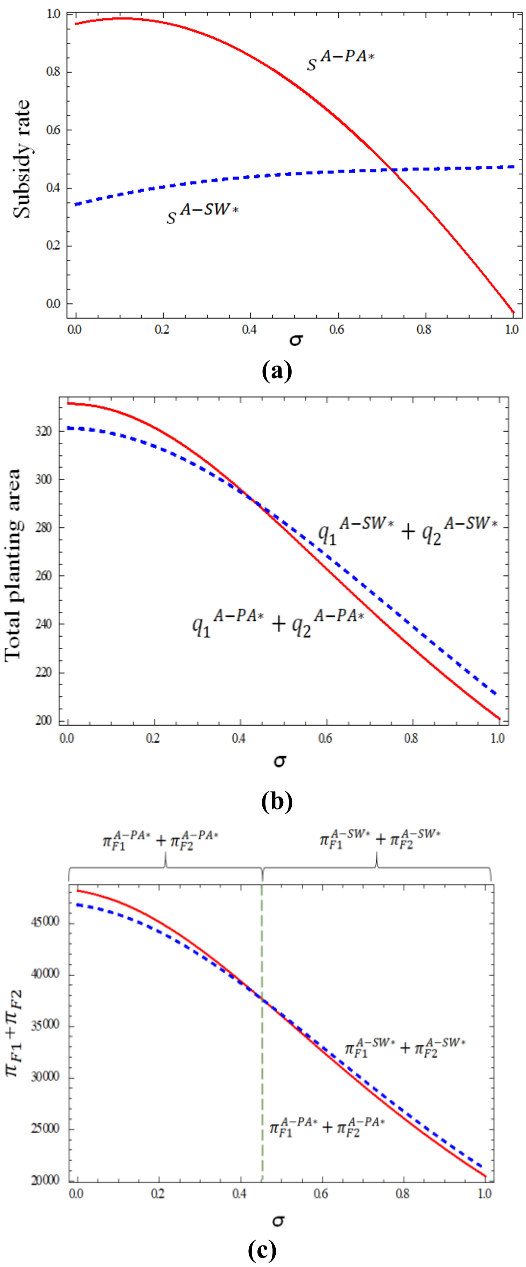


FIGURE 8. **Impact of yield uncertainty σ on the subsidy programs performance.**

6) IMPACT OF YIELD UNCERTAINTY ON THE SUBSIDY PROGRAMS PERFORMANCES

From Fig.8 (a), we can find that with the increase of yield uncertainty, the optimal subsidy rate in A-PA is decreasing, while the optimal subsidy rate in A-SW is increasing. This is because the government's purpose in A-PA is to maximize the income of the farmer with limited funds. When the yield risk is high, if the government provides a higher subsidy interest rate to stimulate the farmer to expand production, it is likely that the actual yield of the farmer will be too low, hence the farmer's profit will be damaged. However, the government's goal in A-SW is to maximize social welfare. As the yield risk increases, the supply of agricultural products also decreases. The company's sales revenue and consumer surplus are affected by the low supply of agricultural products. In order to increase the supply of agricultural products, that is, to improve social welfare, the government will set a higher subsidy rate to stimulate farmers to expand production, so as to avoid a sharp reduction in agricultural product supply due to high yield risks. As shown in Fig.8 (b) the total biofuel feedstocks output decreases with increasing yield risk, but the output declines slowly in A-SW, which is related to the gradual increase in the subsidy rate A-SW. Therefore, when the yield risk is low, the government subsidy rate is higher in A-PA, the total output of biomass crops is also larger, and the total income of farmers is relatively high. With the increase of yield risk, the subsidy rate and the total output of biomass crops in A-SW is gradually higher than that in A-PA. Finally, when the yield risk is large, the total profit of farmers in A-SW is relatively large.

7) SUBSIDY EFFICIENCY UNDER DIFFERENT SUBSIDY PROGRAMS

Unlike Proposition 7, we define the efficiency ratio $\tau^i = \frac{\pi_{F1}^{i*}}{s^i c q_1^{i*}}$ for $i \in \{A-PA, A-SW$ because only the farmer 1

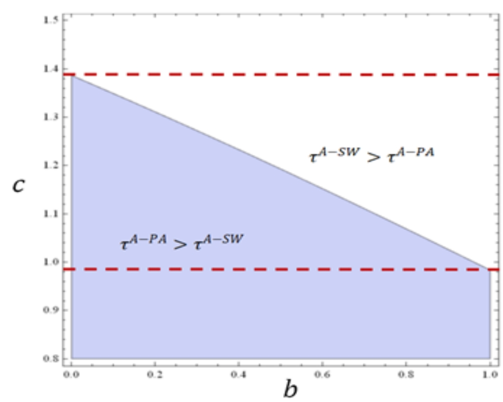


FIGURE 9. **Comparison of subsidy efficiency under different subsidy programs.**

gets government subsidies. Fig.9 shows that the effect of competitive intensity b and planting cost coefficient c on the farmer's income improvement efficiency. From Fig.9, we can see, if planting cost coefficient is small, the subsidy efficiency under PAP is higher than that under SWP. If planting cost coefficient is large, the government choose the maximizing social welfare mode can obtain higher subsidy efficiency. This is because the government needs to pay a large budget to protect the income of the farmer with financial constraints when the planting cost coefficient is large. However, the marginal benefit of subsidy is diminishing. The poor farmer under poverty alleviation programme has achieved higher returns, but the subsidy efficiency is reduced. If the planting cost coefficient is in the middle area, the farmer's income improvement efficiency under PAP is larger (smaller) when the competition between companies is weak (strong).

VI. CONCLUSION

The role of biofuels in the environment and the economy is becoming increasingly important. Using a contract farming scheme, we construct a biofuel supply chain system consisting of the government, the bank, two biofuel companies and two farmers and investigate how to optimize the biofuel supply chain in which farmers are subject to capital constraints and face an uncertain yield environment.

We find that for farmers with high planting efficiency, when the government implements PAP, it is only necessary to determine a low subsidy rate to optimize the income of farmers. However, if the government promotes SWP, the government should set a high (low) subsidy rate to maximize social welfare when competition between enterprises is weak (strong). This finding may help the government develop appropriate subsidy policies for agricultural areas with relatively advanced production methods. We also find that the total biomass feedstock planting area in SWP is larger (smaller) than that in PAP when the planting efficiency is sufficiently high (low). Adequate raw materials are available to facilitate stable operation of the biofuel supply chain. Furthermore, we define the subsidy efficiency ratio to indicate the efficiency of farmers' income improvement. Accordingly, we notice that each unit of government expenditure can bring more income improvement to farmers under SWP when the planting efficiency is lower than a certain threshold. This finding reveals that although SWP aims to maximize social welfare, it is more efficient to help farmers increase their income in areas with relatively backward production methods.

Next, we extend our model to the case in which one farmer needs to borrow from the bank and another farmer has sufficient funds. We find a counter-intuitive conclusion. When the planting efficiency is sufficiently low, PAP can help farmers obtain the best benefits. When the planting efficiency increases, the government's implementation of SWP can make farmers' incomes optimal. However, when the planting efficiency is sufficiently high, the total income of farmers is optimal in the benchmark case without the government subsidy. This finding reveals that sometimes the government's subsidy policy will be counterproductive and damage the overall income of farmers. Therefore, for agricultural areas with high planting efficiency, the government may not need to implement a subsidy policy.

APPENDIX

A. PROOF OF EQUATION (2)

$$\begin{aligned}\pi_{F1} &= E[w_1 q_1 \varepsilon - c(q_1)^2 (1+r-s)]^+ \\ &= \int_{\tilde{\varepsilon}}^{B} \left[w_1 q_1 \varepsilon - c\left(q_1\right)^2 (1+r-s)\right] f(\varepsilon) d\varepsilon\end{aligned}$$

where $\tilde{\varepsilon} = \frac{c(1+r-s)q_1}{w_1}$, the profit of the farmer is 0 when realization of product $\varepsilon \leq \tilde{\varepsilon}$.the optimal production quantity q_1^* should satisfy the following first order partial derivative condition:

$$\begin{aligned}\frac{\partial \pi_{F1}}{\partial q_1} &= \int_{\tilde{\varepsilon}}^{B} \left[w_1 q_1 \varepsilon - c\left(q_1\right)^2 (1+r-s)\right] f(\varepsilon) d\varepsilon \\ &= w_1 \int_{\tilde{\varepsilon}}^{B} [\varepsilon - \frac{2c\,(1+r-s)\,q_1}{w_1}] f(\varepsilon) d\varepsilon\end{aligned}$$

where bankruptcy threshold satisfy $\tilde{\varepsilon} = \frac{c(1+r-s)q_1}{w_1}$. Therefore, $\frac{\partial \pi_{F1}}{\partial q_1} = w_1 \int_{\tilde{\varepsilon}}^{B} \left[\varepsilon - 2\tilde{\varepsilon}\right] f\,(\varepsilon)\, d\varepsilon = 0$ Obviously when $\frac{\partial \pi_{F1}}{\partial q_1}\,|q_1 = A > 0$ and $\frac{\partial \pi_{F1}}{\partial q_1}\,|q_1 = B < 0$, since $\frac{\partial \pi_{F1}}{\partial q_1}$ is continuous, there exist q_1^* such that $\frac{\partial \pi_{F1}}{\partial q_1} = 0$. Because there is a one-to-one mapping between $\tilde{\varepsilon}$ and q_1, there exist $\tilde{\varepsilon}$ such that $\int_{\tilde{\varepsilon}}^{B} [\varepsilon - 2\tilde{\varepsilon}] f(\varepsilon) d\varepsilon$ =0, i.e. $\int_{\tilde{\varepsilon}}^{B} \varepsilon f\,(\varepsilon)\, d\varepsilon = 2\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})$. Let $\Psi\,(\varepsilon) = \int_{\tilde{\varepsilon}}^{B} [\varepsilon - 2\tilde{\varepsilon}] f(\varepsilon) d\varepsilon$, We have $\Psi'\,(\varepsilon) = \varepsilon f\,(\varepsilon) - 2\bar{F}\,(\varepsilon) = \bar{F}\,(\varepsilon)\,[h\,(\varepsilon) - 2]$. (i) for any ε satisfy $h\,(\varepsilon) \leq 2$, then π_{F1} is concave function respective with ε. (ii) there exist ε satisfy $h\,(\varepsilon) > 2$, Because the random variable of yield uncertainty μ has the properties of Increasing Generalized Failure Rate (IGFR). We can find that, when $\varepsilon \in \left[A, h^{-1}\,(2)\right]$, $\Psi'\,(\varepsilon) > 0$, when $\varepsilon \in \left[h^{-1}\,(2)\,, B\right]$, $\Psi'\,(\varepsilon) < 0$. We have $\Psi'\,(\varepsilon)$ is unimodal function with respect to ε. When $\Psi\,(A) = \bar{\varepsilon} - 2A \geq 0$, note that $\Psi\,(B) = 0$, there is no solution in (A, B). Contradiction, i.e. When $\Psi\,(A) = \bar{\varepsilon} - 2A \geq 0$, We have $h\,(\varepsilon) \leq 2$ Combining with $\Psi\,(A) = \bar{\varepsilon} - 2A < 0$ and $\Psi\,(B) = 0$, we have $\Psi\,(\varepsilon) = 0$ has unique solution in (A, B).

B. PROOF OF THEOREM 1

According to Proof of Equation(2),when the wholesale price are given,the optimal quantity of farmer is $q_i = \frac{w_i \tilde{\varepsilon}}{c(1+r-s)}$. The company's profit function is

$$\pi_{Ci} = \frac{\tilde{\varepsilon}(a-w_i)w_i}{c(1+r(1-s))} - \sigma^2 \left(\frac{\tilde{\varepsilon}^2 w_i^2}{c^2(1+r(1-s))^2} + \frac{b\tilde{\varepsilon}^2 w_1 w_2}{c^2(1+r(1-s))^2}\right)$$

where $\sigma^2 = \delta^2 + \bar{\varepsilon}^2$. So, w_1 and w_2 can be determined as the unique solution to the implicit function

$$\frac{d\pi_{C1}}{dw_1} = \frac{\tilde{\varepsilon}(c(1+r-rs)(a-2w_1) - \tilde{\varepsilon}\sigma^2(bw_2+2w_1))}{c^2(1+r-rs)^2} = 0$$

and

$$\frac{d\pi_{C2}}{dw_2} = \frac{\tilde{\varepsilon}(c(1+r-rs)(a-2w_2) - \tilde{\varepsilon}\sigma^2(bw_1+2w_2))}{c^2(1+r-rs)^2} = 0.$$

Combining the above two equations, we can get the optimal wholesale price are $w_1^* = w_2^* = \frac{ac(1+(1-s)r)}{(2+b)\sigma^2\tilde{\varepsilon}+2c(1+(1-s)r)}$, then $q_1^* = q_2^* = \frac{a\tilde{\varepsilon}}{2c(1+r-rs)+(2+b)\tilde{\varepsilon}\sigma^2}$.

Further we get the expected profit function of the farmers and the companies

$$\pi_{F1}^* = \pi_{F2}^* = \frac{a^2c\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})(1+r-rs)}{(2c(1+r-rs)+(2+b)\tilde{\varepsilon}\sigma^2)^2},$$

$$\pi_{C1}^* = \pi_{C2}^* = \frac{a^2\tilde{\varepsilon}(c(1+r-rs)+\tilde{\varepsilon}\sigma^2)}{(2c(1+r-rs)+(2+b)\tilde{\varepsilon}\sigma^2)^2}.$$

C. PROOF OF PROPOSITION 1

For a given subsidy s, we find that

(1) $\frac{dw_i}{ds} = -\frac{a(2+b)c\tilde{\varepsilon}r\sigma^2}{(2c(1+r-rs)+(2+b)\tilde{\varepsilon}\sigma^2)^2} < 0$, $\frac{dq_i}{ds} = \frac{2ac\tilde{\varepsilon}r}{(2c(1+r-rs)+(2+b)\tilde{\varepsilon}\sigma^2)^2} > 0$, $\frac{d\pi_{ci}}{ds} = \frac{a^2c\tilde{\varepsilon}r(2c(1+r-rs)+(2-b)\tilde{\varepsilon}\sigma^2)}{(2c(1+r-rs)+(2+b)\tilde{\varepsilon}\sigma^2)^3} > 0$.

(2) It is to obtain that $\frac{d\pi_{Fi}}{ds} = \frac{a^2c\tilde{\varepsilon}r(2c(1+r-rs)-(2+b)\tilde{\varepsilon}\sigma^2)}{(2c(1+r-rs)+(2+b)\tilde{\varepsilon}\sigma^2)^3}$, so we have if $c > \frac{(2+b)\tilde{\varepsilon}\sigma^2}{2}$, then $\frac{d\pi_{Fi}}{ds} > 0$. If $c < \frac{(2+b)\tilde{\varepsilon}\sigma^2}{2}$, then $\frac{d\pi_{Fi}}{ds} > 0$ when $s \in \left(0, \frac{1+r}{r} - \frac{(2+b)\tilde{\varepsilon}\sigma^2}{2cr}\right)$; $\frac{d\pi_{Fi}}{ds} < 0$ when $s \in \left(\frac{1+r}{r} - \frac{(2+b)\tilde{\varepsilon}\sigma^2}{2cr}, 1\right)$

D. PROOF OF PROPOSITION 2

Under PAP, $s^{PA*} = \frac{2c(1+r)-(2+b)\tilde{\varepsilon}\sigma^2}{2cr}$. The feasible scope of subsidy is $s^{PA*} \in (0,1)$.Let $\frac{2c(1+r)-(2+b)\tilde{\varepsilon}\sigma^2}{2cr} < 0$, we have $c < \frac{(2+b)\tilde{\varepsilon}\sigma^2}{(2+2r)}$; let $\frac{2c(1+r)-(2+b)\tilde{\varepsilon}\sigma^2}{2cr} > 1$, we have $c > \frac{(2+b)\tilde{\varepsilon}\sigma^2}{2}$. Therefore under PAP, the optimal subsidy interest rate $s^{PA*} = 0$ when $c < c_1$, and the optimal subsidy interest rate $s^{PA*} = 0$ when $c > c_2$.

E. PROOF OF PROPOSITION 3

$\frac{d\Pi^{PA*}}{db} = \frac{a^2(4c(1+r)-(8+b+2\tilde{\varepsilon}+b\tilde{\varepsilon}+(2+b)\tilde{\varepsilon}(1+\bar{F}(\tilde{\varepsilon})))\sigma^2)}{4(2+b)^3\sigma^4}$. Let $\frac{d\Pi^{PA*}}{db} = 0$, we have b $=b_1 = \frac{4c(1+r)-2(4+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}))\sigma^2}{(1+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}))\sigma^2}$.

(1) If $c < \frac{(4+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}))\sigma^2}{2(1+r)}$, $b_1 < 0$ always hold, then $\frac{d\Pi^{PA*}}{db} < 0$.

(2) If $c > \frac{3(3+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}))\sigma^2}{4(1+r)}$, $b_1 > 1$ always hold, then $\frac{d\Pi^{PA*}}{db} > 0$.

(3) If $c \in \left(\frac{(4+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}))\sigma^2}{2(1+r)}, \frac{3(3+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}))\sigma^2}{4(1+r)}\right)$, then $\frac{d\Pi^{PA*}}{db} > 0$ when $b \in (0, b_1)$; then $\frac{d\Pi^{PA*}}{db} < 0$ when $b \in (b_1, 1)$.

F. PROOF OF PROPOSITION 4

(1) Under SWP, let $\frac{ds^{PA*}}{dc} = \frac{\tilde{\varepsilon}(-4+b+2\tilde{\varepsilon}+b\tilde{\varepsilon}+(2+b)\tilde{\varepsilon}g)\sigma^2}{2c^2(1+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}))r} = 0$ we have b $=b_2 = \frac{6}{1+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})} - 2$.

(2) if $b \in (0, b_2)$, then $\frac{ds^{SW*}}{dc} < 0$; if $b \in (b_2, 1)$, then $\frac{ds^{SW*}}{dc} > 0$.

Under PAP, $\frac{ds^{PA*}}{dc} = \frac{(2+b)\tilde{\varepsilon}\sigma^2}{2c^2r} > 0$.

G. PROOF OF PROPOSITION 5

(1) $\frac{ds^{PA*}}{db} = -\frac{f\sigma^2}{2cr} < 0$, $\frac{dq_i^{PA*}}{db} = -\frac{a}{2(2+b)^2\sigma^2} < 0$, $\frac{d\pi_{ci}^{PA*}}{db} = -\frac{a}{2(2+b)^2\sigma^2} < 0$.

(2) Let $\frac{d\pi_{Fi}^{SW*}}{db} = -\frac{n_1+n_2}{n_3} = 0$, where

$$n_1 = a^2\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})\left(1+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})\right)^2\sigma^2(6c(1+r))$$

$$n_2 = \left(-7+b+2\tilde{\varepsilon}+b\tilde{\varepsilon}+(2+b)\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})\right)\sigma^2$$

$$n_3 = 8\left(2c+\left(-1+b+2\tilde{\varepsilon}+b\tilde{\varepsilon}+(2+b)\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})\right)\sigma^2\right)^3.$$

we have $b_3 = \frac{(7-2\tilde{\varepsilon}(1+\bar{F}(\tilde{\varepsilon})))\sigma^2-6c(1+r)}{(1+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}))\sigma^2}$ If $b \in (0, b_3)$ then $\frac{d\pi_{Fi}^{SW*}}{db} > 0$. If $b \in (b_3, 1)$ then $\frac{d\pi_{Fi}^{PA*}}{db} < 0$.

(3) If $b \in (0,1)$ then $\frac{d\pi_{Fi}^{PA*}}{db} = -\frac{a^2\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})}{8(2+b)^2\sigma^2} < 0$.

H. PROOF OF PROPOSITION 6

Let $s^{SW*} - s^{PA*} = \frac{\tilde{\varepsilon}(3\sigma^2-2c(1+r))}{c(1+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}))r} = 0$, we have $c_3 = \frac{3\sigma^2}{2(1+r)}$.

If $c < c_3$, then $s^{SW*} > s^{PA*}$, if $c > c_3$, then $s^{SW*} < s^{PA*}$.

According to Proposition 1 $\frac{dq_i}{ds} > 0$, [[space]]$\frac{d\pi_{ci}}{ds} > 0$. We can get the conclusion

(1) If $c < c_3$, then $s^{SW*} > s^{PA*}$, $q^{SW*} > q^{AP*}$, $\pi_{C1}^{SW*} > \pi_{C1}^{PA*}$.

(2) If $c > c_3$, then $s^{SW*} < s^{PA*}$, $q^{SW*} < q^{AP*}$, $\pi_{c1}^{SW*} < \pi_{c1}^{PA*}$.

I. PROOF OF PROPOSITION 7

$$\tau^{\mathrm{PA}} - \tau^{\mathrm{SW}} = -\frac{4c\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})r(1+r)(2c(1+r)-3\sigma^2)}{(1+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}))(2c(1+r)+(2+b)\tilde{\varepsilon}\sigma^2)^2}.$$

If c $< \frac{3\sigma^2}{2(1+r)}$, then subsidy efficiency $\tau^{\mathrm{PA}} > \tau^{\mathrm{SW}}$, Otherwise there is $\tau^{\mathrm{PA}} \leq \tau^{\mathrm{SW}}$.

J. PROOF OF PROPOSITION 8

(1) $\frac{dq_1^{A-PA*}}{db} = -\frac{a(8(1-b)c+(2-b)^2\sigma^2)}{2(8c-(b^2-4)\sigma^2)^2} < 0$, $\frac{dq_2^{A-PA*}}{db} = -\frac{a\sigma^2}{32c^2+16c\sigma^2} < 0$

$$\frac{d\pi_{F1}^{A-PA*}}{db} = -\frac{a^2(2-b)\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})\left(4c+(2-b)\sigma^2\right)}{4\left(8c-\left(b^2-4\right)\sigma^2\right)^2} < 0,$$

$$\frac{d\pi_{F2}^{A-PA*}}{db} = -\frac{a^2\sigma^2(4c+(2-b)\sigma^2)}{128c(2c+\sigma^2)^2} < 0$$

(2) $\frac{dq_1^{A-PA*}}{dc} = \frac{2a(2-b)b}{(8c-(b^2-4)\sigma^2)^2} > 0$, According to monotonicity $\pi_{F1}^{A-PA*}, \pi_{C1}^{A-PA*}$ are increasing in c.

(3) $\frac{d(q_1^{A-PA*}+q_2^{A-PA*})}{dc} = -\frac{2-b}{c^2} - \frac{4b}{(2c+\sigma^2)^2} - \frac{32(b-2)b}{(8c+4\sigma^2-b^2\sigma^2)^2} < 0$ is decreasing in c.

K. PROOF OF THEOREM 4

$$A_1 = A_{11} + A_{13} - A_{13} + 4c(A_{14} + A_{15})\sigma^4 - A_{16}$$

where

$$A_{11} = (32c^3(1+\tilde{\varepsilon}(\bar{F}(\tilde{\varepsilon})-1))(1+r) - a_{11},$$
$$a_{11} = 8c^2(4\tilde{\varepsilon}^2(1+\bar{F}(\tilde{\varepsilon})),$$
$$A_{12} = 4(-1+b)(1+r) + \tilde{\varepsilon}(b(-1+\bar{F}(\tilde{\varepsilon}))(1+r),$$
$$A_{13} = 4(1+\bar{F}(\tilde{\varepsilon}) + (-1+\bar{F}(\tilde{\varepsilon}))r)))\sigma^2,$$
$$A_{14} = (-2+b)(4+b)\tilde{\varepsilon}^2(1+g) - 2(-1+2b)(1+r),$$
$$A_{15} = \tilde{\varepsilon}(4b^2 + 2(7+\bar{F}(\tilde{\varepsilon}) + a_{15}),$$
$$a_{15}(-1+\bar{F}(\tilde{\varepsilon}))r) - b(9+\bar{F}(\tilde{\varepsilon}) + (-1+\bar{F}(\tilde{\varepsilon}))r),$$
$$A_{16} = (-2+b)^2\tilde{\varepsilon}(-4+b+(2+b)\tilde{\varepsilon}(1+\bar{F}(\tilde{\varepsilon})))\sigma^6).$$
$$A_2 = 16c^2\,(1+r) - A_{21} - A_{22}$$

where

$$A_{21} = 4c\left(b\left(1+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})\right) - a_{21}\right)\sigma^2,$$
$$a_{21} = 2\left(2\left(\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})\right)+r\right),$$
$$A_{22} = (4-8\tilde{\varepsilon}+b(2+b)(1+\tilde{\varepsilon})+a_{22})\sigma^4,$$
$$a_{22} = (-2+b)(4+b)\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})\,.$$
$$A_3 = 16c^2(1+r) + 8c(2\tilde{\varepsilon}+2\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})+r)\sigma^2 - A_{31}$$

where

$$A_{31} = (4-8(\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}))+a_{31})\sigma^4,$$
$$a_{32} = b^2(5+2\tilde{\varepsilon}(\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon}))).$$
$$B_1 = (4cr(2c+\sigma^2)(4c(\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})+1) - B_{11}),$$

where

$$B_{11} = ((-2+b)\tilde{\varepsilon}(1+\bar{F}(\tilde{\varepsilon})) - 2 + 4b)\sigma^2.$$
$$B_2 = a(4c(1+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})) - B_{21}),$$

where

$$B_{21} = (-2(1+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})) + b_{21})\sigma^2,$$
$$b_{21} = b(4+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})).$$
$$B_3 = 4c(a^2\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})\,(4c(1+\tilde{\varepsilon}+\tilde{\varepsilon}\bar{F}(\tilde{\varepsilon})) - B_{21}).$$

The proof process of theorem 4 is similar to theorem 2 and thus is omitted.

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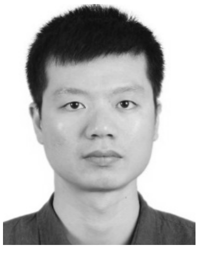

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