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The choice of cooperation mode in the bioenergy supply chain with random biomass feedstock yield

Zigong Cai [a], Fei Ye [a,**], Zefei Xie [a], Li Zhang [b,*], Ting Cui [b,***]

[a] South China University of Technology, Guangzhou, 510640, PR China
[b] Guangdong University of Finance and Economics, Guangzhou, 510640, PR China

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ABSTRACT

A successful cooperation mode between bioenergy producers and farmers can effectively promote the supply of biomass feedstock, which plays an important role in the bioenergy industry. In this study, we examine two prevailing cooperation modes in bioenergy supply chain, namely contract farming (CF) and land as shares (LS). This study assesses how each cooperation mode influences the planting acreage, the feedstock quality and the profits of supply chain participants. Under CF, the farmer and the bioenergy producer sign a contract in which the bioenergy producer purchases all feedstock produced by the farmer. Under LS, the farmer converts their land use rights into company shares, so that the bioenergy producer will share part of sales revenue with the farmer. First, we find that the optimal planting scale of biomass feedstock under LS is larger than that under CF when the bioenergy market size is sufficiently large. If the market size is relatively small, the supply quantity of biomass feedstock under LS depends on the marginal value of feedstock quality. Second, when the bioenergy market is sufficiently large, the farmer and the bioenergy producer under LS can achieve a win-win situation, which improves the reliability of the bioenergy supply chain. Third, we extend our model to the case where the government implements subsidies for biomass feedstock. We find that when the subsidy is high enough, the biomass feedstock quantity under LS will be larger. In addition, government subsidy does not necessarily improve the profit of all supply chain participants and excessive government subsidy may adversely affect the reliability of the bioenergy supply chain.

1. Introduction

Bioenergy, produced from renewable biomass feedstock (for example, agricultural residues, energy crops, wood), is considered to be one of the most important renewable energy sources due to its environmental friendliness, low cost and carbon neutrality (Zahraee et al., 2019). It is estimated that by 2035, bioenergy will have replaced about half of the world's gasoline and diesel, with significant economic and environmental benefits (Mao et al., 2018).

The success of the bioenergy industry is inseparable from the supply of biomass feedstock. The United States and Brazil spend a lot of government money every year to improve the production of bioenergy feedstock, such as sugarcane and corn (Mao et al., 2018). In September 2020, China pledged at the UN General Assembly to achieve carbon neutrality by 2060 (China Daily, 2020). In fact, cassava is regarded as an important bioenergy feedstock in China due to its advantages of drought resistance, easy cultivation, and high starch content (Ye et al., 2017). In order to obtain a reliable supply of cassava, the Chinese government actively promotes cooperation between the farmer and the bioenergy producer. The "company + farmer" cooperation modes are believed to be able to effectively expand the scale of cassava cultivation, while ensuring that the bioenergy producers can obtain a reliable supply of cassava, which is beneficial for the production of bioenergy (Ye et al., 2017).

In this study, we focus on the "company + farmer" cooperation modes in the bioenergy supply chain, namely contract farming (CF) and land as shares (LS). CF means that the farmer signs a legally binding forward contract with a company before the production of biomass feedstock. The contractual parties agree on the wholesale price, and transaction time. The farmer organizes the production according to the

* Corresponding author.
** Corresponding author.
*** Corresponding author.
E-mail addresses: yefei@scut.edu.cn (F. Ye), 20181042@gdufe.edu.cn (L. Zhang), Cuiting@gdufe.edu.cn (T. Cui).

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contract and the bioenergy producer acquires biomass feedstock at the end of the production season (Singh, 2002). Unlike the traditional wholesale price contract, the bioenergy producer under CF offers only a contract price to the farmer, but does not specify quantity. China's bioenergy industry has a huge demand for biomass feedstock and the bioenergy producer purchases all the output of the farmer (Ye et al., 2020). The extensive planting patterns of farmers have resulted in a low quality of cassava, such as a low starch content. The bioenergy produced by using low-quality cassava may contain many impurities, which will reduce consumers' willingness to buy. Therefore, the bioenergy producer is willing to purchase high-quality cassava at a higher price to encourage farmers to improve the quality of their cassava. CF solves the production constraints faced by the farmer through vertical integration and helps the bioenergy producer reduce the transaction costs and stabilize the quantity of acquisitions (Awi et al., 2019; Ye et al., 2020).

As an agricultural product, the price of biomass feedstock is affected by the relationship between demand and supply. For example, weather conditions, food stocks, bird flu and other such emergencies have all caused considerable risks and uncertainties in agricultural production (Haile et al., 2014). Farmers not only face uncertain demand but also extreme fluctuation of the market price. Land as shares (LS) plays an important role in the agricultural supply chain because it encourages participants in the supply chain to share the risk and enhance the stability of the supply chain (Fu et al., 2018). Under LS, the farmer converts their land use rights into company shares, so that the bioenergy producer obtains the land use rights. The bioenergy producer then hires the farmer as an employee to take charge of the production of biomass feedstock. After the sale of bioenergy, the bioenergy producer will share part of the sales revenue with the farmer. Unlike the traditional revenue-sharing contract, the farmer is a shareholder and joins the bioenergy producer as a worker. LS can not only improve the efficiency of labor distribution and land use efficiency, but also increase the income of farmers (Hoken, 2012; Xie et al., 2017).

The prevalence of CF and LS raises several research questions: (1) What is the difference between the optimal planting acreage and biomass feedstock quality under different cooperation modes? (2) Given China's agricultural cooperation modes face a high risk of default in practice, under what conditions can the farmer and the bioenergy producer achieve a win-win situation so as to ensure a stable supply of biomass feedstock? (3) In order to promote the development of the bioenergy supply chain, the government will implement subsidies to biomass feedstock growers. Therefore, what is the impact of the government subsidy on the above issues?

To address these questions, we consider a two-level supply chain consisting of one farmer and one bioenergy producer without government subsidy. The biomass feedstock yield is uncertain due to climate and for other reasons. We assume the farmer and the bioenergy producer are risk-neutral profit maximizers. We analyze the optimal cooperation mode as a Stackberg game. Under CF, the farmer decides the planting acreage and biomass feedstock quality, and the bioenergy producer decides the wholesale price to purchase biomass feedstock. Under LS, the bioenergy producer decides how much land needs to be rented from the farmer. The feedstock quality is determined by the farmer, depending on the energy and time the farmer is willing to spend. We then extend our model to the case where the government subsidizes the land users.

Our work contributes to the literature in three ways. First, we derive the Stackberg equilibrium of the farmer cooperating with the bioenergy producer under different cooperation modes. Cooperation modes optimized on both parameters - planting acreage and biomass feedstock quality - are analyzed for the first time. These research results not only extended the qualitative research on LS by Xie et al. (2017), but also addressed the research gap in Ye et al. (2020) and Golmohammadi et al. (2019), namely the quality of biomass feedstock. For the biomass feedstock quality, the optimal quality under LS is larger than under CF when both the dividend proportion and the marginal value of quality are large enough. For the biomass feedstock quantity, the market size plays a significant role in promoting cassava planting acreage under LS. When the market size is so large that it exceeds the threshold, the optimal planting acreage under LS is larger than under CF. When the bioenergy market size is not very large, whether the farmer under LS can obtain a higher optimal planting acreage depends on the marginal value of the biomass feedstock quality.

Second, we not only discuss the mode under which channel members can obtain more benefits, which is similar to the research of Hsu et al. (2019), but also analyze how channel members can achieve a win-win situation. A cooperation mode allowing the farmer to make higher profits does not necessarily give the bioenergy producer a satisfactory profit. For example, the farmer obtains higher profits under CF, but the bioenergy producer is better off under LS. At this time, it is difficult for the farmer and the bioenergy producer to cooperate, resulting in an unstable supply of biomass feedstock. We show the cases in which the farmer can obtain more benefits and the participants in the cooperation model can achieve a win-win situation. When both the farmer and the bioenergy producer can achieve higher profits in a unified cooperation mode to achieve a win-win situation, the breakdown of cooperation will not occur. We find that, if the basic salary is relatively large, the farmer and the bioenergy producer can achieve a win-win situation under LS with a large market size, thereby enhancing the stability of the bioenergy supply chain.

Third, we explain the impact of government subsidy, as an exogenous parameter, on the farmer and the bioenergy producer, which is similar to the research of Peng et al. (2019). However, the government subsidizes every unit of farmland to encourage land users to expand production in our paper, while Peng et al. (2019) only considered the subsidy for the farmer. We find that excessive government subsidy may lead to overproduction of biomass feedstock, which may cause the cooperation mode to fail. We find that when the basic salary and government subsidy are relatively low (high), the farmer and the bioenergy producer can achieve a win-win situation under CF (LS). In addition, if the per unit farmland yield is low, both the farmer and the bioenergy producer can obtain more profits under LS. If the yield per unit of planting acreage is high, the farmer and the bioenergy producer under CF can achieve a win-win situation when government subsidy is low.

The remainder of this paper is organized as follows. In section 2, we review the relevant literature. In section 3, we describe the problem definition and the assumptions. We analyze the decision-making behavior of the farmer and the bioenergy producer under different cooperation modes in section 4. Section 5 studies the impact of government subsidy on different cooperation modes. Section 6 provides management implications. Conclusions are presented in section 7 along with future research directions. All proofs are relegated to the appendix.

2. Literature review

Biomass feedstock such as corn, sugar cane, and cassava that are used as raw materials for biomass energy are easily affected by severe weather events such as typhoons and blizzards. Therefore, our work is closely related to studies of agricultural supply chain management under uncertain supply. Kazaz (2004) investigated the impact of yield-dependent trading costs on pricing and production planning with random yield and demand. Furthermore, Tan et al. (2012) believed that the uncertainty of agricultural product supply is due to the uncertainty of maturity time, delivery time, and crop yield, and a set of production plans was proposed to mitigate risk. Considering both price and quantity uncertainty in biofuel feedstock crop supply, Zheng et al. (2012) analyzed the development trend of the biofuel industry in Washington. Golmohammadi et al. (2019) studied a farmer's production planning, pricing and capacity planning issues under supply and demand uncertainties, and extended the production planning model from single-period cases to multi-period cases. Qian (2021) proposed a multi-period model including the uncertainty of yield, spot market price and share price to study the optimal production capacity and equity investment strategy of a cash-constrained farmer. However, this stream of literature does not consider the impact of biomass feedstock quality on market demand. In practice, farmers will decide how much time and effort they will devote to cultivating crops in order to obtain high-quality biomass feedstock. In our study, the bioenergy based on high-quality biomass feedstock can be sold at a higher price in the market and the bioenergy producer is also willing to purchase high-quality biomass feedstock produced by farmers at a higher price.

Another related literature stream relates to supply chain contracts. Some scholars, from the perspective of empirical research, believe that if the participation in the contract is closely related to the two parties and has a solid foundation for cooperation, CF will be fulfilled smoothly (Sartorius et al., 2007; Huang et al., 2018). Many scholars have studied the contract coordination problem of CF, and have proposed the rebate contract, cost sharing contract and revenue sharing contract, and confirmed that these contract mechanisms can increase farmers' profits from CF (He et al., 2008; Chen et al., 2010). Recently, Anderson et al. (2019) investigated a tree level agricultural supply chain consisting of suppliers, growers, and buyers and showed a new double discount contract can help growers avoid planting risks. Hsu et al. (2019) analyzed a new farming contract in which the smallholder farmers raise their dairy animals during the maturing stage and then the enterprise raises them during the milk production period. Fan et al. (2019) studied the "protection price + subsidy" contract and "buyback + revenue sharing" contract which are applied to the problem of insufficient raw material supply. Cao et al. (2020) designed a cost-sharing contract and a buyback contract to coordinate the greening efforts in the agri-food supply chain. Assa et al. (2021) found that introducing price index insurance into agricultural contracts can effectively increase the possibility of agricultural supply chain investment, especially in developing countries that lack agricultural investment. Kang et al. (2021) proposed a corporate social responsibility cost-sharing joint revenue-sharing contract to increase the profits of all participants in the agricultural supply chain. Liu et al. (2021) designed an incentive contract with transfer payments to promote the e-retailer to share information with the fresh product supplier. In contrast to the foregoing works, we compare two typical contracts, namely CF and LS, and compare the decision-making behavior choices of channel members. In addition, we further study the win-win solutions for channel members to improve the reliability of the bioenergy supply chain.

Biomass feedstock yield is uncertain and the government often implements subsidy schemes to reduce planting risks. Therefore, the studies related to production planning with government subsidy in the context of agribusiness are also relevant to our research. Wiedenmann et al. (2015) found that the government plays an important role in agricultural production planning. Different agricultural subsidy policies will have a great impact on agricultural production. Demirdogen et al. (2016) investigated the effects of different policies on agricultural planting, using farm-level data from Turkey, and found that input support policies have a stronger effect on farmers' land allocation decisions compared with output support policies. Akkaya et al. (2016) investigated the effectiveness of three types of intervention - price support, cost support, and yield enhancement efforts - as well as different policy implementation methods. In recent research, Alizamir et al. (2019) examined two subsidy programs for farmers: the Price Loss Coverage program and the Agriculture Risk Coverage program. They found that the subsidy program may cause farmers to reduce production. Peng et al. (2019) analyzed the impact of subsidy on farmers' income and found that the agricultural subsidy had a positive impact on farmers with a high degree of risk aversion, but a negative impact on farmers with a low degree of risk aversion. Akkaya et al. (2021) studied the impact of taxes and subsidies on the application of new agricultural technologies and social welfare. Zhou et al. (2021) found that the government's provision of agricultural information such as market prices and farming techniques to farmers does not always increase farmers' income. The above studies only discuss subsidy programs for farmers, while the subsidy program in our study is for the land user. We consider the situation that different participants in the bioenergy supply chain receive government subsidies. In particular, the farmer receives subsidies under CF, while the bioenergy producer receives subsidies under LS.

3. Model setting and notation

We assume that a basic bioenergy supply chain includes a farmer and a bioenergy producer, wherein "a farmer" does not only mean a single farmer but also a group of farmers (Yu et al., 2019). The farmer under CF needs to decide how much acreage to plant. For ease of exposition, we use the planting acreage, q, as the measurement of this quantity decision. In the process of planting agricultural products, there are many kinds of cost, such as the purchase of seeds, fertilizers, etc. In this study, we consider a two-dimensional cost structure. First, there is a baseline cost to plant cassava and harvest cassava at the basic quality standard. This cost follows a quadratic function 12cq2. The quadratic cost function captures the increasing marginal cost of acquiring land and acts as a soft capacity constraint, as widely adopted in agricultural models (Alizamir et al., 2019; Hsu et al., 2019) and supported by anecdotal evidence. For example, the estimated total cost curves in the U.S. corn belt have provided evidence to support this assumption (Peterson, 1997). An article in Businessweek (Bjerga and Wilson, 2016) reported that factors such as higher borrowing costs make it more difficult for farmers to raise funds to expand the scale of planting. Second, the farmer can choose to improve the quality of cassava by refining the planting process. In rural areas of developing countries, due to backward production means, improving the quality of crops mainly depends on the time and energy farmers are willing to spend. For example, farmers spend more time on weeding and pest control in the field. We use θ to denote the quality level, and the costs of investing in quality improvement follow $\frac{1}{2}k\theta^2$ for each unit of planting acreage. Similar cost functions have been commonly adopted in prior literature (Mu et al., 2016; Hsu et al., 2019).

The amount of cassava harvested at the end of the growing season depends on the farm yield, which is influenced by weather conditions and other unpredictable factors throughout the season. Let random variable u represent the yield per unit area, and we denote the mean and standard deviation of the yield distribution by μ and σ, respectively. Under CF, the bioenergy producer commits to purchasing agricultural products produced by the farmer. In practice, the company can use the standard schemes to test the agricultural products' quality (Mu et al., 2016; Hsu et al., 2019). Following prior literature, we use $w + \theta$ to indicate the price of the bioenergy producer's purchase of cassava where w is the wholesale price when the biomass feedstock quality is at its basic level. Moreover, we assume that the price renegotiation case does not exist in this setting (Plambeck et al., 2007; Niu et al., 2016).

Without loss of generality, we don't consider processing loss (Ye et al., 2020). The bioenergy price depends on its own quantity and quality through the following linear inverse demand curve: $r = a - bqu + e\theta$ where $a\ (> w_0)$ denotes the exogenous market size for the biomass feedstock, b represents the sensitivity of market price to changes in feedstock supply, and e is the marginal value of quality. We assume $e \geq 1$ so that it is beneficial to improve quality given that the wholesale price of the biomass feedstock is at $w + \theta$. Similar assumptions can be found in previous literature (Mu et al., 2016; Hsu et al., 2019).

Under LS, the bioenergy producer leases land from the farmer for production. Therefore, the bioenergy producer needs to determine the planting acreage q and bear the cost of planting $\frac{1}{2}cq^2$. At the same time, the bioenergy producer will hire the farmer to produce biomass feedstock and provide a basic salary H during a production cycle. The basic salary can improve the life of the farmer after losing the farmland and is generally linked to local workers' salaries. Accordingly, the farmer as a worker, bears the cost of quality improvement $\frac{1}{2}k\theta^2$ per unit acreage. The farmer uses the land as an asset for shares in the bioenergy producer.

Therefore, the bioenergy producer will share part of the sales income as dividends to the farmer, which can be regarded as the land rent given to the farmer by the bioenergy producer. We use λ $(0 < \lambda < 1)$ to represent the dividend proportion so that the sales dividends obtained by farmers are λrqu. Similar revenue-sharing settings have been adopted by literature in the operations management and marketing fields (Niu et al., 2016; Fu et al., 2018). We summarize the parameters in Table 1.

The subscripts '*CF*', '*LS*', '*s-CF*' and '*s-LS*' stand for contract farming, land as shares, contract farming with government subsidy and land as shares with government subsidy, respectively. We use superscript '*F*' to label the farmer and '*C*' the bioenergy producer. We add superscript '*' to the corresponding variables to represent their optimal values.

4. Analysis

In this section, we first present the results obtained from CF and then we formulate LS as well as derive the corresponding performance measures.

4.1. Contract farming

Facing the bioenergy producer's wholesale price $w+\theta$, a risk-neutral farmer needs to make a decision on quality and quantity. In this case, the farmer's expected profit function is as follows:

$$\pi^F_{CF}(q,\theta) = (w+\theta)q\mu - \frac{1}{2}k\theta^2 q - \frac{1}{2}cq^2 \tag{1}$$

Lemma 1. *The optimal planting acreage and quality of the farmer under contract farming are* $q^*_{CF} = \frac{w\mu+\mu^2/2k}{c}$ *and* $\theta^*_{CF} = \frac{\mu}{k}$.

We can find that the optimal quantity q^*_{CF} and quality θ^*_{CF} are reduced as the cost c and k increases. This is consistent with the reality. With higher planting cost, the farmer will choose to reduce the scale of biomass feedstock to avoid risks. Because w is the wholesale price when the bioenergy feedstock' quality is at its basic level, it has no effect on θ_{CF}.

After purchasing biomass feedstock, the bioenergy producer processes it for sale. Therefore, the bioenergy producer's expected income can be expressed as

$$\pi^C_{CF}(w) = E[(a-bqu+e\theta)qu - (w+\theta)qu] \tag{2}$$

Equation (2) can be simplified to the following form:

$$\pi^C_{CF}(w) = (a+e\theta)q\mu - bq^2\gamma - (w+\theta)q\mu \tag{3}$$

where $\gamma = E(u^2) = \mu^2 + \sigma^2$. The bioenergy producer and the farmer conduct a Stackberg game. It's easy to find that the bioenergy producer's expected income function is the concave function of contract price w. Therefore, the optimal contract wholesale price is

$$w^*_{CF} = \frac{2ack - 3c\mu + 2ce\mu - 2b\mu\gamma}{4k(c+b\gamma)} \tag{4}$$

According to equation (4) we find that if $a < a_0 = \frac{3c\mu+2b\mu\gamma-2ce\mu}{2ck}$, $w < 0$. Therefore, we assume that $a > a_0$. This assumption is in line with reality. Only when the market size is large enough, will the bioenergy producer reach a cooperative relationship with the farmer. Moreover, from equation (4) the optimal planting acreage of the farmer under CF is $q^*_{CF} = \frac{\mu(2ak+(2e-1)\mu)}{4k(c+b\gamma)}$. Obviously, both the bioenergy market size a and the marginal value of the quality e can increase the planting scale of feedstock, thereby ensuring the supply of bioenergy.

4.2. Land as shares

Under this cooperation mode, the farmer takes the land as an asset to the bioenergy producer and receives dividends λrqu. At the same time, the farmer is often hired by the bioenergy producer as an employee to participate in planting activities. Therefore, as an employee, the farmer needs to invest time and energy $\frac{1}{2}k\theta^2$ in planting to improve the biomass feedstock quality. In addition, the farmer will also receive a basic salary H. The farmer's expected income can be expressed as

$$\pi^F_{LS}(\theta) = E\left[\lambda(a-bqu+e\theta)qu - \frac{1}{2}k\theta^2 q + H\right] \tag{5}$$

It is easy to find that the optimal quality of the farmer is $\theta^*_{LS} = \frac{\lambda e\mu}{k}$. The higher the dividend proportion λ is, the more incentive the farmer will have to improve the biomass feedstock quality.

For the bioenergy producer under LS, it needs to share part of the income λrqu with the farmer and give the farmer a basic salary H. In order to get the most sales revenue, the bioenergy producer needs to decide how much farmland to lease to the farmer. Therefore, the bioenergy producer's expected income can be expressed as

$$\pi^C_{LS}(q) = E\left[(1-\lambda)(a-bqu+e\theta)q\mu - \frac{1}{2}cq^2 - H\right] \tag{6}$$

Equation (6) can be simplified to the following form:

$$\pi^C_{LS}(q) = (1-\lambda)(a+e\theta)q\mu - (1-\lambda)bq^2\gamma - \frac{1}{2}cq^2 - H \tag{7}$$

Lemma 2. *Under land as shares, the bioenergy producer's optimal planting acreage is* $q^*_{LS} = \frac{(1-\lambda)\left(a+\frac{\lambda e^2\mu}{k}\right)\mu}{2(1-\lambda)b\gamma+c}$

The optimal planting acreage is affected by planting cost c and quality improvement cost k. Higher input costs will reduce the optimal planting acreage. In addition, the expansion of market size a and the marginal value of the quality e will stimulate the bioenergy producer to expand production. Although the smaller the dividend proportion λ, the less income the bioenergy producer needs to transfer to the farmer, the bioenergy producer with a small dividend proportion may not have more enthusiasm to expand the planting scale of biomass feedstock.

4.3. Comparison

In this subsection, we compare the performances of the two business models.

Proposition 1. *When* $\lambda e > 1$, $\theta^*_{LS} > \theta^*_{CF}$. *When* $0 < \lambda e \leq 1$, $\theta^*_{LS} \leq \theta^*_{CF}$.

From Proposition 1, we find that if the dividend proportion λ multiplied by the marginal value of quality e is larger than 1, the optimal quality under LS is larger than under CF. Otherwise, the optimal quality under LS is smaller. The following explanation may support this finding. Under the two cooperation modes, the optimal quality of biomass

Table 1
Notation.

q	The planting acreage, the farmer's decision variable under CF, the bioenergy producer's decision variable under LS
u	Random variable of the per-acre yield and $E(u) = \mu$, $D(u) = \sigma^2$
θ	The bioenergy feedstock quality, the farmer's decision variable
c	The farmer's planting cost coefficient
k	The quality improvement cost coefficient
w	Unit wholesale price, the bioenergy producer's decision variable under CF
a	The bioenergy market size
b	The bioenergy price sensitivity
e	The marginal value of quality
λ	The dividend proportion
H	The farmer's basic salary under LS

feedstock increases with the increase of the per-acre yield μ and decreases with the increase of the quality improvement cost k. However, the optimal quality under LS is also related to the dividend proportion λ and the marginal value of quality e as part of the farmer's income comes from the bioenergy producer's sales revenue dividend. Therefore, when the farmer under LS holds a relatively high dividend proportion λ or marginal value of quality e, the farmer has incentives to raise biomass feedstock quality to obtain higher dividends.

Proposition 2. *(1) When* $a > \max(a_1, a_0), q^*_{LS} > q^*_{CF}$. *(2) When* $a_0 < a < a_1$, *if* $1 < e < e_1, q^*_{LS} < q^*_{CF}$; *if* $e > e_1, q^*_{LS} > q^*_{CF}$.

From Proposition 2, we know that when the market size is so large that it exceeds the threshold (i.e., $a > \max(a_1, a_0)$), the optimal planting acreage under LS is larger than under CF. In other words, a big enough market size can more effectively stimulate the bioenergy producer under LS to plant biomass feedstock. Interestingly, when a is below the threshold (i.e., $a < a_1$), the optimal planting acreage under LS is not immediately lower than under CF. We also note that the optimal quality under LS is high given a large e. High quality cassava can help the bioenergy producer achieve greater profits. Therefore, the bioenergy producer under LS will expand its planting scale to produce higher quality biomass feedstock when the marginal value of quality e is large enough to exceed the threshold level (i.e., $e > e_1$). Apparently, the bioenergy producer lacks the incentive to expand production under LS when e is low, and then the optimal planting acreage under CF is higher. In other words, for the bioenergy supply chain, when the bioenergy market size is large, LS can make the supply of biomass feedstock more sufficient, while when the bioenergy market size is small, we need to decide which is the best mode to promote the supply of biomass feedstock according to the marginal value of quality of biomass feedstock.

Proposition 3. (1) *If* $0 < \lambda < \lambda_1$, *there are thresholds* H_1, *if* $0 < H < H_1$, $\pi^{F*}_{CF} > \pi^{F*}_{LS}$.(2) *If* $\lambda_1 < \lambda < 0.5$, *there are thresholds* $H_2 (H_2 < H_1)$, a_2, $a_3 (a_2 < a_3)$.*When* $0 < H < H_2$, *if* $a_0 < a < a_3$, $\pi^{F*}_{CF} > \pi^{F*}_{LS}$; *if* $max(a_0, a_3) < a$, $\pi^{F*}_{CF} < \pi^{F*}_{LS}$. *When* $H_2 < H < H_1$, *if* $a_0 < a < a_2$, $\pi^{F*}_{CF} < \pi^{F*}_{LS}$; *if* $a_2 < a < a_3$, $\pi^{F*}_{CF} > \pi^{F*}_{LS}$; *if* $a_3 < a$, $\pi^{F*}_{CF} < \pi^{F*}_{LS}$.*When* $H_1 < H$, $\pi^{F*}_{CF} < \pi^{F*}_{LS}$.

The conditions stated above provide insight about the performance of the farmer under the different cooperation modes. When the dividend proportion λ and the basic salary H are low enough (i.e., $\lambda < \lambda_1 H < H_1$), the bioenergy producer can only give the farmer under LS very little remuneration, so the farmer is more inclined to choose CF at this time.

With the increase of the dividend proportion λ (*i.e.*, $\lambda_1 < \lambda$), the farmer under LS will expand the production scale. When the basic salary is low enough, that is, $0 < H < H_2$, the farmer under CF will obtain higher profits when the market size a is sufficiently small, while the farmer under LS will be better off when the market size a is sufficiently large. In other words, a low salary does not necessarily lead to low income for the farmer under LS. When the market size is large enough, the farmer under LS can also obtain a higher income. When the basic salary is medium, that is $H_2 < H < H_1$, although the small market size adversely affects the farmer, the farmer under LS receives higher income dividends and basic salary, thus obtaining higher returns than the farmer under CF. In addition, when the market is sufficiently large, the farmer under LS can produce more cassava to obtain higher income. Finally, it is obvious that when the basic salary is very high (i.e., $H_1 < H$), the farmer under LS can obtain a higher income than the farmer under CF.

Proposition 4. *When the dividend proportion is sufficiently low (i.e.,* $\lambda < \lambda_1$*), there are salary thresholds* $H_3, H_4 (H_3 < H_4)$ *and the results of the bioenergy producer's revenue comparison under different modes are as follows:*

(1) *When* $0 < H < H_3$, $\pi^{C*}_{CF} < \pi^{C*}_{LS}$.

(2) *When* $H_4 < H$, *if* $a_0 < a < a_4$, $\pi^{C*}_{CF} > \pi^{C*}_{LS}$; *if* $a_4 < a$, $\pi^{C*}_{CF} < \pi^{C*}_{LS}$.

The above Proposition shows that if the dividend proportion is sufficiently low, the bioenergy producer's mode choice is related to the basic salary H and the market size a. When the bioenergy producer needs to pay a relatively small salary (i.e., $H < H_3$), the bioenergy producer under LS is better off because the bioenergy producer pays lower labor costs. However, when the salary that needs to be paid to the farmer increases (i.e., $H > H_4$), the bioenergy producer can obtain higher income by choosing LS (CF) when the wholesale price is high (low). This finding shows that even if the bioenergy producer under LS needs to bear high labor costs, as long as the market is sufficiently large, the bioenergy producer under LS can still obtain high profits.

4.4. Model calibration

In this subsection, we report the results of the numerical experiments that further explore the impacts of mode parameters on the cooperation modes. In our survey of some farms in Guangxi, the biggest cassava producing area in China, supplying more than 60% of national quantity, we found that the dividend proportion is generally between 10% and 30%, so this paper assumes that the dividend proportion λ is 15%. We also assume $u \sim N(164.25, 225)$, $a = 18, c = 70 > c_1 = 35, k = 90, e = 5, b = 0.01$. These settings ensure that we operate in the feasible region of the parameters. As shown in Fig. 1, the area with CF (LS) indicates that the performance under CF (LS) is better.

Fig. 1(a) illustrates the impact of H and a on the farmer's cooperation mode choice. If the basic salary is very small (i.e., $H < H_2$), the farmer is better off under LS only when the market size is sufficiently large. However, with a decrease in basic salary (i.e., $H_2 < H < H_1$), the farmer under LS can obtain more guaranteed income. Therefore, the farmer's income under LS is higher even if the market size is relatively small. Obviously, if the bioenergy producer under LS can give the farmer a high basic salary (i.e., $H > H_1$), the farmer will be more inclined to choose LS.

Fig. 1(b) illustrates the impact of H and a on the farmer's cooperation mode choice. We also find that with the increase in basic salary, that is, the cost of hiring the farmer under LS increases, the region with CF gets larger, which means that the bioenergy producer is increasingly inclined to choose CF. In addition, compared with the bioenergy producer under CF, the expansion of market scale can better improve the profit of the bioenergy producer in LS. Therefore, as the basic salary available to the farmer increases, only when the market size is high, will the farmer choose CF.

The cooperation mode under which the farmer can obtain higher profits is not necessarily optimal for the bioenergy producer. Furthermore, only a cooperation mode that allows all participants to obtain a sufficiently high income can ensure the stability of cooperation, thereby improving the reliability of the bioenergy supply chain. Fig. 1 (c) shows the situation in which the bioenergy producer and the farmer achieve a win-win situation. The 'non-cooperative region', that is, the blank area, indicates that the farmer and the bioenergy producer cannot achieve a win-win situation under this condition. From Fig. 1(a) and (b), we can see that the expansion of the market scale has a stronger effect on the farmer and the bioenergy producer. Therefore, when the market size is large enough, LS can achieve a win-win situation for the farmer and the bioenergy producer, and the reliability of the bioenergy supply chain is guaranteed. If the market is small, it is difficult for the farmer and the bioenergy producer to obtain a higher income from a high basic salary. Only when the basic salary is low can the participants under CF achieve a win-win situation.

5. Extension: government subsidy

To stimulate a reliable and adequate supply of biomass and bioenergy, many countries have implemented subsidy programs to encourage expansion of the biomass planting acreage (Ye et al., 2020). In this section, we consider a government subsidy which is widely used in rural China. The subsidy rewards users of agriculture land to reduce

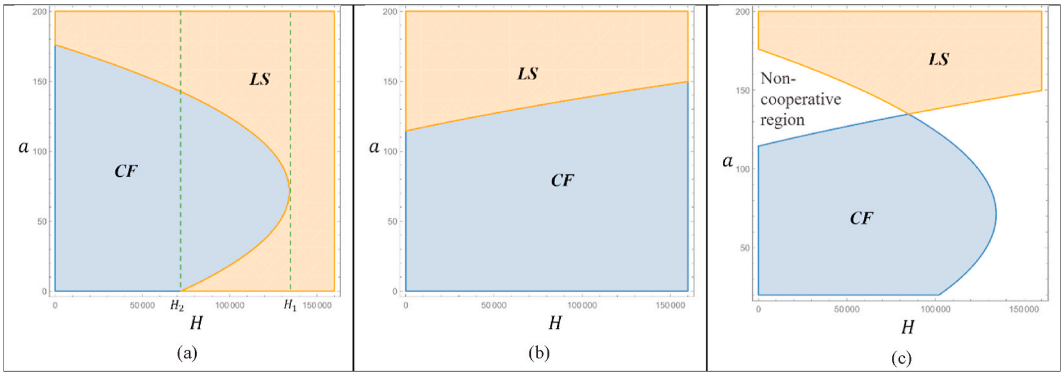

Fig. 1. The impact of the basic salary H and the market size a on competition mode selection.

planting costs. Specifically, the bioenergy producer under LS receives the government subsidy because the bioenergy producer owns the right to use the farmland. Let $s > 0$ reflect the level of subsidy. The total subsidy the farmer (bioenergy producer) under CF (LS) can get is sq.

5.1. Contract farming with government subsidy

Given the government subsidy, the farmer's expected profit can be expressed as

$$\pi^F_{s-CF}(q,\theta) = (w+\theta)q\mu - \frac{1}{2}k\theta^2 q - \frac{1}{2}cq^2 + sq \tag{8}$$

Lemma 3. *Under contract farming with government subsidy, the optimal planting acreage and quality of biomass feedstock follow* $q^*_{s-CF} = \frac{w\mu + \frac{\mu^2}{2k} + s}{c}$ *and* $\theta^*_{s-CF} = \frac{\mu}{k}$.

We can find that government subsidy aimed at encouraging the farmer to expand acreage cannot stimulate the farmer to improve cassava quality. Furthermore, the bioenergy producer's expected profit is

$$\pi^C_{s-CF}(w) = (a+e\theta)q\mu - bq^2\gamma - (w+\theta)q\mu \tag{9}$$

Combined with the content of section 4, the optimal wholesale price under CF is

$$w^*_{s-CF} = \frac{2ack - 3c\mu + 2ce\mu - 2b\mu\gamma}{4k(c+b\gamma)} - \frac{s(c+2by)}{2u(c+by)} \tag{10}$$

From equation (9), we can find that government subsidy can make the farmer willing to accept a lower contract wholesale price, because the farmer can get more government subsidy by expanding the planting acreage. In order to satisfy that the contract wholesale price is not negative, we assume that the market size is large enough: $a > a'_o = \frac{1.5c\mu + b\mu\gamma - ce\mu + s(ck+2bky)}{2ck}$.

Lemma 4. *The farmer's optimal planting acreage with government subsidy is*

$$q^*_{s-CF} = \frac{(2e-1)\mu^2 + 2k(s+a\mu)}{4k(c+b\gamma)} \tag{11}$$

Since the marginal value of quality $e > 1$, the farmer under CF will always be willing to plant to obtain income. It is worth noting that the increase in per-acre yield μ will not necessarily improve the scale of farming. This is because an excessively high per-acre yield μ may lead to an oversupply of biomass feedstock, resulting in a reduction in the bioenergy producer's profits. From equations (9) and (10), we can find that as the subsidy increase, the contract price decreases but the supply of biomass feedstock increases. In other words, with a larger planting acreage, thus, a higher government subsidy, the farmer can accept a lower contract price to produce more biomass feedstock. In the extreme case of over-subsidies, the farmer is even willing to grow feedstock at very low contract prices, which actually makes the government subsidy inefficient.

5.2. Land as shares with government subsidy

Under LS, the farmer transfers the right to use the farmland to the bioenergy producer, so the farmer does not receive the government subsidy. Therefore, the farmer's expected profit is

$$\pi^F_{s-LS}(\theta) = \lambda(a+e\theta)q\mu - \lambda bq^2\gamma - \frac{1}{2}k\theta^2 q + H \tag{12}$$

the bioenergy producer's expected profit is

$$\pi^C_{s-LS}(q) = (1-\lambda)(a+e\theta)q\mu - (1-\lambda)bq^2\gamma - \frac{1}{2}cq^2 - H + sq \tag{13}$$

Lemma 5. *Under land as shares with government subsidy, the optimal quality of the farmer is* $\theta^*_{s-LS} = \frac{\lambda e\mu}{k}$, *and the optimal planting acreage is* $q^*_{s-LS} = \frac{(1-\lambda)\left(a+\frac{\lambda e^2\mu}{k}\right)\mu + s}{2(1-\lambda)b\gamma + c}$.

Similar to contract farming, the quality of crops under LS is not affected by government subsidy, but government subsidy is conducive to expanding acreage. According to Lemma 5, the farmer's optimal profit under LS with government subsidy can be expressed as:

$$\pi^{F*}_{s-LS} = \Theta\frac{B+s}{D} - \lambda b\gamma\left(\frac{B+s}{D}\right)^2 + H \tag{14}$$

where $\Theta = \frac{2k\lambda - (\lambda e\mu)^2}{2k(1-\lambda)}, B = (1-\lambda)\left(a + \frac{\lambda e^2\mu}{k}\right)\mu, D = 2(1-\lambda)b\gamma + c$.

The bioenergy producer's optimal profit is

$$\pi^{C*}_{s-LS} = \frac{(B+s)^2}{2D} - H \tag{15}$$

From equations (14) and (15), we can find that the bioenergy producer's optimal profit can increase as government subsidy increases. However, large government subsidy may lead to a decline in the farmer's profit. We can find that large government subsidy will stimulate the bioenergy producer to expand production scale. Excessive planting acreage will increase the cost of quality improvement as well as reduce the dividend income of the farmer because of the excessive supply of biomass feedstock. This may lead to the farmer's profit under LS decreasing when government subsidy is large.

5.3. Comparison

Proposition 5. *If the market size is sufficiently large (i.e.,* $a > max(a_0', a_6)$*),* $q^*_{s-LS} > q^*_{s-CF}$*, and if the market size is sufficiently small (i.e.,* $a_0' < a < a_6$*), there is a subsidy threshold* $s_1 > 0$ *such that the comparison of planting acreages in different modes is as follows:*

(1) *when* $s > s_1, q^*_{s-LS} > q^*_{s-CF}$*;*

(2) *when* $s < s_1$*, if* $1 < e < e_3, q^*_{s-LS} < q^*_{s-CF}$*; if* $e > e_3, q^*_{s-LS} > q^*_{s-CF}$*.*

Government subsidy can have a positive impact on planting acreage under different cooperation modes. Proposition 5 shows that when the market size is sufficiently large, then the planting acreage under LS is larger. However, if the market size is sufficiently small, the comparison of biomass feedstock planting acreage is related to the subsidy amount and the marginal value of quality. When the government subsidy is large (i.e., $s > s_1$), then the bioenergy raw materials under LS are larger. Interestingly, even if the government subsidy is small (i.e., $s < s_1$), the planting acreage under CF is greater than under LS when the marginal value of quality is low enough. This proposition means that even if the farmer under CF receives low government subsidy, they will not necessarily produce less biomass feedstock than under LS.

Proposition 6. *If the salary is high enough (i.e.,* $H > H_5$*), the farmer's profit under different modes is related to the amount of subsidy: when* $0 < s < s_2, \pi^{F*}_{s-LS} > \pi^{F*}_{s-CF}$*; when* $s > s_2$*,* $\pi^{F*}_{s-LS} < \pi^{F*}_{s-CF}$*.*

Proposition 6 shows that even if the farmer can obtain high salary (i.e., $H > H_5$), when government subsidy is high enough (i.e., $s > s_2$), the farmer's profit under CF is higher than under LS. This is because the farmer under LS does not receive the government subsidy, while the farmer under CF can receive the government subsidy. Even if the farmer under LS can obtain a high salary, the farmer under CF has a larger income than under LS when the government subsidy is sufficiently high.

Proposition 7 (1). *If the salary is high enough (i.e.,* $H > H_6$*), the bioenergy producer's profit under different modes is related to the amount of subsidy: when* $0 < s < s_3, \pi^C_{s-LS} < \pi^C_{s-CF}$*; when* $s > s_3$*,* $\pi^C_{s-LS} > \pi^C_{s-CF}$*.(2) If the salary is relatively small (i.e.,* $H < H_6$*), the bioenergy producer is better off under LS when the market size is large enough (i.e.,* $a > \max(a_0, a_5)$*).*

The bioenergy producer's profit under LS decreases (increases) with the increase in basic salary (government subsidy). Therefore, if the bioenergy producer pays a high salary (i.e., $H > H_6$), the bioenergy producer's profit under LS will be lower than under CF because of lower government subsidy. If the government is willing to provide higher subsidies to promote the expansion of planting scale, then the bioenergy producer under LS will directly benefit, thereby obtaining higher income than under CF. In addition, even if the basic salary is at a relatively low level (i.e., $H < H_6$), it cannot guarantee that the bioenergy producer can obtain a higher income. At this point, we find that the bioenergy producer under LS is better off when the market size is sufficiently large.

5.4. Model calibration

We use the parameter settings in section 4.4 to verify the above Proposition. As shown in Fig. 2 (a), when the basic salary is low, the farmer is better off under CF. When the basic salary exceeds the threshold (i.e., $H > H_5$), the farmer under CF obtains greater benefits when government subsidy is high. Fig.2 (a) and Fig.2 (b) are interrelated. Fig. 2 (b) shows the same content as proposition 7 (1) & (2). As the bioenergy producer's salary costs increase, only when the government subsidy is high enough, will the bioenergy producer's profit under LS be higher than under CF. Furthermore, we also study the conditions for the farmer and the bioenergy producer to achieve a win-win situation. According to Fig. 2 (c), we can find that the bioenergy producer and the farmer under CF will achieve a win-win situation when salary and subsidy are relatively low. In addition, LS also allows participants to achieve a win-win situation when the basic salary and government subsidy are relatively large.

We continue to study the impact of yield mean μ and government subsidy s on cooperation mode selection. Fig. 3 (a) and Fig. 3 (b) respectively depict the choice of the farmer and the bioenergy producer. As shown in Fig. 3 (a), the farmer under CF can obtain higher profit even without government subsidy when the cassava yield is large enough. This is because the bioenergy producer under CF must purchase all the cassava produced by the farmer according to the contract, so the farmer under CF can obtain sufficient income through the mass production of cassava.

In addition, when the yield per unit acreage is low, the farmer under CF will get more benefits when the government subsidy is large. Similarly, when the yield per unit acreage is low, the farmer under CF has low production enthusiasm, but the bioenergy producer under LS can control the planting acreage to increase production to meet market demand. Therefore, the bioenergy producer under LS can achieve higher profit even without government subsidy when biomass feedstock yield is low. As biomass feedstock yield rises, the bioenergy producer under CF is able to obtain enough cassava to produce the bioenergy to meet market demand, resulting in higher incomes.

Fig. 3 (c) illustrates the cooperation mode with government subsidy under which the farmer and the bioenergy producer achieve a win-win situation. When the yield per unit area is small, the bioenergy producer and the farmer under LS can each obtain a larger income. When the yield per unit area is high, the cooperation contract can be fulfilled smoothly and then participating members under CF are better off. We notice that when government subsidy is quite high, it is difficult for the farmer and the bioenergy producer to achieve a win-win situation. This is because the huge subsidy causes the subsidized party to choose over-production

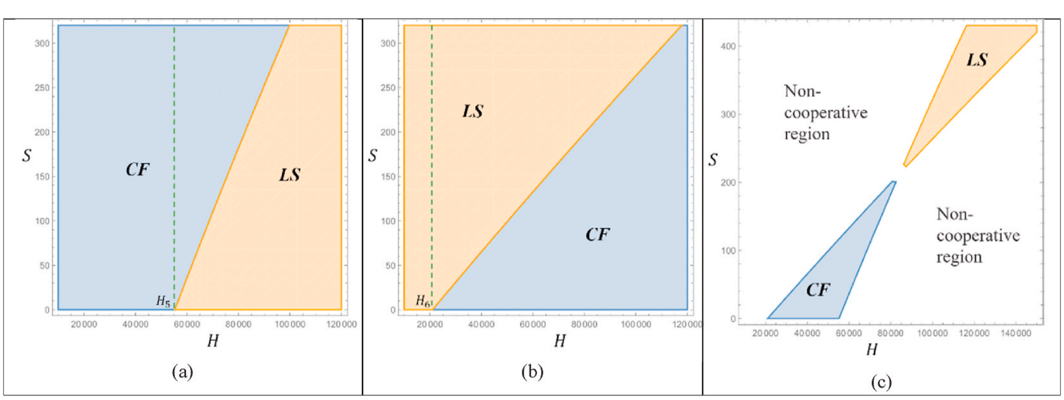

Fig. 2. The impact of the basic salary H and the government subsidy s on competition mode selection.

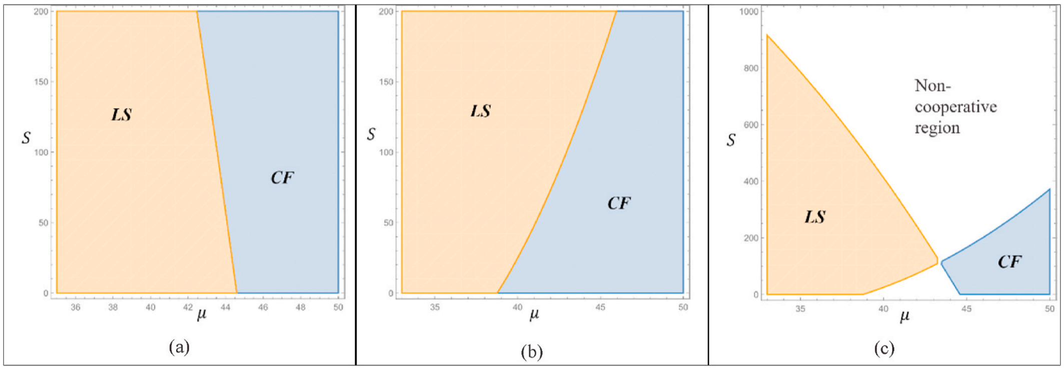

Fig. 3. The impact of the yield mean μ and the government subsidy $s$on cooperation mode selection.

which leads to the other party in the channel being exposed to high risks.

6. Discussion

In this section, we first compare the relevant literature with our research in detail to highlight our contribution. Then, we compare the results of this study with those of existing studies, and present some management implications.

Many studies have investigated the reliability of the bioenergy supply chain, but few have compared the cooperation modes between the farmer and the bioenergy producer in the bioenergy supply chain. Our research is similar to Ye et al. (2017), Fan et al. (2019) and Ye et al. (2020), in that it concerns a contract between the farmer and the bioenergy producer. The sale price of bioenergy is affected by bioenergy feedstock, and the biomass feedstock yield is uncertain. However, compared with their work, our research is different in the following aspects:

(1) In our research, we not only consider the quantity decision of the farmer, but also consider the effort to improve the quality of biomass feedstock. At the same time, the higher the biomass feedstock quality, the higher the price of bioenergy. In their research, only farmers' decision-making on the quantity is considered.
(2) We analyze two prevailing cooperation modes between the farmer and the bioenergy producer, contract farming and land as shares, and they only study contract farming.
(3) We study the government subsidy for biomass feedstock growers, and analyze under what circumstances government subsidies can enable supply chain participants to achieve a win-win situation, whereas the above-mentioned research ignores these points.

By comparing our study with their research results, we draw the following conclusions and management implications:

(1) Under CF, the increase in contract price can effectively promote the quantity of biomass feedstock, while the increase in planting costs inhibits the farmer's willingness to plant (see Lemma 1). These conclusions are consistent with those found in Fan et al. (2019) and Ye et al. (2017, 2020). In addition, we further find that the quality of biomass feedstock under CF is mainly related to the per unit yield and quality improvement cost. When the unit yield of biomass feedstock increases, the farmer will be more motivated to improve the quality of biomass feedstock. In other words, better seeds or more advanced planting techniques can not only increase the yield of biomass feedstock, but also stimulate the farmer to improve the quality of biomass feedstock, thereby obtaining higher profit.
(2) Under LS, the greater the dividend ratio, the more adequate the supply of biomass feedstock, which is consistent with Fan et al.'s (2019) results. Similar to CF, the marginal value of quality can promote the yield of biomass feedstock, and the planting cost and quality effort cost are not conducive to an increase in the scale of biomass feedstock planting (see Lemma 2).
(3) We find that the farmer under LS is more susceptible to marginal value of quality and is more willing to improve the quality of biomass feedstock when the marginal value is high (see Proposition 1). In addition, when the bioenergy market is large, the supply of biomass feedstock under LS is more abundant than under CF. If the bioenergy market is small, the bioenergy producer will produce more biomass feedstock to make bioenergy when the marginal value of quality is large, and the farmer under CF will plant more biomass feedstock when the marginal value of quality is small (see Proposition 2).
(4) A cooperation mode that allows the farmer to obtain higher income may not necessarily lead to higher income for the bioenergy producer. When all channel entities can obtain higher profits to achieve a win-win situation, the bioenergy supply chain is more reliable. We find that when the bioenergy market is large, all channel entities under LS can achieve a win-win situation, so that the bioenergy supply chain is more reliable. If the bioenergy market is small, the supply chain under CF is more reliable when the basic salary is low (see Fig. 1).
(5) If the government subsidy is high, the farmer may be willing to accept extremely low contract prices in order to obtain the high subsidy, which will lead to excessive production of biomass feedstock (see Lemma 4). This finding is consistent with that of Ye et al. (2020). We also find that if the government subsidy is high, the supply of biomass feedstock under LS is higher than under CF. If the government can only provide a lower subsidy, the farmer under CF can produce more biomass feedstock when the marginal value of quality is low (see Proposition 5).
(6) If the government subsidy is relatively low, all bioenergy supply chain members, with the low basic salary, can achieve a win-win situation under CF. If the government subsidy is relatively high, all bioenergy supply chain members, with the high basic salary, can choose LS mode to achieve a win-win situation (see Fig. 2). In other words, the government can decide which production mode to subsidize according to the amount of its own subsidy budget, thereby improving the reliability of the bioenergy supply chain.

In addition, we also draw other useful conclusions. Fig. 3 shows that channel entities with low per unit yield can choose LS mode to achieve a win-win situation. For biomass feedstock with higher per unit yield, channel entities under CF can achieve a win-win situation and the reliability of the bioenergy supply chain is very strong. However, it should be noted that the government subsidy is not as large as possible.

An Excessive government subsidy may prevent supply chain members from achieving a win-win situation.

7. Conclusions and future research

Resource shortages, energy crises and environmental deterioration have become serious global economic and social problems. Bioenergy has attracted the attention of governments all over the world because it is renewable and relatively clean. The success of the bioenergy industry is inseparable from a reliable supply of biomass feedstock. Therefore, in this study, we examine two cooperation modes in the bioenergy supply chain, namely contract farming (CF) and land as shares (LS). Under CF, the bioenergy producer purchases biomass feedstock produced by the farmer according to contracts during the ripening season. Under LS, the farmer transfers the land use rights to the bioenergy producer and benefits from the bioenergy producer's income dividends. We focus on the biomass feedstock planting acreage, the biomass feedstock quality and the profit of supply chain participants in order to examine the setting in which profit can be optimized.

We first discuss the decision-making behavior of the bioenergy producer and the farmer under different cooperation modes without the government subsidy. We find that when the market size is large enough or the marginal value is high enough, the biomass feedstock planting acreage under LS is always larger. In other words, as the government pays more and more attention to bioenergy and the market demand for bioenergy continues to rise, the LS will be more suitable for promotion than CF to produce sufficient biomass feedstock. In addition, if the farmer under LS has a high dividend ratio or marginal value of quality, then the quality of bioenergy feedstock under LS will be higher than that under CF. We also analyze how the farmer and the bioenergy producer choose cooperation modes to maximize their income at different salary levels. The participants in the cooperation mode sometimes choose not to cooperate because they can only make relatively low profits from the mode. Therefore, we study the cooperation mode choice of channel members, and find that when the bioenergy market size is very high, the channel members under LS can get higher income, thus improving the reliability of the bioenergy supply chain. When the market size is low, if the basic salary is relatively high, the channel members can't achieve a win-win situation, and it is difficult to guarantee the sufficient supply of biomass feedstock. This result reveals that the high basic salary sometimes does not necessarily have a positive impact on the reliability of the bioenergy supply chain.

We extend our model to the case where the government subsidizes the land users. The farmer's profit under CF and the bioenergy producer's profit under LS increase with the increase of government subsidy. If the market size is sufficiently small, the planting scale of bioenergy feedstock under LS is relatively large when the government subsidy is large. If both the market size and government subsidy are sufficiently low, the feedstock's planting scale is related to the marginal value of quality. At this time, the planting scale under LS will be smaller than that under CF when the marginal value of quality is relatively low. We find that the biomass feedstock quality is mainly related to the dividend ratio and the marginal value of quality, and the government subsidy can't directly promote the farmer to improve the feedstock quality.

We also observe that if the bioenergy producer can only provide a low salary, the farmer and bioenergy producer can achieve a win-win situation under CF when government subsidy is low. If the farmer can receive a higher salary, then channel members under LS can achieve a win-win situation when government subsidy is high. These results can help the government to promote different cooperation modes based on the subsidy budget to improve the reliability of the bioenergy supply chain. Furthermore, if the government subsidy is low, LS can create a win-win situation when the yield mean is low; and all members under CF can achieve a win-win situation when the yield mean is high. In fact, the biomass feedstock yield is largely affected by uncertain factors such as weather, which reduces the reference value of this conclusion to the government. However, the government can make full use of modern information technology such as big data technology to accurately predict the biomass feedstock yield, so as to rationally arrange the government subsidy to improve the reliability of the bioenergy supply chain.

Compared with other modeling of bioenergy supply chain, our model emphasizes a win-win situation among channel members and the government subsidy for land users. In our study, LS was analyzed quantitatively and compared with CF for the first time, which has enriched the research on the cooperation modes of bioenergy supply chain. Our analysis provides better understanding for the practitioners on the bioenergy supply chain under different cooperation modes, helping them to obtain higher returns. Furthermore, the farmer and the bioenergy producer can determine the appropriate cooperation mode according to the bioenergy market size and basic salary to achieve a win-win situation. Our study also provides some reference for the government on understanding how the farmland subsidy will affect the supply chain. The government can promote the reliability of the bioenergy supply chain by implementing a suitable subsidy framework. However, an excessive subsidy may have a negative impact on the reliability of the bioenergy supply chain.

There are a number of potential research directions to extend our work. First, we assume that only one farmer and one bioenergy producer cooperate in the cooperation mode. But in reality, there is often cooperation between multiple farmers and the bioenergy producer. However, it should be noted that when researching multiple homogeneous farmers and the bioenergy producer, the results are similar to those of this paper. It would be more meaningful to analyze multiple heterogeneous farmers because there is a competitive relationship between them and they face different planting costs. Second, the government can take a role in supply chain gaming. It will be a meaningful direction to set the government subsidy as an endogenous parameter and discuss the impact of government decision-making on other channel members.

CRediT authorship contribution statement

Zigong Cai: Methodology, Writing – original draft, preparation. **Fei Ye:** Supervision. **Zefei Xie:** Validation. **Li Zhang:** Writing – review & editing. **Ting Cui:** Writing – original draft, Writing-the second round of revised drafts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Proof of Lemma 1

The farmer's expected profit function under CF is expressed as:

$$\pi_{CF}^{F}(q,\theta)=(w+\theta)q\mu-\frac{1}{2}k\theta^2q-\frac{1}{2}cq^2$$

We find that:

$$\frac{\partial\pi_{CF}^{F}}{\partial q}=(w+\theta)\mu-\frac{1}{2}k\theta^2-cq,\frac{\partial^2\pi_{CF}^{F}}{\partial q\partial\theta}=\mu-k\theta,\frac{\partial^2\pi_{CF}^{F}}{\partial^2 q}=-c<0;$$

$$\frac{\partial\pi_{CF}^{F}}{\partial\theta}=q\mu-k\theta q,\ \frac{\partial^2\pi_{CF}^{F}}{\partial^2\theta}=-kq<0$$

Let $\frac{\partial\pi_{CF}^{F}}{\partial q}==0$, $\frac{\partial\pi_{CF}^{F}}{\partial\theta}=0$ and we can get the station point $M_0\left(\frac{w\mu+\frac{\mu^2}{2k}}{c},\ \frac{\mu}{k}\right)$. In this point,

$$\frac{\partial^2\pi_{CF}^{F}}{\partial^2 q}\times\frac{\partial^2\pi_{CF}^{F}}{\partial^2\theta}-\frac{\partial^2\pi_{CF}^{F}}{\partial q\partial\theta}\times\frac{\partial^2\pi_{CF}^{F}}{\partial q\partial\theta}=ckq-(\mu-k\theta)^2=w\mu k+\frac{\mu^2}{2}>0$$

According to the definition of the Hessian matrix, it is easy proved that the function π_{CF}^{F} is the maximum at point M_0. Therefore, the optimal planting acreage and quality under CF are $q_{CF}^{*}=\frac{w\mu+\mu^2/2k}{c}$ *and* $\theta_{CF}^{*}=\frac{\mu}{k}$.

Proof of equation (4)

The bioenergy producer's expected income is

$$\pi_{CF}^{C}(w)=(a+e\theta)q\mu-bq^2\gamma-(w+\theta)q\mu$$

Substitute $q=\frac{w\mu+\mu^2/2k}{c},\theta=\frac{\mu}{k}$ into the above formula, the bioenergy producer's expected income can be expressed as

$$\pi_{CF}^{C}(w)=\frac{u^2(u+2kw)(2c(ak-u+eu-kw)-b(u+2kw)y)}{4c^2k^2}$$

$\frac{\partial\pi_{CF}^{C}}{\partial w}=\frac{u^2(c(2ak+(-3+2e)u-4kw)-2b(u+2kw)y)}{2c^2k}$, $\frac{\partial^2\pi_{CF}^{F}}{\partial^2 q}=-\frac{2u^2(c+by)}{c^2}<0$. There the function: $\pi_{CF}^{C}(w)$ is a concave function for w. Let $\frac{\partial\pi_{CF}^{C}}{\partial w}=0$, we find that $w=\frac{2ack-3c\mu+2ce\mu-2b\mu\gamma}{4k(c+b\gamma)}$.

Proof of Proposition 2

The difference between the optimal planting acreage under CF and LS is expressed as:

$$q_{LS}^{*}-q_{CF}^{*}=\frac{\mu\left(g_{q1}e^2-g_{q2}e+g_{q3}\right)}{4k(c+by)(c+2by(1-\lambda))}$$

where $g_{q1}=(4c\mu(1-\lambda)\lambda+4b\mu y(1-\lambda)\lambda)>0$, $g_{q2}=(2c\mu+4b\mu y(1-\lambda))>0$, $g_{q3}=c\mu+2b\mu y(1-\lambda)+2ack(1-2\lambda)>0$.

We define $\Delta^q=g_{q1}e^2-g_{q2}e+g_{q3}$, $a_1=\frac{u(2bcy(1-\lambda)^2+2b^2y^2(1-\lambda)^2+c^2(0.5-\lambda))}{4ck(c+by)\lambda(1-\lambda)}$.

(1) If $a>a_1$, that is $\Delta_0=(-g_{q2})^2-4g_{q1}g_{q3}<0$, it is easy to find that $q_{LS}^{*}>q_{CF}^{*}$.

(2) If $a<a_1$, we notice that $\Delta_0>0$. We notice that Δ^q is a concave function for e and we can get two solutions to the function where $e_1^{'}=\frac{-g_2-\sqrt{\Delta_0}}{2g_1}$ and $e_1=\frac{-g_2+\sqrt{\Delta_0}}{2g_1}$. However, $e_1^{'}<0$and $e_1>1$. Therefore, when$1<e<e_1,\Delta^q<0$; when $e>e_1,\Delta^q>0$.

Proof of Proposition 3

The difference between the optimal farmer's profit under CF and LS is expressed as:

$$\Delta^F=\pi_{CF}^{F*}-\pi_{LS}^{F*}=m_1\left(g_{F1}a^2+g_{F2}a+g_{F3}\right)-H$$

where $m_1=\frac{\mu^2}{c+by)(c+by)(c+by)^2(c+by2(1-\lambda))^2}$, $g_{F1}=k^2(-b^3y^3(1-\lambda)^2\lambda+g_{F11}+g_{F12}+g_{F13})$, $g_{F11}=c^3(0.125-(1-\lambda)\lambda)$, $g_{F12}=b^2cy^2(0.5+\lambda((5.5-2\lambda)\lambda-4)$,

$g_{F13}=bc^2y(0.5+\lambda((4-\lambda)\lambda-3.5))$, $g_{F2}=(-b^3e^2y^3(1-\lambda)^2\lambda^2+g_{F21}+g_{F22}+g_{F23})$, $g_{F21}=b^2cy^2(-0.5(1-\lambda)^2+e(1-\lambda)^2+e^2\lambda^2(-3.5+(5.5-2\lambda)\lambda))$,

$g_{F22}=0.125c^3(\pi-1+e(2+12e\lambda^2(\lambda-1)))$, $g_{F23}=bc^2y(0.5(\lambda-1)+e(1+\lambda(-1+e\lambda(-4+(5-\lambda)\lambda)))$,$g_{F3}=cu^2(g31+g32+g33)$ $g_{F31}=$

$0.125b^2y^2\left((1-\lambda)^2-4e(1-\lambda)^2+4e^2(1-\lambda)^2-4e^4(1-\lambda)\lambda^3\right)$, $g_{F32}=0.03125c^2(1+e(4(-1+e)+8e^3(1-\lambda)\lambda^3))$, $g_{F33}=bcy(0.125(1-\lambda)+e(-0.5+0.5e(1-\lambda)+0.5\lambda+e^3(-1+\lambda)\lambda^3))$.

Δ^F is a quadratic function for a and we define $t_1=(8c^3+28bc^2y+32b^2cy^2+8b^3y^3)$, $t_2=(-8c^3-32bc^2y-44b^2cy^2-16b^3y^3)$, $t_3=(8bc^2y+16b^2cy^2+8b^3y^3)$, $t_4=-c^3-4bc^2y-4b^2cy^2$, $t_5=\frac{3t_1t_3-t_2^2}{3t_1^2}$, $t_6=\frac{27t_1^2t_4-9t_1t_2t_3+2t_2^3}{27t_1^3}$, $\lambda_1=\sqrt[3]{-\frac{t_6}{2}+\sqrt{\left(\frac{t_6}{2}\right)^2+\left(\frac{t_4}{3}\right)^3}}+\sqrt[3]{-\frac{t_6}{2}-\sqrt{\left(\frac{t_6}{2}\right)^2+\left(\frac{t_4}{3}\right)^3}}-\frac{t_2}{3t_1}$. We find that if $0<\lambda<\lambda_1$, $g_{F1}>0$, $g_{F2}<0$. Let $\Delta_1=(mg_{F2})^2-4mg_{F1}(mg_{F3}-H)<0$, that is $H<H_1=mg_{F3}-\frac{mg_{F2}^2}{4g_{F1}}$. In other words, if $0<\lambda<\lambda_1$ and $H<H_1$, $\Delta^F>0$, that is $\pi_{CF}^{F*}>\pi_{LS}^{F*}$.

If $\lambda_1<\lambda<0.5$, $g_{F1}<0$, $g_{F2}>0$ and there are two thresholds $H_1>H_2=mg_{F3}$.

(1) If $\lambda_1<\lambda<0.5$ and $H<H_2$, that is $mg_{F3}-H>0$and $\Delta_1>0$. We solve the quadratic equation $\Delta^F=0$ to get two solutions $a_2=\frac{-mg_{F2}-\sqrt{\Delta_1}}{2mg_{F1}}$, $a_3=\frac{-mg_{F2}+\sqrt{\Delta_1}}{2mg_{F1}}$ in which $a_2<0$, $a_3>0$. At this time, if $a_0<a<a_3$, $\Delta^F>0$; if $max(a_0,a_3)<a$, $\Delta^F<0$.

(2) If $\lambda_1<\lambda<0.5$ and $H_2<H<H_1$, that is $mg_{F3}-H<0$and $\Delta_1>0$. We solve the quadratic equation $\Delta^F=0$ to get two solutions $a_2=\frac{-mg_{F2}-\sqrt{\Delta_1}}{2mg_{F1}}$, $a_3=\frac{-mg_{F2}+\sqrt{\Delta_1}}{2mg_{F1}}$ in which $a_2>0$, $a_3>0$. At this time, if $a_0<a<a_2$, $\Delta^F<0$; *if* $a_2<a<a_3$, $\Delta^F>0$; *if* $a_3<a$, $\Delta^F<0$.

(3) If $\lambda_1<\lambda<0.5$ and H_1, that is $mg_{F3}-H<0$and $\Delta_1<0$. At this time, $\Delta^F<0$.

Proof of Proposition 4

The difference between the optimal farmer's profit under CF and LS is expressed as:

$$\Delta^C=\pi_{CF}^{C*}-\pi_{LS}^{C*}=m_2\left(g_{C1}a^2+g_{C2}a+g_{C3}\right)+H$$

where $m_2=\frac{\mu^2}{k^2(c+by)(c+by2(1-\lambda))^2}$, $g_{C1}=(b^2y^2(1-\lambda)^2\lambda+c^2(-0.25+(1-0.5\lambda)\lambda)+g_{C1})$, $g_{C11}=bcy(-0.5+\lambda(3.+\lambda(-3.5+\lambda)))$, $g_{C2}=(-b^3e^2y^3(1-\lambda)^2\lambda^2+g_{C21}+g_{C22}+g_{C23})$, $g_{C21}=b^2cy^2(-0.5(1-\lambda)^2+e(1-\lambda)^2+e^2\lambda^2-3.5+(5.5-2\lambda)\lambda))$, $g_{C22}=c^3(-0.125+e(0.25-1.5e\lambda^2(1-\lambda)))$, $g_{C23}=bc^2y(-0.5+0.5\lambda+e(1+\lambda(-1+e\lambda(-4+(5-\lambda)\lambda))))$, $g_{C3}=cu^2(b^2y^2g_{C31}+g_{C32}+g_{C33})$, $g_{C31}=(0.125(1-\lambda)^2-0.5e(1-\lambda)^2+0.5e^2(1-\lambda)^2-e^4(0.5(1-\lambda))\lambda^3)$, $g_{C32}=c^2(0.03125+e(0.125(e-1)-e^3(-0.5(1-\lambda))\lambda^3))$,$g_{C33}=bcy(0.125(1-\lambda)+e(-0.5+e(0.5(1-\lambda))+0.5\lambda+e^3\lambda^3(\lambda-1)))$.

Δ^C is a quadratic function for a and we find that if $0<\lambda<\lambda_1$, $g_{C1}<0$, $g_{C2}>0$.

Let $\Delta_2=(mg_{C2})^2-4mg_{C1}(mg_{C3}+H)<0$, that is $H<H_3=\frac{mg_{C2}^2}{4g_{C1}}-mg_{C3}$. Because $g_{C1}<0$, $H_3<H_4=-mg_{C3}$. If $0<\lambda<\lambda_1$ and $0<H<H_3$, that is $\Delta_2<0$ and $m_2g_{C3}+H<0$. At this time, $\Delta^C<0$. If $0<\lambda<\lambda_1$ and $H>H_4$, that is $\Delta_2>0$ and $m_2g_{C3}+H>0$. We solve the quadratic equation $\Delta^C=0$ to get two solutions $a_4=\frac{-m_2g_{C2}+\sqrt{\Delta_2}}{2m_2g_{C1}}$, $a_5=\frac{-m_2g_{C2}-\sqrt{\Delta_2}}{2m_2g_{C1}}$ in which $a_4>0$, $a_5<0$. At this time, if $a_0<a<a_4$, $\Delta^C>0$; if $a_4<a$, $\Delta^C<0$.

Proof of Proposition 5

The difference between the optimal planting acreage under CF and LS is expressed as:

$$q_{s-LS}^{*}-q_{s-CF}^{*}=\frac{g_{q1}e^2-g_{q2}e+g_{q3}+s(2ck+4bky\lambda)}{4k(c+by)(c+2by(1-\lambda))}$$

where $g_{q1}=(4cu(1-\lambda)\lambda+4buy(1-\lambda)\lambda)>0$, $g_{q2}=(2cu+4buy(1-\lambda))>0$. $g_{q3}=cu+2buy(1-\lambda)+2ack(1-2\lambda)>0$.

We define $s_1=\frac{(g_{q2})^2}{4g_{q1}(2ck+4bky\lambda)}-\frac{g_{q3}}{(2ck+4bky\lambda)}$,$\Delta^{s-q}=g_{q1}e^2-g_{q2}e+g_{q3}+s(2ck+4bky\lambda)$.

If $s>s_1$, that is $\Delta_3=(g_{q2})^2-4g_{q1}[g_{q3}+s(2ck+4bky\lambda)]\langle 0$, so $\Delta^{s-q}>0$.

If $s<s_1$, that is $\Delta_3>0$, we notice that Δ^{s-q} is a concave function for e and we can get two solutions to the function where $e_2'=\frac{-g_{q2}-\sqrt{\Delta_3}}{2g_{q1}}$ and $e_2=\frac{-g_2+\sqrt{\Delta_3}}{2g_1}$. However, $e_2'<0$and $e_2>1$. Therefore, when.$1<e<e_2,\Delta^{s-q}<0$; when $e>e_2,\Delta^{s-q}>0$.

Proof of Proposition 6

After the government implemented the subsidy, the difference between the optimal farmer's profit under CF and LS is expressed as:

$$\Delta_S^F=\pi_{s-CF}^{F*}-\pi_{s-LS}^{F*}=m_1'\left(G_{F1}s^2+G_{F2}s\right)+H_5-H$$

where $G_{F1}=(0.125c^3k^2+0.5bc^2k^2y(1+\lambda)+b^3k^2y^3\lambda+0.5b^2ck^2y^2(1.\lambda)^2)$,

$G_{F2}=G_{F21}+G_{F22}+G_{F23}+G_{F24}+G_{F25}$, $G_{F21}=b^2c(-0.5+e)k\mu^2y^2+b^2c(1-2e)k\mu^2y^2\lambda$, $G_{F22}=b^2c(-0.5+e(1+1.5e))k\mu^2y^2\lambda^2+b^3e^2k\mu^2y^3(1-\lambda)\lambda^2-2b^2ce^2k\mu^2y^2\lambda^3$, $G_{F23}=am_3=a(bc^2k^2\mu y(1-3\lambda)+c^3k^2\mu(0.25-\lambda)+b^2ck^2\mu y^2(1+(-3+\lambda)\lambda))$, $G_{F24}=c^3k\mu^2(-0.125+e(0.25-0.5e\lambda^2))$, $G_{F25}=bc^2k\mu^2y\left(-0.5+0.5\lambda+e\left(1-\lambda-e\lambda^3\right)\right)$, $H_5=m_1(g_{F1}a^2+g_{F2}a+g_{F3})$, $m_1'=\frac{m_1}{\mu^2}$.

If $H>H_5$, that is $0>H_5-H$. Because $G_{F1}>0$, we find that $\Delta_4=(m_1'G_{F2})^2-4m_1'G_{F1}(H_5-H)>0$. We solve the quadratic equation $\Delta_S^F=0$ to get two solutions $s_2'=\frac{-m_1'G_{F2}-\sqrt{\Delta_4}}{2m_1'G_{F1}}$, $s_2=\frac{-m_1'G_{F2}+\sqrt{\Delta_4}}{2m_1'G_{F1}}$ in which $s_2'<0$, $s_2>0$. In other words, If $H>H_5$, $\Delta_S^F<0$ when $0<s<s_2$, and $\Delta_S^F>0$ when $s>s_2$.

Proof of Proposition 7

After the government implemented the subsidy, the difference between the optimal bioenergy producer's profit under CF and LS is expressed as:

$$\Delta_S^C = \pi_{s-LS}^{C*} - \pi_{s-CF}^{C*} = m_2^{'}\left(G_{C1}s^2 + G_{C2}s\right) + H_6 - H$$

where $G_{C1} = \left(0.25ck^2 + 0.5bk^2y\lambda\right)$, $G_{C2} = ack^2u(0.5-\lambda) - G_{C21} - G_{C22}$, $G_{C21} = cku^2(-0.25 + e(0.5 + e\lambda(\lambda - 1)))$, $G_{C22} = bku^2y(-0.5 + 0.5\lambda + e(1 + \lambda(-1 - e + e\lambda)))$, $H_6 = m_2(g_{C1}a^2 + g_{C2}a + g_{C3})$, $m_2^{'} = \frac{m_2}{\mu^2}$.

(1) If $H > H_6$, that is $0 > H_6 - H$. Because $G_{C1} > 0$, we find that $\Delta_5 = (m_2^{'}G_{c2})^2 - 4m_2^{'}G_{C1}(H_6 - H) > 0$. We solve the quadratic equation $\Delta_S^C = 0$ to get two solutions $s_3^{'} = \frac{-m_1^{'}G_{C2} - \sqrt{\Delta_5}}{2m_2^{'}G_{C1}}$, $s_3 = \frac{-m_1^{'}G_{C2} + \sqrt{\Delta_5}}{2m_2^{'}G_{C1}}$ in which $s_3^{'} < 0$, $s_3 > 0$. In other words, If $H > H_6$, $\Delta_S^C < 0$ when $0 < s < s_3$, and $\Delta_S^C > 0$ when $s > s_3$.

(2) If $H < H_6$, that is $0 < H_6 - H$. If $a > a_7 = \frac{G_{C21} + G_{C22}}{ck^2u(0.5-\lambda)}$, that is $G_{C2} > 0$. Therefore, If $H < H_6$ and $a > \max(a_0, a_5)$, $\Delta_S^C > 0$.

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