**Modeling of China’s cassava-based bioethanol supply chain operation and coordination**

**Abstract:** As a useful alternative to petroleum-based fuel, biofuels are playing an increasingly important role due to their economic, environmental, and social benefits. Cassava is viewed as an important and highly attractive nonedible feedstock for the production of biofuels. In this paper, a game-theoretic approach is proposed to explore decision behavior within a cassava-based bioethanol supply chain under the condition of yield uncertainty. In addition, a production cost sharing contract is proposed to overcome the double marginalization effect due to competition between supply chain players. With data from China’s cassava-based bioethanol industry, the paper analyzes the effects of the farmer’s capacity, risk aversion, yield uncertainty, the conversion ratio, the bioethanol’s market price and ethanol plant’s operation cost on optimal decisions within the supply chain and its overall performance. In addition, the effectiveness of the proposed production cost sharing contract is tested, and the results show that it can enhance the supply of cassava, increase the utility of the whole supply chain and reduce the level of greenhouse gas (GHG) emissions. The implications are set out for policy makers regarding how to promote the development of the biofuel industry, to guarantee the supply of feedstock, to reduce GHG emissions and to promote rural development.

**Key words:** Cassava; Bioethanol; Supply chain; Coordination; GHG emission

1. **Introduction**

The energy crisis and environmental pollution are two major problems of the 21st century. Countries all over the world are exploring renewable sources of energy as an option for the achievement of sustainable development (Azadeh et al., 2014; Zhang et al., 2016a). This issue is particularly important in China. China is becoming the world’s largest energy consumer; it used 20.3% of global energy in 2010, and this proportion is becoming larger due to China’s expanding economy (Sharma et al., 2013). However, China has insufficient domestic energy resources (especially oil) to meet this demand. As reported by the General Administration of Customs of the People’s Republic of China, in 2015 imported oil accounted for about 60% of China’s total need. Moreover, the Chinese government promised to cut national greenhouse gas (GHG) emissions by 40-50% by 2020, relative to their 2005 levels (Liu et al., 2013).

Biofuels, produced from renewable feedstocks (e.g. agricultural residues, energy crop, wood), are viewed as one of the most utilized sources of renewable energy (Zhang et al., 2016b), and the promising alternatives to fossil fuels, especially within the transportation sector, for reasons relating to both energy security and environmental improvement (Papapostolou et al., 2011; Shabani et al., 2014; Holmgren et al., 2015). There is great interest in biofuels in China. In the past years, the China’s production for bioethanol is increasing year by year (as shown in Fig. 1), and in 2013, bioethanol accounted for 25% of China’s total consumption of gasoline and equivalent fuels (as shown in Fig. 2). In addition, the development of the biofuel industry is conducive to the promotion of rural development, which is particularly important for China, a large developing country with a high population density and a large rural population that depend upon the land for their livelihood. Hence, China has launched a large program to promote biofuel production, which is projected to reach 62 million tonnes in 2020, as shown in Fig. 3.

**Insert Figs. 1 to 3 Here**

However, China is presently producing insufficient quantities of biofuel. As shown in Fig. 3, the targeted bioethanol production in 2020 is 10 million tonnes, but production was only 2.3 million tonnes in 2015, significantly lower than the original target. Moreover, China used to rely heavily on corn to produce bioethanol, which led to an extensive food vs. fuel debate. Recently, China has announced a national bioethanol policy that promotes the use of nonedible feedstocks for bioethanol production. Cassava is viewed as an important and highly attractive bioethanol crop in China. First, it has high starch content and is therefore well suited to high-volume ethanol production (Leng et al., 2008). Second, unlike other crops, cassava can be harvested all year round and can tolerate harsh natural conditions, especially drought (Jakrawatana et al., 2015). Moreover, it can be planted on marginal lands where other crops do not grow well (Dai et al., 2006). Third, the processing of cassava into ethanol is more efficient than it is with other energy corps such as sugarcane, maize, wheat, and sweet potato, and this reduces the costs of production (Dai et al., 2005; Liu et al., 2013). Fourth, it is a non-staple food in China, and so there is no direct competition with food crops (Liu et al., 2013). The cassava-based bioethanol industry has grown rapidly in China, especially in Southern China, and is expected to triple its output over the next decade (Yao, 2011), with an associated increase in the production of cassava (Jansson et al., 2009).

Despite these advantages, many problems have been encountered in the development of the Chinese cassava-based bioethanol industry. Unlike Western countries, China implements what is termed a ‘household responsibility’ small-scale peasant economy system in agriculture. The land is owned by small-scale farmers, and cassava is mainly planted by thousands of them, scattered across the country (Wen and Zhang, 2015); cultivation is characterized by low intensity of fertilizer use and little use of mechanized planting. This leads to low yields of cassava (Liu et al., 2013) and China is suffering an undersupply of cassava. Consequently, China has been the world’s biggest net importer of cassava since the 1990s; imported cassava accounts for more than 60% of China’s total domestic need, and the figure increases each year (Li et al., 2013).

How to improve the domestic supply of cassava has become an important issue for the Chinese government. One way round this is for the large ethanol plants to cooperate with these small-scale farmers through a “contract farming scheme” to implement intensive cultivation (Yao, 2011). Such a scheme is, in theory at least, mutually beneficial for both supply chain players. On the one hand, it provides farmers with critical material inputs, financial credit, technical assistance, and the opportunity to gain market access, so as to improve the cassava yield per unit area, to increase the starch content of the cassava, and to reduce the risk of price fluctuation. On the other hand, it ensures large ethanol plants get the required cassava at a fixed price with certainty of delivery – in terms of quantities, quality, and time – without owning a farm (Melese, 2010).

In practice, however, the ethanol plant and the small-scale farmers remain separate entities, with conflicting objectives and reaching different decisions, though they cooperate in the “contract farming scheme” (Li et al., 2012). The ethanol plant holds a powerful position in the contract farming scheme. In this context, the present study uses the leader–follower Stackelberg game (von Stackelberg, 1952) to model and analyze the interactions between the ethanol plant and the farmers’ decision-making structure. The Stackelberg game is widely applied in the supply chain management field to model the problem of the supply chain players’ competitive optimization (Chiang et al., 2003; Esmaeili et al., 2009; Chen et al., 2012; Hsiao and Chen, 2014). Recently, the Stackelberg game has been used in studies of the biomass supply chain to analyze the competitive decision-making behavior for separate players (Nasiri and Zaccour, 2009; Sun et al., 2013; Wen and Zhang, 2015).

However, little attention has been paid specifically to the coordination issue in relation to the biomass supply chain (Sharma et al., 2013). To a large extent, the performance of the cassava-based bioethanol supply chain depends on the degree of coordination and integration between the ethanol plant and the farmers (Sharma et al., 2013). Research on supply chain contracts (Cachon, 2003) has provide good insights into the optimal design of coordination mechanisms for a contract farming scheme. Unfortunately, that research cannot be applied to the biomass/cassava biofuel supply chain directly, as that supply chain has some unique characteristics (Sharma et al., 2013). For example, cassava yield varies greatly with natural conditions, such as weather, pests and diseases (Kazaz, 2004; Kazaz and Webster, 2011). In addition, the small-scale cassava farmers often show risk-averse behavior as they have limited capacity and small financial reserves (Sandmo, 1971; Bijman, 2008). In light of the characteristics of the cassava-based bioethanol supply chain, this paper aims to develop a coordination contract that could improve the supply of cassava and the performance of the cassava-based bioethanol supply chain, consisting of a large ethanol plant and multiple small-scale cassava farmers.

The paper proceeds as follows. Section 2 proposes our basic assumptions and models for the decision-making behavior of the small-scale cassava farmers, the ethanol plant, and the supply chain, respectively. In addition, a production cost sharing contract is developed to improve the supply of cassava and supply chain performance. In Section 3, by way of a case study, the model is applied to China’s cassava-based bioethanol supply chain. Implications for policy makers are provided in Section 4. Finally, conclusions are summarized in Section 5.

1. **Model development and analysis**

***2.1 Problem statement***

We consider a contract farming cassava-based bioethanol supply chain consisting of a risk-neutral ethanol plant and risk-averse small-scale cassava farmers, as shown in Fig. 4. Cassava is newly cultivated by many small-scale farmers and converted to bioethanol by the ethanol plant, which then sells the bioethanol to the market. The timeline of events for the supply chain is described in Fig. 5.

**Insert Figs. 4 and 5 Here**

Before the cassava planting season, the ethanol plant and small-scale cassava farmers sign a cassava purchasing contract: the ethanol plant will purchase the total yield of cassava at a wholesale price of () from the farmers. Then the farmers determine the quantity of cassava they will plant, , under the limited capacity constraint, . Taking into account the desirable properties for tractability and marginal decreasing returns within a small-scale peasant economy, the farmers’ cassava planting cost function (including the cost of seed, fertilizers, herbicide, etc.) is assumed to be a convex increasing function, that satisfies (Nasiri and Zaccour, 2009). To ease the computational burden, we assume that all the small-scale cassava farmers are homogenous in terms of the cassava planting cost structure, capacity and risk aversion. In addition, to reflect natural conditions such as weather, pests and diseases, the cassava yield is assumed to be random, as the study in Kazaz and Webster (2011). Thus, each farmer’s yield of fresh cassava is , where the random yield rate ) is distributed on , and has a continuous probability density function, , and a cumulative distribution function, ,, .

In the harvesting season, the ethanol plant purchases all yields of cassava and processes it into bioethanol with an operation cost of ) (including the costs of labor, power, water, depreciation, etc.) and a conversion ratio of cassava to bioethanol ) (that is, one of fresh cassava can be processed to be of bioethanol, ). Then the ethanol plant sells the bioethanol at price ) to the market.

Throughout the paper, subscripts D, SC, C, F and P denote variables pertaining to the decentralized system, centralized system, coordinated system, the farmer and the ethanol plant, respectively. Accordingly, for instance, , and , respectively, denote the farmer’s quantity of cassava to be planted under decentralized system, coordinated system, and the supply chain’s quantity of cassava to be planted under centralized system. and denote the ethanol plant’s wholesale price under decentralized system and coordinated system. A summarized mathematical nomenclature is given at the end of the paper.

* 1. ***The decision model for the decentralized system***

With the problem set in the decentralized system, interactions between the ethanol plant and the farmers are modeled using the leader–follower Stackelberg game. The ethanol plant acts as a leader while the farmers act as followers. In our analysis we first solve for the farmers’ (follower’s) optimal quantity of cassava to be planted, , in response to the ethanol plant’s wholesale price decision, , and then embed this response into the ethanol plant’s (leader’s) problem to derive the optimal wholesale price, , for the fresh cassava.

1. **The farmer’s decision in the decentralized system**

Each farmer decides how much cassava he should plant to maximize his profit function in the random yield environment:

(1)

Because the farmer is risk-averse, the objective is to maximize utility rather than expected profit. Here, we adopt Conditional Value-at-Risk (CVaR) as the decision criterion to measure the risk-averse farmer’s performance. The CVaR criterion measures the average value of the profit falling below the -quantile level (Chen et al., 2009). For more details on CVaR see Rockafellar and Uryasev (2000, 2002).

According to the general definition of CVaR, the risk-averse farmer’s objective is to maximize the following utility function:

(2)

Where is the expectation operator, represents the upper limit on the profit under a certain , represents a set of real numbers, reflects the degree of risk aversion (the smaller is, the more risk-averse the farmer will be; means that the farmer is risk-neutral).

Substituting Eq. (1) into Eq. (2), we have

(3)

From Eq. (3), we can obtain the optimal value of , which satisfies . (The detail of determining is given in the electronic supplementary material)

Putting into Eq. (3), the risk-averse farmer’s utility function can be converted to

(4)

From Eq. (4), we can determine the risk-averse farmer’s optimal quantity of cassava to plant for a given ethanol plant’s wholesale price in decentralized system. This is Theorem 1.

***Theorem 1 The risk-averse farmer’s optimal quantity of cassava to plant in the decentralized system is:***

***(5)***

***Where .***

**Proof.** The detail is given in the electronic supplementary material.

1. **The ethanol plant’s decision in the decentralized system**

The ethanol plant determines the wholesale price offered to the farmers to maximize its utility:

(6)

Where is the conversion ratio of fresh cassava to bioethanol.

By substituting of Eq. (5) into Eq. (6), the ethanol plant’s utility function can be rewritten as

(7)

From Eq. (7), we can get the ethanol plant’s optimal wholesale price in the decentralized system. This is Theorem 2.

***Theorem 2 The ethanol plant’s optimal wholesale price in the decentralized system is:***

*(8)*

**Proof.** The detail is given in the electronic supplementary material.

From Theorems 1 and 2, we can model the effects of the farmer’s risk aversion on the optimal quantity of cassava to plant and wholesale price. This is Corollary 1.

***Corollary 1 In decentralized system, the risk-averse farmer’s optimal quantity of cassava to plant increases in, while the ethanol plant’s optimal wholesale price decreases in .***

**Proof.** The detail is given in the electronic supplementary material.

Corollary 1 suggests that the more risk-averse the farmer is, the smaller will be the quantity of cassava he chooses to plant. The optimal quantity determined by the risk-averse farmer is less than that of a risk-neutral farmer, which is consistent with studies on the risk-averse decision maker. Correspondingly, the ethanol plant will charge a higher wholesale price to encourage the more risk-averse farmer to increase the quantity of cassava planted.

Substituting into Eq. (5), the risk-averse farmer's optimal quantity of cassava to plant can be rewritten as

(9)

Then, the utilities of the farmer and the ethanol plant in the decentralized system are, respectively:

(10)

(11)

And the whole supply chain’s utility is:

(12)

1. **The environmental impact on greenhouse gas (GHG) emission**

Following the studies done by Ou et al. (2009) and Liu et al. (2013), we use the Life Cycle Assessment (LCA) method, a standardized methodology that has been frequently applied (Zhang et al., 2015), to analyze the environmental impact of the cassava-based bioethanol supply chain across the whole of the product life cycle, from the plantation of fresh cassava to the usage of bioethanol fuel (named E10 in China, because the fuel is ethanol added to gasoline to a concentration of 10% by volume).

Greenhouse gases (GHG) emissions are the major cause of climatic change. These emissions are mainly either direct or indirect emissions of CO2, CH4 and N2O. According to the Global Warming Potential Value (GWP), emissions of these three key GHGs can be converted into respective CO2 equivalents (CO2, e) by using the following equation (IPCC, 2001):

GHGLCA = 23 CH4, LCA + 296 N2OLCA + CO2, LCA (13)

Where GHGLCA is the whole life cycle GHG (CO2, e) emission, CH4, LCA is the direct and indirect whole life cycle CH4 emission, N2OLCA is the direct and indirect whole life cycle N2O emission, and CO2, LCA is the direct and indirect whole life cycle CO2 emission.

We use the Net GHG Reduction Value (NGRV) to evaluate the GHG emission reduction effect of bioethanol produced from cassava across its whole life cycle. NGRV is the difference between the LCA GHG emission of Conventional Gasoline (CG) and the cassava-based Ethanol Gasoline, that is:

NGRV = GHGLCA, CG – GHG LCA, biofuel  (14)

* 1. ***The decision model for a centralized system***

To set a benchmark, a centralized system decision model is considered. In practice, the ethanol plant is much more powerful than the small-scale farmers (Bijman, 2008); accordingly, in this centralized system, the ethanol plant vertically integrates the whole supply chain and determines the farmer’s quantity of cassava to plant.

Combining Eq. (1) and Eq. (6), the objective function of the centralized system is:

(15)

From Eq. (15), we can get the optimal quantity of cassava to plant in the centralized system. This is Theorem 3.

***Theorem 3 The optimal quantity of cassava to plant in the centralized system is:***

***(16)***

**Proof.** The detail is given in the electronic supplementary material.

Then the whole supply chain’s utility in this centralized system is:

(17)

Comparing Eqs. (9) and (16), as well as Eqs. (12) and (17), suggests the Corollary 2, to illustrate the comparison between the decentralized and centralized systems.

***Corollary 2 The optimal quantity of cassava to plant and the utility of the whole supply chain in decentralized system is no more than those of the centralized system, ,*** *.***Proof.** The detail is given in the electronic supplementary material.

Corollary 2 indicates that competition in the decentralized system between the ethanol plant and the small-scale farmers will lead to double marginalization of the whole supply chain, and thus a lower supply of cassava and reduced supply chain performance. To avoid this double marginalization, coordination along the supply chain (i.e. between players, ethanol plant and farmers) becomes necessary so as to increase the supply of cassava and the performance of the supply chain.

* 1. ***Coordination through the use of production cost sharing contract***

Small-scale farmers often lack the enough financial and technical resources to implement intensive cultivation. Commonly, under a contract farming scheme, the ethanol plant shares part of the production cost by providing the small-scale farmers with critical inputs (seeds and fertilizer) and technical assistance, so as to smooth the planting processes, improve the operational efficiency, and ensure the yield and quality of cassava (Melese, 2010). Here, we examine the effect of introducing a production cost sharing contract between the ethanol plant and the farmers. We assume the small-scale farmers bear a certain fraction of the total cultivation cost, (), while the remaining fraction is borne by the ethanol plant.

With the introduction of production cost sharing contract, the small-scale farmer’s profit function is

(18)

Under the CVaR criterion, the risk-averse farmer’s objective is to maximize the following utility function:

(19)

Similar to the decentralized system scenario, we can get the optimal value of using the CVaR definition, which satisfies . Accordingly, the risk-averse farmer’s utility function (19) can be converted to

(20)

From Eq. (20), we can get the farmer’s optimal quantity of cassava to plant for a given ethanol plant’s wholesale price after the introduction of the production cost sharing contract. This is Theorem 4.

***Theorem 4 The risk-averse farmer’s optimal quantity of cassava to plant with the production cost sharing contract is:***

***(21)***

***Where .***

**Proof.** The proof is similar to that for Theorem 1.

With production cost sharing contract, the ethanol plant's utility function is

(22)

From Eq. (22), we can get the ethanol plant’s optimal wholesale price after the introduction of production cost sharing contract. This is Theorem 5.

***Theorem 5 The ethanol plant’s optimal wholesale price with the production cost sharing contract is:***

*(23)*

**Proof.** The proof is similar to that of Theorem 2.

By substituting into (21), the risk-averse farmer's optimal quantity of cassava to plant under production cost sharing contract can be rewritten as

(24)

In addition, the utilities of the farmer, the ethanol plant and the whole supply chain after the introduction of production cost sharing contract are, respectively:

(25)

(26)

(27)

1. **Case study: Cassava in China**
   1. ***The production of cassava in China***

China’s production of cassava has increased every year. Fig. 6 shows the planting area and yield of cassava in China for the period 2004-2013. Four provinces of South China, Guanagxi, Guangdong, Yunnan and Hainan, together account for more than 90% of national production. However, the planting area of cassava in China is still relatively small and accounts for only 1.4% of the global total planting area of cassava in 2013. (See Fig. 7 for the global total planting area and yield of cassava.) Moreover, the yield per unit area in China, at around 16 , is relatively low in comparison with 31 in India and 22 in Thailand (Jansson et al., 2009). China’s undersupply of cassava means that it has been the world’s biggest net importer of cassava since the 1990s; imported cassava accounts for more than 60% of China’s total domestic need, and the figure increases each year (Li et al., 2013).

**Insert Figs. 6 and 7 Here**

Therefore, it is very important in China to know how to increase the total planting area and yield of cassava, so as to improve the supply of cassava to meet the increasing domestic market demand. In addition, the expansion of cassava cultivation offers great potential benefit to small-scale farmers and for agricultural development more generally; furthermore, greater use of this renewable source of energy will increase the country’s energy security and help to tackle climate change.

* 1. ***Case study specifications***

In this section, we present an empirical application of the proposed use of production cost sharing coordination contract in the contract farming cassava-based bioethanol supply chain. The key parameters are provided by averaged data from the cassava-based bioethanol industry in Guangxi province, which accounts for more than 60% of national production in China (Dai et al., 2006).

A cassava-based bioethanol supply chain consisting of an ethanol plant and homogenous small-scale cassava farmers () has the following characteristics: Cassava-based bioethanol market price ; the ethanol plant’s processing cost (including the costs of labor, power, water, depreciation, etc.); the conversion ratio of cassava to bioethanol (that is, seven of fresh cassava can be processed to be one of bioethanol); the farmer’s planting cost . In addition, to highlight the impacts of yield uncertainty, as well as the farmer’s capacity constraint and risk aversion, we perform sensitivity analyses with wide range of yield uncertainty, capacity, and degree of risk aversion. We assume the random yield rate follows a uniform distribution with , where , and ranges from to cover low to high yield uncertainty (represents low uncertainty, and represents high uncertainty) (Tsay, 2002). We assume the farmer’s capacity, , ranges from . For risk aversion, and respectively represent the risk-averse and risk-neutral farmer.

In addition, to evaluate the environmental impact of the cassava-based bioethanol supply chain, we calculate the Net GHG Reduction Value (NGRV) using Eqs. (13) and (14). In determining the value of the supply chain in terms of reducing GHG emissions, we use the data reported Yin et al. (2013) for land they classify as ‘moderately suitable’ for cassava plantation, as shown in Table 1.

**Insert Table 1 Here**

* 1. ***Results and discussions***
     1. **Effects of capacity and risk aversion on decisions and performances**

To show the effects of the farmer’s capacity and risk aversion on optimal decisions, utility and environmental impacts, we set the farmer’s capacity, , range from , let and represent the risk-averse and risk-neutral farmers, and let for a moderate level of yield uncertainty. The results are showed in Table 2 and Fig. 8.

**Insert Table 2 Here**

Fig. 8(a) indicates that where capacity is relatively small, the farmer prefers to provide as much cassava as possible, no matter what his degree of risk aversion is. As capacity becomes larger, a more risk-averse farmer prefers to provide lesser quantities of cassava , to reduce the risk due to yield uncertainty, which confirms the results of Corollary 1 and previous studies that order quantity decreases as the decision maker becomes more risk averse. Correspondingly, the ethanol plant would set a lower wholesale price for farmers with a smaller capacity, but a higher wholesale price for more risk-averse farmers and the farmers with larger capacity, to encourage them to increase the quantity of cassava planted (as shown in Fig. 8(b)). From Fig. 8(a) and Fig. 8(c) we can see that, the optimal quantity of cassava to plant and the utility of the decentralized supply chain are no more than those in the centralized one, which confirms the result of Corollary 2. From Table 1 we know the NGRV for per unit cassava-based biofuel is 104177.3 compared with that of conventional gasoline. Then we can calculate the NGRV of the proposed decentralized and centralized cassava-based biofuel supply chain, as shown in Fig. 8(d). From Fig. 8(d) we can see that the centralized contract farming supply chain can really help to achieve more GHG emission reduction compared with that of a decentralized system. In addition, the difference between these two systems will be increased for the more risk-averse the farmers and for farmers with a larger capacity (Fig. 8(a) , (c) and (d)).

**Insert Fig. 8 Here**

* + 1. **Effects of yield uncertainty and risk aversion on decisions and performances**

To reveal the effects yield uncertainty and the farmer’s risk aversion on optimal decisions and levels of performance, we set , change from 5 to 30 , and let and represent the risk-averse and risk-neutral farmers, with the results shown in Fig. 9. Compared with a risk-neutral farmer ( case), a more risk-averse farmer ( case) tends to choose to plant smaller quantities of cassava, to mitigate risk as the yield uncertainty increases (Fig. 9(a)). The ethanol plant tends to set a higher wholesale price for a more risk-averse farmer when yield uncertainty is high, to encourage the farmer to increase the quantity of cassava (Fig. 9(b)). Again, the supply chain utility and the reduction of GHG emissions in the decentralized system are no more than those in the centralized system, with the difference between the decentralized and centralized systems increasing with increasing yield uncertainty (Fig. 9(c) and (d)). Especially where the farmer is more risk-averse, and the yield uncertainty becomes very high ( for example), the quantity of cassava planted will sharply decrease (Fig. 9(a)), leading to a sharp decrease in the supply chain utility and in the reduction of GHG emissions (Fig. 9(c) and (d)), even though the ethanol plant offers a relatively high wholesale price to the farmers for fresh cassava (Fig. 9(b)).

**Insert Fig. 9 Here**

* + 1. **Effects of the conversion ratio and risk aversion on decisions and performances**

We next investigate the effects of the conversion ratio and the farmer’s degree of risk aversion on optimal decisions and levels of performance. We set ,, and and change from 0 to , as shown in Fig. 10. As expected, with the higher conversion ratio for cassava to biofuel, the ethanol plant will set a higher wholesale price (Fig. 10(b)), to encourage the farmer to increase the quantity of cassava planted (Fig. 10(a)) and, correspondingly, the utility and environmental performance of the whole supply chain can be improved (Fig. 10 (c)(d)).

**Insert Fig. 10 Here**

* + 1. **Effects of the bioethanol’s market price and ethanol plant’s operation cost on decisions and performances**

In this section, we further investigate the effects of the bioethanol’s market price and the ethanol plant’s operation cost on optimal decisions and levels of performance. We set ,. We let and change within , where and , respectively. Then, we let and represent the scenario for risk-averse and risk-neutral farmers, resepectively. The optimal decisions and performances are shown in Figs. 11 and 12.

Figs. 11 and 12 indicate that, as the optimal quantity of cassava planted is less than the farmer’s capacity level, with the increase in the bioethanol’s market price or the decrease in the ethannol plant’s operation cost , the ethanol plant tends to set a higher wholesale price (Fig. 11 (b) and Fig. 12(b)), and the farmer will consequently set a larger quantity of cassava planted (Fig. 11 (a) and Fig. 12(a)). As a result, the utility and environmental performance of the whole supply chain will be improved (Figs. 11 and 12 (c)(d)). That is, if the Chinese government tends to promote the production of bioethanol due to its economic, environmental and social benefits, it can provide a subsidy for bioethanol’s market price or for the ethanol plant directly to decrease the ethanol plant’s operation cost.

However, as the optimal quantity of cassava planted equals to the farmer’s capacity level, the quantity of cassava planted decisoin and NGRV of the cassava-based supply chain will not be affected by the change of bioethanol’s market price and ethanol plant’s operation cost any more. Under this situation, the government should not provide any more subsidy for bioethanol’s market price or for the ethanol plant, otherwise, all the benefit from the subsidy will be snatched by the ethanol plant, and does not help to encourage the production of bioethanol and reduce GHG emission.

**Insert Figs. 11 and 12 Here**

* + 1. **Analysis of the effectiveness of the production cost sharing contract**

1. ***Improved performance with the use of the production cost sharing contract***

We set the utility of each player and the reduction of GHG emission (NGRV) in the decentralized system as a baseline, and define improved performance with the use of the production cost sharing contract to be . As above, is the fraction of the production cost that is shared. Fig. 13 plots against the performance of each player ().

As indicated in Fig. 13, the use of the production cost sharing contract improves the utility of both the ethanol plant and the supply chain as a whole, as well as the reduction of GHG emission. Interestingly, the more the ethanol plant takes on the production cost (the smaller is), as well as the more risk-averse the farmer is, the larger will be the improved utility and the reduction of GHG emission of the whole supply chain (as shown in the shaded areas in Fig. 13(b), (c) and (d)). This is because the ethanol plant’s sharing of the production cost can encourage the farmers to increase the quantity of cassava planted, which in turn will increase the utility of the supply chain’s utility and improve environmental performance.

Against expectation, however, we find that sharing the costs of cassava cultivation with the ethanol plant does not necessarily improve the farmer’s utility; this which is shown in Fig. 13(a), where only the shaded areas indicate that the farmer’s utility is improved. This is because that as the ethanol plant shares some of the cost of cultivation, the farmer tends to increase the quantity of cassava planted, but then the ethanol plant sets a lower wholesale price for this larger yield, and this can actually mean a decrease in the farmer’s overall utility.

**Insert Fig. 13 Here**

1. ***Efficiency of the use of the production cost sharing contract***

In addition, to see whether the use of the production cost sharing contract can achieve perfect coordination along the supply chain, we set the utility of the centralized system as the benchmark to test the efficiency of the coordination contract, defined by . The result is shown in Fig. 14.

Fig. 14 shows that as the ethanol plant takes on more of the production cost (the smaller is), production cost sharing contract can indeed achieve perfect coordination along the supply chain, under certain condition (the 100% parts in Fig. 14). If the ethanol plant takes on too little of the production cost (the larger is), the farmer does not have enough incentive to increase the quantity of cassava planted, leading to performance loss across the supply chain as a whole. Moreover, with a higher yield uncertainty ( in Fig. 14(a)), with larger capacity on the part of the farmer ( in Fig. 14(b)), and the more risk-averse the farmer is (in Fig. 14(c)), the less able is the introduction of a production cost sharing contract to achieve perfect coordination along the supply chain.

**Insert Fig. 14 Here**

1. **Policy implications**

The findings of this study on the cassava-based bioethanol supply chain have implications for policy makers in China regarding how to enhance the supply of feedstock, and to improve the economic and environmental performance of the biofuel supply chain. ***First,*** the results suggest that the adoption of a contract farming scheme formed by a large agribusiness firm and small-scale farmers is conductive to increasing the feedstock supply and the performance of the supply chain, because it ensures long-term supply chain cooperation and coordination, mitigates market risk and reduces transaction cost; thus promoting the adoption of this kind of contract farming scheme would be the first step and an efficient way for the government to promote the development of the biofuel supply chain, which in turn would promote rural development, guarantee energy security and reduce GHG emissions. ***Second,*** the results indicate that the more of the production cost the large agribusiness firm takes on, the larger will be the increases in feedstock supply and performance of the whole supply chain. Thus, the government should adopt policies (e.g., favorable tax, subsidy) that give large agribusiness firms (the ethanol plant in this study) an incentive to take on more of the production cost through the provision of financial and technical support (in this study, to the small-scale farmers, especially during planting), so as to increase the supply of feedstock, which in turn will improve both the economic and the environmental performance of the whole biofuel supply chain. In addition, we find increases in the conversion ratio from cassava to bioethanol lead to increases in both supply and performance. Specifically, then, the government should adopt policies that encourage agribusiness firms to increase the conversion ratio from feedstock to biofuel through innovation and perhaps technological interventions. ***Third,*** the results reveal that the small-scale farmers’ performance can be improved only under certain conditions, due to the competition between the large agribusiness firm and the small-scale farmers. Hence, a rational farmer might not want to join the contract farming scheme. In such a situation the government could offer a financial subsidy or support to encourage small-scale farmers to join the contract farming scheme and increase their incomes, thereby promoting the development of biofuel supply chains.

1. **Conclusions**

Biofuel is increasingly important role for its economic, environmental, and social benefits. Supply chain management can play a critical role in promoting the development of the biofuel industry. Using the case study for China’s cassava-based bioethanol industry, this paper investigates the operation and coordination issue along the supply chain, so as to guarantee the supply of feedstock, reduce GHG emissions and promote rural development. First, incorporating the unique characteristics of China’s cassava cultivation, this paper analyses the decision behavior of the ethanol plant and of the small-scale cassava farmers in a supply chain under the condition of high yield uncertainty. The results show that competition between the ethanol plant and the small-scale farmers will lead to a double marginalization of the supply chain and less cultivation of cassava, and this effect will be enlarged as the yield uncertainty increases, as risk aversion of the farmer increases, and as the capacity the farmer has increases. To overcome this double marginalization effect, we look at the use of a production cost sharing contract to improve the supply and the performance of the cassava-based bioethanol supply chain. The results indicate that the proposed production cost sharing contract is conductive to increasing both the supply of cassava and the economic and environmental performance of the cassava-based bioethanol supply chain. The more of the production cost the ethanol plant takes on, through the provision of financial and technical support, the larger is the supply of cassava and the better is the performance of the supply chain; indeed, perfect coordination along the supply chain can be achieved under certain conditions.

The contract model proposed in this paper is a modification of the traditional supply chain coordination model. The research reported here thereby adds to the theory and expands its application. The production cost sharing contract is easy to implement in practice and can be generalized to other biofuel supply chains with different feedstocks, such as corn cobs, corn stover, switchgrass, miscanthus, and woody biomass. Other supply chain coordination contracts (e.g. revenue sharing contracts, quantity discount contracts) could also be applied to the biofuel supply chain. In addition, we consider only the two-level biofuel supply chain and certain demand environment in this study. It would be of interest to investigate the optimization of the whole biofuel supply chain system, from raw materials to final consumption, under uncertain demand environment. And the competition between several large agribusiness firms and contract farming supply chains will be worth further exploration. Last but not least, since the renewable energy is of great importance to the government, it would be of interest to explore the role of government as a player in the biofuel supply chain, to investigate how government policy can provide incentives and support, and how it can affect the decision making behavior of various players in the biofuel supply chain, so as to improve the generation and utilization of renewable energy.

**Insert Table for Notations Here**

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