Optimal Contracts to Induce Biomass Production under Risk

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Abstract

There is growing interest in biomass from perennial grasses (e.g. switchgrass and miscanthus) for bioenergy production because of their high yields, their potential to be grown on low quality land with minimal competition with food crops and, and their ability to achieve significant reduction in greenhouse gas (GHG) emissions relative to fossil fuels and corn ethanol. In order to guarantee the steady supply of biomass feedstock for mandated biofuel production, a crucial question confronting the biorefinery and policy makers is how to coordinate a market for biomass production. This paper addresses this issue by analyzing the potential design of biomass production contracts between biomass growers and biorefineries to promote the development of the industry. We approach the issue from both the landowner and biorefinery perspectives. We analyze and examine how the optimal contract design depends on both the farmers' and biorefinery's characteristics. We also contribute to the existing literature examining the role of risks in contract design by how the risks from multiple sources interact and jointly determine the optimal contract terms. Our preliminary findings suggest that farmers' land allocation decisions depend on the joint distribution of their individual land quality and risk preferences. For a given level of risk aversion, farmers with low land quality are more willing to sign contracts with biorefineries to produce bioenergy crops due to the low opportunity cost of foregoing row crop production. For a given land quality, the farmer's choice of biomass contract design varies with their level of risk aversion. More risk averse farmers prefer the fixed lease design to avoid exposure to yield and price risk. As the level of risk aversion is reduced, preferences shift towards the fixed price and profit sharing contract designs since they can gain higher payoff in exchange for the higher risks they are bearing. For reasonable ranges of land quality levels and heterogeneity of risk aversion levels, the optimal solution for the biorefinery tends to include offering of multiple contract designs to producers in the region. The biorefinery can induce highest participation and obtain highest profit in a region with higher concentrations of low land quality. Furthermore, greater profits can be obtained by establishing a processing plant in an area where farmers have low risk aversion.

Keywords: Contract Farming, Bioenergy Crops, Risk Preference

1. Introduction

There is growing interest in the commercial scale production of perennial grasses as energy crops in the U.S. for use as a feedstock in biofuel processing. Demand for these energy crops is anticipated to grow to meet the requirement for cellulosic biofuel mandated by the Renewable Fuel Standard (RFS2). While commercial production of cellulosic biofuels is yet to begin there is considerable uncertainty about the willingness of farmers to grow energy crops, the type of land on which they will be grown and the contractual arrangements needed to induce their production. Domestic production of these crops is still limited to experimental scales. Farmers are unfamiliar with their production processes and future prospects for profitability, causing hesitation in switching away from traditional crop production. Furthermore, the refining industry has yet to invest in commercial bioprocessing facilities with capacities capable of producing RFS2 mandated volumes. This "chicken-and-egg" problem is driven by a number of uncertainties associated with both market-based and political factors. A key question confronting biorefiners, farmers, and policy makers is how to coordinate markets for the production and sale of biomass crops. Vertical integration via contracting relationships represents one potential solution.

In the contract literature, contract design depends on several factors such as transaction costs, information asymmetries, liquidity constraints, and risk. The seminal paper by Coase (1937) explains the extent of vertical integration as a way to avoid transaction costs. A number of empirical studies have supported the importance of transaction costs in shaping contract design and questioned the relative importance of risk motivations (Allen and Lueck 1992, Allen and Lueck 1993, Allen and Lueck 1995). However, other authors have found support for agricultural contract designs which are motivated by production risk, price risk, and the risk preferences of the contracting parties (Ackerberg and Botticini 2002; Heuth and Ligon 1999; Gillespie and Eidman 1998; Johnson and Foster 1994).

Furthermore, survey work has shown that higher levels of vertical integration are used when investment in specific assets is required or there exist large sources of uncertainty (Lafontaine and Slade 2007; Lajili, et al. 1997; Sykuta and Parcell 2003). For biofuel feedstock producers, almost all the above conditions are met. Dedicated bioenergy crops such as switchgrass and miscanthus require multi-year investments which include an initial

establishment period, specific equipment and input needs, and the learning of appropriate management techniques.

The traditional agricultural risks such as weather and agricultural crop price uncertainty remain important factors in the decision to begin producing perennial grasses. Soil moisture and temperature conditions are important during the establishment phase (Larson 2008), and also impact yields and feedstock quality during growth (Sanderson, et al. 1997). While crops like switchgrass have been found to be relatively resistant to drought and excessive moisture, weather-driven production uncertainties are further emphasized by the lack of production experience. The costs of producing energy crops include not only the operational costs of establishing, harvesting, storing and transporting these crops but also the foregone income from using land that has some alternative value for producing a conventional crop. Variability in the profitability of the alternative crop make the opportunity cost of using land to produce a long lived energy crop also variable. Additionally, the production of energy crops exposes farmers to energy market volatility since the price of biomass is likely to be linked to the price of oil. The large capital requirements associated with the construction of a processing facility and the costs of storing excess biomass and transporting it to other markets make it costly to have either insufficient biomass (leading to idle capacity) or surplus biomass (leading to storage issues).

Existing studies for biomass crops have focused on these vertical integration questions primarily from the perspective of the producer. Larson, et al. (2008) analyze four types of biomass production contracts and farmers' willingness to supply feedstocks under each alternative. Bocqueho and Jacquet (2010) examine farmers' adoption behavior for switchgrass and miscanthus production under liquidity constraints and a range of risk preferences.

This paper extends the biomass contract literature by incorporating both the farmers' adoption decisions and the biorefinery's vertical integration choices under a range of potential contract designs. We analyze how the menu of contracts offered by the refiner, and the willingness of the farmers to adopt biomass production under each contract type, depends on characteristics such as variation in land quality, farmer risk preferences, and sources of production and price risk. Thus, we contribute to the growing literature on biofuels and biomass crop production as well as the existing literature on the role of risk in the design of agricultural contracts and the resulting market equilibriums.

We include three types of contact designs – fixed land lease, fixed price contract, and profit-sharing contract - representing various levels of vertical integration between the refiner and biomass producers. The farmer's decision of land allocation to biomass production under contract or traditional row crop production is linked to their individual land quality and risk preferences. The contract terms offered by the profit-maximizing refiner are subject to the distribution of risk preferences and land quality across farmers within their contracting region. We provide a range of numerical solutions to our model using simulation methods which are then compared to a baseline scenario calibrated to current conditions in southern Illinois.

Our results show that farmers with low land quality, or smaller opportunity costs of row crop production, are more likely to accept biomass production contracts. The higher their level of risk aversion, the more likely farmers are to prefer the fixed lease contract design. Preferences for the three contract types, the resulting terms of those contracts, and the distribution of refiner and farmer profits are also shown to change as the relative levels of risk among energy and biomass prices, biomass production, and row crop returns is altered. These results should be useful to biofuel processors in making their investment decisions based on characteristics of potential locations for the refinery and preferences of the farmers within the location's contracting area.

The paper is organized as follows. Section 2 of the paper introduces the setup of the analytical model. Section 3 presents the data used in the simulation analysis. The simulation results and sensitivity analysis is summarized in section 4. Section 5 concludes the paper and discusses the implications.

2. Model Setup

2.1 Farmer's Problem

Suppose there are N heterogeneous farmers in an agricultural region and each of them owns a parcel of farmland of 1 acre. The quality (or productivity) of each parcel of farmland is represented by q_i. The individual land quality q_i is a random draw from a continuous beta distribution $Beta(\alpha, \beta)$. The lowest land quality level is 0 and the highest land quality level is Q. Farmers can either choose to plant traditional row crops or to plant bioenergy crops under contracts on their croplands. The land quality determines the profit of the traditional row crops,

but not bioenergy crops. We make this assumption because bioenergy crops such as switchgrass and miscanthus can be grown productively on low quality land (McLaughlin, et al. 1999). The per-acre profit of the traditional row crops is denoted as $\pi_C(q_i)$. The profit is an increasing function of land quality level. For each given land quality level q_i , $\pi_C(q_i)$ is exogenous and follows a distribution of $N(\bar{\pi}_C q_i, \sigma_C{}^2)$.

We express each farmer's per-acre production function of bioenergy crops as:

$$Y_B = Y_B(\bar{Y}_B, \varepsilon_1),$$

where Y_B is the biomass yield (in tons) per acre produced by farmers, it is determined by two factors. The first one is the average per-acre biomass yield $\bar{Y}_B$. Another term is ε_1 which represents stochastic yield disturbance. The yield shock is positive if $\varepsilon_1 > 0$, while $\varepsilon_1 < 0$ means a negative yield shock. Biomass yield is increasing in disturbance term ($\frac{\partial Y_B}{\partial \varepsilon_1} > 0$). We assume that the disturbance term (ε_1) is the same for every farmer and it follows a normal distribution with mean 0 and standard deviation σ_1. To be more specific, we further assume that the average biomass yield and stochastic terms are separable.

$$Y_B = \bar{Y}_B + \varepsilon_1$$

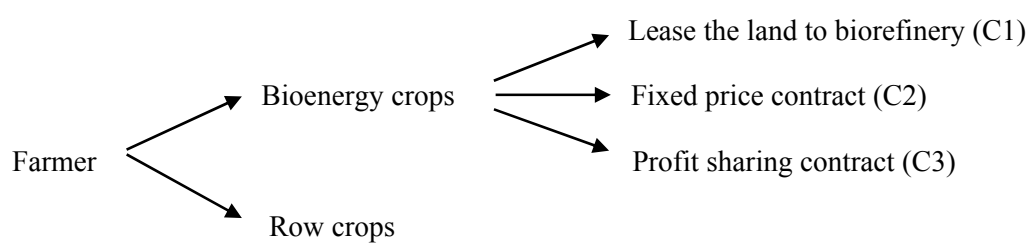

Figure 1. Farmer's Decision Tree

A farmer's per-acre profit may come from two sources: bioenergy crop production under contract or traditional row crop production. As shown in Figure 1, if the farmer chooses to produce bioenergy crops on his land, there are three contract options. These include leasing the land to the biorefinery to produce bioenergy crops at a fixed rental price of the land (Contract 1,

i.e. C1), selling a guaranteed amount of biomass at a fixed price to the biorefinery (Contract 2, i.e. C2), selling biomass at a price indexed to the profits of the biorefinery (Contract 3, i.e. C3). Under C3 we assume that the farmer receives a specified share of the refinery's revenue. The per-acre profit of growing bioenergy crops is the revenue they get under each scenario minus the associated production costs.

$$\pi_{Bi} = PM_i - C_o,$$

where PM_i is the per-acre revenue that farmer i receives and C_o is the biomass production cost. It includes the cost of seed, fertilizer, herbicides and machinery. The revenue received will be a function of both biomass yield and biomass price ($PM_i = PM_i(P_B, Y_{Bi})$). Profits from the row crop are represented by $\pi_C(q_i)$.

On a given acre of land, farmers have four options. The first option (Option 1) is a fixed payment scheme (i.e. leasing contract) under which the biorefinery pays a fixed dollar amount per acre to the farmers and undertakes the production of the energy crop itself. Leasing represents the highest level of vertical integration. The profit of a farmer from the leasing contract is:

$$\pi_{B1} = \omega_1$$

Under contract 2 the biorefinery pays a fixed price ($\bar{P}_1$) per ton of biomass and farmers commit to deliver a specified amount ($\bar{Y}_B$) tons of biomass to the biorefinery. For the committed amount of biomass, the biorefinery pays $\bar{P}_1$ dollars per ton. If the harvest of biomass exceeds/falls short of the committed amount, farmers have the option of selling the surplus/buying the deficit from the spot market at a price of ($P_B - T_C$) dollars per ton where T_C is the cost per ton of transporting the biomass to the spot market. The spot market price (P_B) is assumed to be exogenous and follows a normal distribution of $N(\bar{P}_B, \sigma_B^2)$. We assume that the random variables are independent of each other. The biorefinery needs to determine the level of $\bar{P}_1$ in the production contract. The profit of the farmer under a fixed price contract is:

$$\pi_{B2} = \begin{cases} \bar{P}_1\bar{Y}_B + (P_B - T_C)(Y_B - \bar{Y}_B) - C_0 \; if \; Y_B > \bar{Y}_B \\ \bar{P}_1\bar{Y}_B - (P_B + T_C)(\bar{Y}_B - Y_B) - C_0 \; if \; Y_B \leq \bar{Y}_B \end{cases}$$

Under contract 3 (the profit sharing contract C3), the biorefinery pays α percent of its revenue $P_E G\bar{Y}_B$ to farmers where G is the conversion efficiency (gallons per ton of biomass) with which biomass is converted to ethanol that is sold at the price P_E. A farmer under this contract agrees to deliver a committed amount ($\bar{Y}_B$ tons) of biomass to the biorefinery and will need to sell any excess biomass at ($P_B - T_C$) dollars per ton or buy the deficit at $(P_B + T_C)$ dollars per ton. The farmer's profit from the profit sharing contract is:

$$\pi_{B3} = \begin{cases} \alpha P_E G\bar{Y}_B + (P_B - T_C)(Y_B - \bar{Y}_B) - C_0 \; if \; Y_B > \bar{Y}_B \\ \alpha P_E G\bar{Y}_B - (P_B + T_C)(\bar{Y}_B - Y_B) - C_0 \; if \; Y_B \leq \bar{Y}_B \end{cases}$$

Option 4 is for farmers to plant a traditional row crop and earn a profit of $\pi_C(q_i)$. The discrete choice between these four mutually exclusive options are denoted by $l_1, l_2, l_3 \; and \; l_4$ each of which is equal to 1 if that option is chosen and zero otherwise and $l_1 + l_2 + l_3 + l_4 = 1$.

A risk averse farmer is assumed to allocate land among these four choices to maximize a second-moment utility function that takes the form $E\pi - \lambda_i {\sigma_\pi}^2$, where the coefficient λ_i measures the degree of risk aversion. The utility function is increasing in expected profit and decreasing in variance of profits. ($U_1 > 0, U_2 < 0, U(0,0) = 0 \, , U_{11} < 0 \; and \; U_{12} = 0$)

$$\max_{\{l_1, l_2, l_3, l_4\}} U^i(E\pi, {\sigma_\pi}^2), \text{ where}$$

$$E\pi = l_1\pi_{B1} + l_2\pi_{B2} + l_3\pi_{B3} + l_4 \, \pi_C(q_i)$$

$${\sigma_\pi}^2 = {l_2}^2{\sigma_{B2}}^2 + {l_3}^2{\sigma_{B3}}^2 + {l_4}^2{\sigma_C}^2$$

$$l_1 + l_2 + l_3 + l_4 = 1$$

The farmers' utility from choosing contract 1 (leasing contract) is ω_1 , the utility from contract type 2 (fixed price contract) is: $\bar{P}_1\bar{Y}_B - C_0 - \lambda_i({\bar{P}_B}^2{\sigma_1}^2 + {\sigma_B}^2{\sigma_1}^2 + {T_C}^2{\sigma_1}^2)$, the utility from contract type 3 is: $\alpha\bar{P}_E G\bar{Y}_B - C_0 - \lambda_i(\alpha^2{\bar{Y}_B}^2G^2{\sigma_E}^2 + {\bar{P}_B}^2{\sigma_1}^2 + {\sigma_B}^2{\sigma_1}^2 + {T_C}^2{\sigma_1}^2)$, and the utility from row crop production is: $\bar{\pi}_C q_i - \lambda_i {\sigma_C}^2$.

Contract type 1 is chosen if the utility from it is higher than from the other three options which requires the following three conditions to be satisfied:

$$\omega_1 \geq \bar{P}_1\bar{Y}_B - C_0 \ - \lambda_i(\bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2)$$

$$\omega_1 \geq \alpha\bar{P}_E G\bar{Y}_B - C_0 \ - \lambda_i(\alpha^2\bar{Y}_B{}^2G^2\sigma_E{}^2 + \bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2)$$

$$\omega_1 \geq \bar{\pi}_C q_i - \lambda_i\sigma_C{}^2$$

These three conditions can also be expressed as:

$$\lambda_i \geq \frac{\bar{P}_1\bar{Y}_B - C_0 \ - \omega_1}{\bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2} \equiv \lambda_1$$

$$\lambda_i \geq \frac{\alpha\bar{P}_E G\bar{Y}_B - C_0 \ - \omega_1}{\alpha^2\bar{Y}_B{}^2G^2\sigma_E{}^2 + \bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2} \equiv \lambda_2$$

$$q_i \leq \frac{\omega_1 + \lambda_i\sigma_C{}^2}{\bar{\pi}_C} \equiv q_1$$

Proposition 1. The farmer with a given land quality level q_i and degree of risk aversion λ_i will choose contract type 1 (i.e. rent out their land to the biorefinery at a fixed payment per acre ω_1) if $\lambda_i \geq \lambda_1$, $\lambda_i \geq \lambda_2$ and $q_i \leq q_1$.

The farmers will choose the first contract if their risk aversion coefficient is greater than λ_1 , which is the difference between profits of first two contracts divided by the variance of the second contract and also greater than λ_2 , which is difference between profits of first two contracts divided by the variance of the third contract and the land quality is lower than the threshold level q_1 . The threshold land quality is an increasing function of risk coefficient λ_i . For the same contract terms and same land quality level, farmers who are more risk averse are more likely to enroll into the first type of contract.

Contract type 2 is chosen if the following conditions are satisfied:

$$\bar{P}_1\bar{Y}_B - C_0 \ - \lambda_i\left(\bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2\right) \geq \omega_1$$

$$\bar{P}_1\bar{Y}_B - C_0 \ - \lambda_i\left(\bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2\right)$$
$$\geq \alpha\bar{P}_E G\bar{Y}_B - C_0 \ - \lambda_i(\alpha^2\bar{Y}_B{}^2G^2\sigma_E{}^2 + \bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2)$$

$$\bar{P}_1\bar{Y}_B - C_0 \ - \lambda_i \left(\bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2\right) \geq \bar{\pi}_C q_i - \lambda_i\sigma_C{}^2$$

These three conditions can also be expressed as:

$$\lambda_i \leq \frac{\bar{P}_1\bar{Y}_B - C_0 \ - \omega_1}{\bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2} \equiv \lambda_1$$

$$\lambda_i \geq \frac{\alpha\bar{P}_E G\bar{Y}_B - \bar{P}_1\bar{Y}_B}{\alpha^2\bar{Y}_B{}^2 G^2\sigma_E{}^2} \equiv \lambda_3$$

$$q_i \leq \frac{\bar{P}_1\bar{Y}_B - C_0 \ - \lambda_i \left(\bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2 - \sigma_C{}^2\right)}{\bar{\pi}_C} \equiv q_2$$

Proposition 2. The farmer with a given land quality level q_i and degree of risk aversion λ_i will choose the fixed price contract if $\lambda_3 \leq \lambda_i \leq \lambda_1$ and $q_i \leq q_2$.

A farmer will choose a fixed price contract if his risk aversion coefficient is between λ_1 and λ_3 and land quality is lower than threshold level q_2 . The threshold land quality (q_2) is a decreasing function of risk coefficient λ_i.

Contract type 3 is chosen if the following conditions are satisfied:

$$\alpha\bar{P}_E G\bar{Y}_B - C_0 \ - \lambda_i \left(\alpha^2\bar{Y}_B{}^2 G^2\sigma_E{}^2 + \bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2\right) \geq \omega_1$$

$$\alpha\bar{P}_E G\bar{Y}_B - C_0 \ - \lambda_i \left(\alpha^2\bar{Y}_B{}^2 G^2\sigma_E{}^2 + \bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2\right)$$
$$\geq \bar{P}_1\bar{Y}_B - C_0 \ - \lambda_i \left(\bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2\right)$$

$$\alpha\bar{P}_E G\bar{Y}_B - C_0 \ - \lambda_i \left(\alpha^2\bar{Y}_B{}^2 G^2\sigma_E{}^2 + \bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2\right) \geq \bar{\pi}_C q_i - \lambda_i\sigma_C{}^2$$

These three conditions can also be expressed as:

$$\lambda_i \leq \frac{\alpha\bar{P}_E G\bar{Y}_B - C_0 \ - \omega_1}{\alpha^2\bar{Y}_B{}^2 G^2\sigma_E{}^2 + \bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2} \equiv \lambda_2$$

$$\lambda_i \leq \frac{\alpha\bar{P}_E G\bar{Y}_B - \bar{P}_1\bar{Y}_B}{\alpha^2\bar{Y}_B{}^2 G^2\sigma_E{}^2} \equiv \lambda_3$$

$$q_i \leq \frac{\alpha \bar{P}_E G \bar{Y}_B - C_0 - \lambda_i \left(\alpha^2 \bar{Y}_B{}^2 G^2 \sigma_E{}^2 + \bar{P}_B{}^2 \sigma_1{}^2 + \sigma_B{}^2 \sigma_1{}^2 + T_C{}^2 \sigma_1{}^2 - \sigma_C{}^2\right)}{\bar{\pi}_C} \equiv q_3$$

Proposition 3. The farmer with a given land quality level q_i and degree of risk aversion λ_i will choose a profit sharing contract if $\lambda_i \leq \lambda_2$, $\lambda_i \leq \lambda_3$ and $q_i \leq q_3$.

A farmer will choose the third type of contract if his risk aversion coefficient is smaller than both λ_2 and λ_3 and land quality is lower than threshold level q_3. The threshold land quality (q_2) is a decreasing function of risk coefficient λ_i. For the same contract terms and same land quality level, farmers who are less risk averse or more risk loving are more likely to enroll in this type of contract.

Row crop production is chosen if the following conditions are satisfied:

$$\bar{\pi}_C q_i - \lambda_i \sigma_C{}^2 \geq \omega_1$$

$$\bar{\pi}_C q_i - \lambda_i \sigma_C{}^2 \geq \bar{P}_1 \bar{Y}_B - C_0 - \lambda_i \left(\bar{P}_B{}^2 \sigma_1{}^2 + \sigma_B{}^2 \sigma_1{}^2 + T_C{}^2 \sigma_1{}^2\right)$$

$$\bar{\pi}_C q_i - \lambda_i \sigma_C{}^2 \geq \alpha \bar{P}_E G \bar{Y}_B - C_0 - \lambda_i \left(\alpha^2 \bar{Y}_B{}^2 G^2 \sigma_E{}^2 + \bar{P}_B{}^2 \sigma_1{}^2 + \sigma_B{}^2 \sigma_1{}^2 + T_C{}^2 \sigma_1{}^2\right)$$

These three conditions can also be expressed as:

$$q_i \geq \frac{\omega_1 + \lambda_i \sigma_C{}^2}{\bar{\pi}_C} \equiv q_1$$

$$q_i \geq \frac{\bar{P}_1 \bar{Y}_B - C_0 - \lambda_i \left(\bar{P}_B{}^2 \sigma_1{}^2 + \sigma_B{}^2 \sigma_1{}^2 + T_C{}^2 \sigma_1{}^2 - \sigma_C{}^2\right)}{\bar{\pi}_C} \equiv q_2$$

$$q_i \geq \frac{\alpha \bar{P}_E G \bar{Y}_B - C_0 - \lambda_i \left(\alpha^2 \bar{Y}_B{}^2 G^2 \sigma_E{}^2 + \bar{P}_B{}^2 \sigma_1{}^2 + \sigma_B{}^2 \sigma_1{}^2 + T_C{}^2 \sigma_1{}^2 - \sigma_C{}^2\right)}{\bar{\pi}_C} \equiv q_3$$

Proposition 4. The farmer with a given land quality level q_i and degree of risk aversion λ_i will choose to plant row crops if $q_i \geq q_1$, $q_i \geq q_2$ and $q_i \geq q_3$.

A farmer will choose to plant traditional row crops if his land quality is greater than q_1, q_2 and q_3. For the same contract terms and same risk aversion level, farmers with high land

quality are more likely to grow traditional row crops. These contract choices are illustrated in the figure 2.

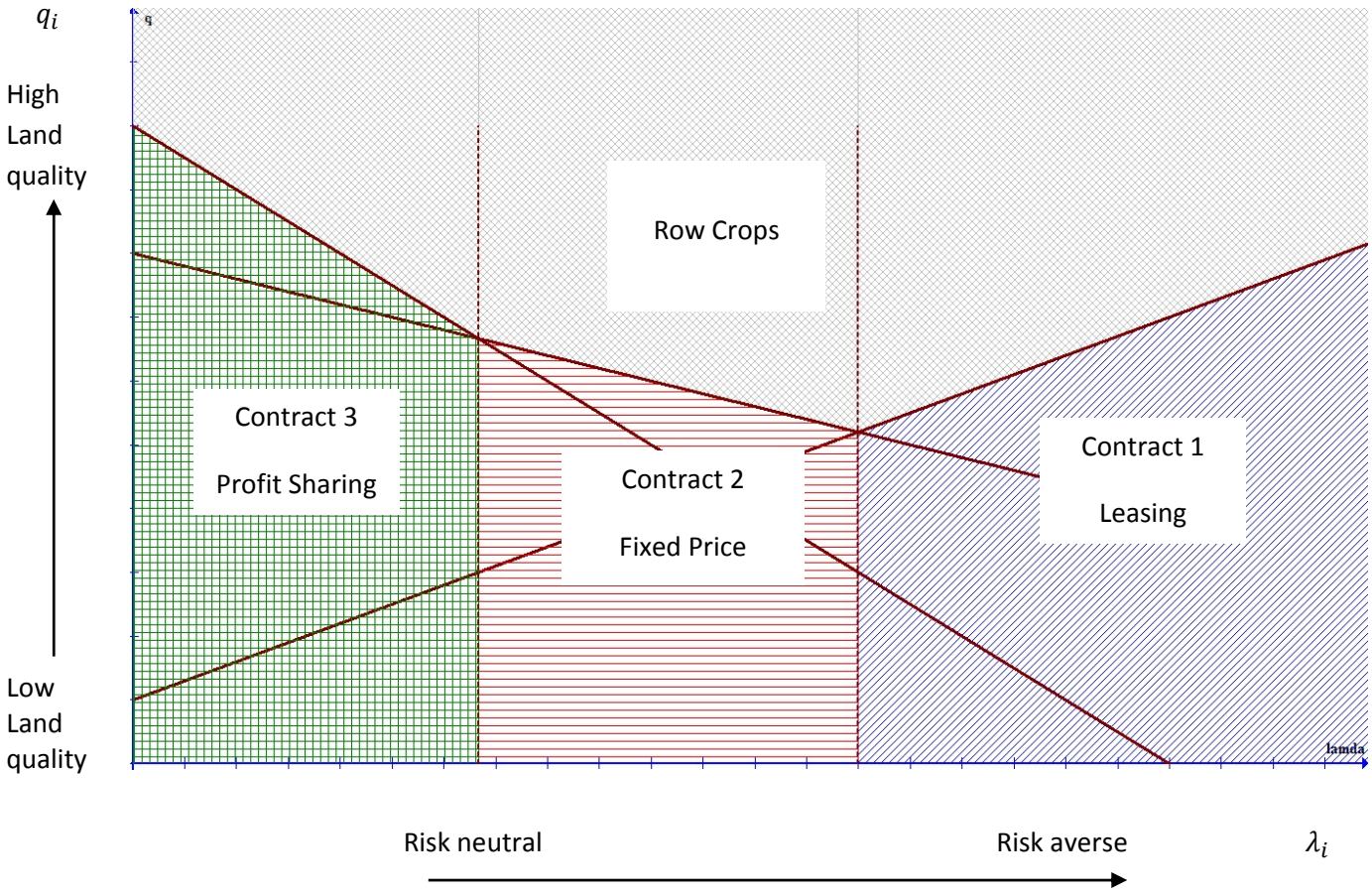

Figure 2. Contract Type Choices by Risk Preference and Land Quality

From figure 2, we can see that the choice of contracts depends on the interaction between individual land quality and farmers' risk aversion coefficient. With the same level of risk aversion, farmers with low land quality are more willing to sign contracts with biorefineries to produce bioenergy crops, while farmers with high land quality would like to grow row crops because they can get a higher return from the row crops production.

With the same level of land quality, farmers with higher risk aversion are more willing to choose the first type of contract because a leasing contract pays them a fixed per acre payment every year and they are not exposed to yield risk and price risk. Farmers with a small risk aversion coefficient are more likely to choose a profit sharing contract. Farmers who have an

intermediate level of risk aversion are likely to choose the fixed payment contract because they only need to bear the yield risk and not the price risk.

The analysis above also shows that the threshold level of land quality under contract 1 is increasing in risk aversion while the threshold levels of land quality in contracts 2, 3 and row crops respectively are decreasing in risk aversion.

Corollary 1. Coexistence of contracts: Farmers with land quality between $q_{13} = \frac{\omega_1}{\bar{\pi}_C} + \frac{\sigma_C{}^2(\alpha\bar{P}_E G\bar{Y}_B - C_0 - \omega_1)}{\bar{\pi}_C(\alpha^2\bar{Y}_B{}^2 G^2\sigma_E{}^2 + \bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2)}$ and

$q_{23} = \frac{\bar{P}_1\bar{Y}_B - C_0}{\bar{\pi}_C} + \frac{(\bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2 - \sigma_C{}^2)(\alpha\bar{P}_E G\bar{Y}_B - \bar{P}_1\bar{Y}_B)}{\bar{\pi}_C(\alpha^2\bar{Y}_B{}^2 G^2\sigma_E{}^2)}$ can choose any of the four options depending on their individual risk aversion coefficient.

This implies that land quality between the two threshold levels q_{13} and q_{23} can be enrolled in any of the four options described above.

2.2 Biorefinery's problem

We consider a biorefinery with a fixed capacity of $\bar{C}$ gallons per year and assume that $\bar{C} > NG\bar{Y}_B$, that is the biorefinery's capacity can be supported by the maximum biomass production in this agricultural region. In order to maintain the commercial capacity of the biorefinery, the expected annual supply of biomass should be $\bar{C}/G$ tons. Here we assume that the biorefinery can obtain biomass from two sources: contract farming and biomass spot market. If farmers' total biomass delivery is lower than the capacity requirement, the biorefinery will buy the shortage part from the spot market at $(P_b + T_C)$ dollars per ton. Otherwise, the excess amount of the biomass can be stored in the biorefinery at $(P_b - T_C)$ dollars per ton. The price of biofuel is denoted as P_E dollars per gallon. It is an exogenous random variable and follows a normal distribution of $N(\bar{P}_E, \sigma_E^2)$.

The profit of the biorefinery is the revenue from biofuel production less the cost of land leasing and the operating cost (V_C dollars per gallon). The revenue is the product of biofuel price (P_E), biofuel conversion rate (G), per acre yield (Y_B) and the total acres of land devoted to

leasing ($N \int_{\lambda>max(\lambda_1,\lambda_2)} \int_{q<q_1} f(\lambda, q)\, d\lambda dq$). The cost for the biorefinery is the per acre payment ω_1 times the total acres of leasing land. The joint distribution of farmers' risk aversion coefficient (λ) and land quality level (q) is denoted by $f(\lambda, q)$.

Under the second type of contract (fixed price contract), the total acres of land are $N \int_{\lambda_3<\lambda<\lambda_1} \int_{q<q_2} f(\lambda, q)\, d\lambda dq$. The biorefinery's per acre revenue is $P_E G \bar{Y}_B$ dollars. Biorefinery also pays $\bar{P}_1 \bar{Y}_B$ dollars per acre to farmers as contract payment.

Under the third type of contract (profit sharing contract), the biorefinery's profit is $(1-\alpha)$ percent of the per acre profit ($P_E G \bar{Y}_B N$) times the total acres devoted to the third contract $N \int_{\lambda<min(\lambda_2,\lambda_3)} \int_{q<q_3} f(\lambda, q)\, d\lambda dq$.

The biorefinery's problem is to maximize profit by choosing the three contract term parameters ω_1 , $\bar{P}_1$ and α .

$$\max_{\{\omega_1, \bar{P}_1, \alpha\}} E\pi_R, \text{ where}$$

$$\pi_R = P_E\, \bar{C} - F_C - V_C \bar{C} - (\omega_1 + C_0) N \int_{\lambda>max(\lambda_1,\lambda_2)} \int_{q<q_1} f(\lambda, q)\, d\lambda dq - \bar{P}_1 \bar{Y}_B N \int_{\lambda_3<\lambda<\lambda_1} \int_{q<q_2} f(\lambda, q)\, d\lambda dq - \alpha P_E G \bar{Y}_B N \int_{\lambda<min(\lambda_2,\lambda_3)} \int_{q<q_3} f(\lambda, q)\, d\lambda dq + (P_B - T_C)(N(1 - \iint_{q>\max\{q_1, q_2, q_3\}} f(\lambda, q) d\lambda dq)\, \bar{Y}_B - \frac{\bar{C}}{G}) \text{ if } (1 - \iint_{q>\max\{q_1, q_2, q_3\}} f(\lambda, q) d\lambda dq) > \frac{\bar{C}}{G\bar{Y}_B}$$

$$\pi_R = P_E\, \bar{C} - F_C - V_C \bar{C} - (\omega_1 + C_0) N \int_{\lambda>max(\lambda_1,\lambda_2)} \int_{q<q_1} f(\lambda, q)\, d\lambda dq - \bar{P}_1 \bar{Y}_B N \int_{\lambda_3<\lambda<\lambda_1} \int_{q<q_2} f(\lambda, q)\, d\lambda dq - \alpha P_E G \bar{Y}_B N \int_{\lambda<min(\lambda_2,\lambda_3)} \int_{q<q_3} f(\lambda, q)\, d\lambda dq - (P_B + T_C)(\frac{\bar{C}}{G} - N(1 - \iint_{q>\max\{q_1, q_2, q_3\}} f(\lambda, q) d\lambda dq)\, \bar{Y}_B) \text{ if } (1 - \iint_{q>\max\{q_1, q_2, q_3\}} f(\lambda, q) d\lambda dq) < \frac{\bar{C}}{G\bar{Y}_B}$$

We now analyze two special cases of this problem.

2.3 Special case: Homogeneous Farmers

Suppose all the farmers in the agricultural region have the same land quality level and risk preference (i.e. $q_i = q_j = q$ for any $i \neq j$ and $\lambda_i = \lambda_j = \lambda$ for any $i \neq j$), their contract

choice will also be the same. The biorefinery's problem is a two-stage problem of first choosing the optimal terms of the contract under each type and then selecting the optimal contract type to offer. If the biorefinery provides only contract 1, the optimal land rent ω_1 is determined by maximizing: $\pi_R = \max_{\omega_1} P_E\,\bar{C} - F_C - V_C\bar{C} - (\omega_1 + C_0)N + (P_B - T_C)\left(N\bar{Y}_B - \frac{\bar{C}}{G}\right)$

$$\text{s.t.} \quad \lambda \geq \frac{\bar{P}_1\bar{Y}_B - C_0 - \omega_1}{\bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + \mathrm{T_C}{}^2\sigma_1{}^2}$$

$$\lambda \geq \frac{\alpha\bar{P}_E G\bar{Y}_B - C_0 - \omega_1}{\alpha^2\bar{Y}_B{}^2 G^2\sigma_E{}^2 + \bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2}$$

$$q \leq \frac{\omega_1 + \lambda\sigma_C{}^2}{\bar{\pi}_C}$$

The optimal rate is as follows:

$$\omega_1{}^* = \bar{\pi}_C q - \lambda\sigma_C{}^2$$

and is increasing in average row crops profit and land quality. It is decreasing in risk preference coefficient and standard deviation of profit of row crops.

The maximized profit is: $\pi_1{}^* = (P_E G\, Y_B - C_0 - \bar{\pi}_C q + \lambda\sigma_C{}^2)N$

If the biorefiner offers contract 2 then the optimal price is determined by maximizing

$$\pi_2 = \max_{\bar{P}_1} P_E\,\bar{C} - F_C - V_C\bar{C} - \bar{P}_1\bar{Y}_B N + (P_B - T_C)\left(N\bar{Y}_B - \frac{\bar{C}}{G}\right)$$

$$s.t.\ \lambda \leq \frac{\bar{P}_1\bar{Y}_B - \omega_1}{\bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2}$$

$$\lambda \geq \frac{\alpha\bar{P}_E G\bar{Y}_B - \bar{P}_1\bar{Y}_B}{\alpha^2\bar{Y}_B{}^2 G^2\sigma_E{}^2}$$

$$q \leq \frac{\bar{P}_1\bar{Y}_B - \lambda\left(\bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2 - \sigma_C{}^2\right)}{\bar{\pi}_C}$$

The optimal solution to this problem is:

$$\bar{P}_1{}^* = \frac{\bar{\pi}_C q + \lambda\left(\bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2 - \sigma_C{}^2\right)}{\bar{Y}_B}$$

The optimal price rate is increasing in average row crops profit, land quality, risk aversion coefficient, average biomass price, standard deviation of yield disturbance, and standard deviation of biomass price. It is decreasing in average biomass yield and standard deviation of row crops profit. The optimal profit is:

$$\pi_2{}^* = \left(P_E G\, Y_B - \bar{\pi}_C q - \lambda\left(\bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2 - \sigma_C{}^2\right)\right) N$$

Biorefinery would like to maximize profit when all farmers sign contract 3.

$$\pi_3 = \max_{\alpha} P_E\, \bar{C} - F_C - V_C\bar{C} - \alpha P_E G\bar{Y}_B N + (P_B - T_C)\left(N\bar{Y}_B - \frac{\bar{C}}{G}\right)$$

$$\lambda \leq \frac{\alpha\bar{P}_E G\bar{Y}_B - \omega_1}{\alpha^2\bar{Y}_B{}^2 G^2\sigma_E{}^2 + \bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2}$$

$$\lambda \leq \frac{\alpha\bar{P}_E G\bar{Y}_B - \bar{P}_1\bar{Y}_B}{\alpha^2\bar{Y}_B{}^2 G^2\sigma_E{}^2}$$

$$q \leq \frac{\alpha\bar{P}_E G\bar{Y}_B - \lambda\left(\alpha^2\bar{Y}_B{}^2 G^2\sigma_E{}^2 + \bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 + T_C{}^2\sigma_1{}^2 - \sigma_C{}^2\right)}{\bar{\pi}_C}$$

The optimal sharing rule is the following:

$$\alpha^* = \frac{\bar{\pi}_C q + \lambda\left(\bar{Y}_B{}^2 G^2\sigma_E{}^2 + \bar{P}_B{}^2\sigma_1{}^2 + \sigma_B{}^2\sigma_1{}^2 - \sigma_C{}^2\right)}{\bar{P}_E G\bar{Y}_B}$$

The optimal sharing rule is increasing in average row crops profit, land quality, risk aversion coefficient, average biomass price, standard deviation of yield disturbance, and standard deviation of biomass price. It is decreasing in average ethanol price, ethanol conversion coefficient and standard deviation of row crops profit.

The maximized profit is:

$$\pi_3{}^* = (P_E G\bar{Y}_B N - \bar{\pi}_C q - \lambda\left(\bar{Y}_B{}^2 G^2 \sigma_E{}^2 + \bar{P}_B{}^2 \sigma_1{}^2 + \sigma_B{}^2 \sigma_1{}^2 - \sigma_C{}^2\right))N$$

Proposition 4. Suppose all farmers have homogeneous land quality q and risk preference λ. The biorefinery prefers contract 1 to contract 2 to contract 3 if farmers are risk averse. The biorefinery prefers contract 3 to contract 2 to contract 1 if farmers are risk loving.

2.4 Special Case: Deterministic Environment

In this special case, we examine the choices if there are no price or yield risks. The farmer compares the payoffs from the four potential land allocation choices under certainty. The farmer gets a payoff of ω_1 from land renting contract, $\bar{P}_1\bar{Y}_B$ from fixed price contract, $\alpha\bar{P}_E G\bar{Y}_B$ from the profit sharing contract, and $\bar{\pi}_C q_i$ from row crops production. The farmer chooses the land renting contract if the following conditions are met.

$$\omega_1 \geq \bar{P}_1\bar{Y}_B - C_0$$

$$\omega_1 \geq \alpha\bar{P}_E G\bar{Y}_B - C_0$$

$$\omega_1 \geq \bar{\pi}_C q_i$$

The fixed price contract will be chosen if the following conditions are true.

$$\bar{P}_1\bar{Y}_B - C_0 \geq \omega_1$$

$$\bar{P}_1\bar{Y}_B \geq \alpha\bar{P}_E G\bar{Y}_B$$

$$\bar{P}_1\bar{Y}_B - C_0 \geq \bar{\pi}_C q_i$$

The farmer will choose profit sharing contract if the following inequalities hold:

$$\alpha\bar{P}_E G\bar{Y}_B - C_0 \geq \omega_1$$

$$\alpha\bar{P}_E G\bar{Y}_B \geq \bar{P}_1\bar{Y}_B$$

$$\alpha\bar{P}_E G\bar{Y}_B - C_0 \geq \bar{\pi}_C q_i$$

Since these three contracts are symmetric, we can show that the biorefinery will get the same signup rate for each type of contract if the payoff from each contract is equal. Hence, we only need to solve for the optimal contract term for one representative contract.

The biorefinery will choose the contract terms to maximize its profit.

$$\pi_R = \max_{\omega_1} E\{P_E\,\bar{C} - F_C - V_C\bar{C} - (C_0 + \omega_1)N\int_0^{\frac{\omega_1}{\bar{\pi}_C}} f(q)\,dq$$
$$-\,(P_B + T_C)\left(\frac{\bar{C}}{G} - N\bar{Y}_B\int_0^{\frac{\omega_1}{\bar{\pi}_C}} f(q)\,dq\right)\}$$

If we further assume that the land quality follows continuous uniform distribution $q \sim U(0,2)$, the lagrangian of this problem can be expressed as:

$$\mathcal{L} = P_E\,\bar{C} - F_C - V_C\bar{C} - (C_0 + \omega_1)\frac{N\omega_1}{2\bar{\pi}_C} - (P_B + T_C)\ (\frac{\bar{C}}{G} - \frac{\bar{Y}_B N\omega_1}{2\bar{\pi}_C})$$

The optimal leasing rate is:

$$\omega_1{}^* = \frac{(\bar{P}_B + T_C)\bar{Y}_B - C_0}{2}$$

The optimal land rent is increasing in average biomass price, transportation cost and average biomass yield. The land rent is decreasing in biomass production cost.

Similarly, we can also solve for the optimal price rate:

$$\bar{P}_1{}^* = \frac{(\bar{P}_B + T_C)\bar{Y}_B + C_0}{2\bar{Y}_B}$$

The optimal price rate is increasing in average biomass price and transportation cost and decreasing in biomass production cost and average biomass yield.

The optimal revenue sharing rate is:

$$\alpha^* = \frac{(\bar{P}_B + T_C)\bar{Y}_B + C_0}{2\bar{P}_E G\bar{Y}_B}$$

The optimal sharing rule is decreasing in average biofuel price and conversion rate.

3. Data Description

We use the following data to parameterize our theoretical model and simulate the optimal contracts given assumptions about land quality and risk preference distributions. The baseline data is shown in table 1.

Table 1. Baseline Scenario Parameter Values

Parameter	Unit	Value	Definition
N		100,000	Number of farmers in an agricultural region
$\overline{Y}_B$	tons/Acre	5	Average biomass yield
σ_1	tons/Acre	1.5	Standard deviation of biomass yield disturbance
$\bar{\pi}_C$	$/Acre	150	Average row crop profit
σ_C	$/Acre	100	Standard deviation of row crop profit
$\overline{P}_B$	$/ton	70	Average biomass price
σ_B	$/ton	20	Standard deviation of biomass price
$\overline{P}_E$	$/gallon	2.3	Average biofuel price
σ_E	$/gallon	0.3	Standard deviation of biofuel price
G	Gallon/ton	90	Biomass conversion rate
C_0	$/Acre	200	Production cost of bioenergy crops
Fc	$/gallon	1.1	Capital cost of the biorefinery
Vc	$/gallon	0.35	Operating cost of the biorefinery
Tc	$/ton	5	Biomass transportation cost

In the absence of a commercial market for bioenergy crops such as switchgrass and miscanthus, we could use the market price of hay as a proxy of biomass price. The price of hay reported by USDA's National Biomass Energy Report (2012) varies across states and across crop types used to produce hay. It ranges from $55 per ton to $85 per ton. However, this price may not cover the costs of producing energy crops which have longer establishment phases. Alternatively one could determine the breakeven price of biomass based on production costs under certainity. The biomass break-even price of producing miscanthus ranges from $53 per ton

to $153 per ton and that of switchgrass ranges from $88 per ton to $144 per ton in the Midwest (Jain, et al. 2010). We assume that the average biomass price is $70 per ton with a standard deviation of $20 per ton.

The biofuel price data is obtained from the Clean Cities Alternative Fuel Price Report (2012). National average price for gasoline is $3.37 per gallon with a standard deviation of $0.27 per gallon in January 2012. This implies an energy equivalent price of ethanol of $2.25 per gallon. We assume the average price of biofuel is $2.3 per gallon with a standard deviation of $0.3 per gallon.

The biomass production cost data is derived from Khanna et al. (2008) and Jain et al. (2010). Khanna et al. (2008) report annualized operating cost of switchgrass is $151.68 per acre and $ 399 per acre for miscanthus. Annualized yield of switchgrass is 2.34 tons per acre and 8.08 tons per acre for miscanthus. Jain et al. (2010) estimate the cost of switchgrass production is from $259 to $412 per acre and $592-$1008 per acre for miscanthus in Illinois. We assume that the production cost of biomass is $200 per acre.

The biomass yield data come from several sources. Jain, et al. (2010) estimated average peak biomass yield for miscanthus in the Midwestern states ranges between 2.83 tons per acre and 19.43 tons per acre, while for switchgrass is between 4.05 tons per acre and 6.48 tons per acre. Koff and Tyler (2011) also reported the biomass yield in Tennessee. Their study shows that the yield of biomass depends on cultivar types. A lowland switchgrass grown on a well-grained soil in Tennessee reached a yield of 8 tons per acre while the yield of switchgrass grown on a poorly drained floodplain in Tennessee could reach 4 tons per acre. The research conducted by Iowa State University Extension (2007) shows the switchgrass yields harvested from production fields in southern Iowa averaged from 1 to 4 tons per acre in a one-cut system harvested after frost while switchgrass yield harvested from research plots in central Iowa ranged from 2 to 6.4 tons. In our analysis, we assume that the yield of biomass is 5 tons per acre with a standard deviation of 1.5 tons per acre.

The average expected row crops profit is assumed to be $150 per acre with a standard deviation of $100 per acre based on Southern Illinois data (Illinois Farm Business Farm Management Association, FBFM). The expected returns are based on regional standards reported

by FBFM gain farmers from 2007 to 2011. The standard deviation is based on the average amount of on-farm return mean value of variation from 1996-2009 for each county.

We assume biomass conversion rate is 90 gallons per ton of feedstock based on (USDOE, date) which reports an expected conversion rate of 96.7 gallons per ton for switchgrass and 81.5 gallons per ton for forest thinning. The conversion rate reported by National Renewable Energy Laboratory (2011) is 79 gallons per ton for corn stover.

The cost of biorefinery can be divided into operating cost (variable costs) and capital cost (fixed costs). Capital costs include equipment installation cost, land cost, site development cost, and indirect costs. Operating costs include natural gas, catalysts, raw materials, waste disposal, electricity, capital depreciation and income tax. The operating costs and credits are $0.34 per gallon and capital charges and taxes are $1.08 per gallon (National Renewable Energy Laboratory (2011)). In our study, we assume that the capital cost of the biorefinery is $1.1 per gallon and operating cost is $0.35 per gallon.

Khanna, et al. (2008) estimates that the average bioenergy crop transportation cost falls within the range $9.5 to $12.25 per ton of switchgrass within a radius of 112-128km. The transportation cost per ton per km is $(1.12+0.07distance) where distance is the round trip distance between the farm and plant. In our study, we assume the average biomass transportation cost is $10 per ton.

In this analysis, we assume that the land quality (q_i) follows a continuous beta (2, 2) distribution. The minimum land quality is 0 and the maximum land quality is 2. The mean land quality is 1 which corresponds to the mean value of net return $150 per acre and standard deviation of $100 per acre in Southern Illinois. The distribution of risk aversion coefficient follows a continuous normal distribution of $N(0.00375, 0.0045^2)$. We determine the mean value of the risk preference by assuming that the risk premium at mean value is 25% of the expected traditional row crops return. The standard deviation is 20% of the mean risk preference coefficient. Our risk preference assumption is based on the work of Kramer and Pope (1981) which study farmers' participation in farm commodity program using a normative risk model based on stochastic dominance theory. Schurle and Tierney (1990) use interval method to estimate the risk aversion behavior of Kansas crop and livestock farmers and find that 80% of

farmers are risk averse, 2% are risk neutral and 18% risk loving. According to our specification 80% of the farmers in the agricultural region are risk averse. We also assume that the two characteristics of farmers are independent of each other. We assume that the refinery is risk neutral.

4. Simulation Results

We simulate the model using baseline parameters discussed in the previous section. First, we solve endogenously for the optimal contract term that maximize the expected profits for the biorefinery and the expected utility of the farmers simultaneously with the farmers' land allocation decision. After the optimal contract term is determined, we perform Monte-Carlo simulation by drawing 100 random realizations from the biomass price, biomass yield, biofuel price and row crop profit distributions. Then farmers' ex-post net returns and utility are calculated for each realization given the terms of the contracts and their land allocation decision. The average outcomes for each contract/crop choice are reported in the tables below.

4.1 Baseline Case

The simulation results from the benchmark case are summarized in the table 2. The optimal contract terms are $90 per acre for leasing contract, $65 per ton for fixed price contract and 34% for profit sharing contract. Under the optimal contract terms, 31% of the farmers choose leasing contract, 12% of the farmers choose fixed price contract and 5% of the farmers choose profit sharing contract. The remaining 53% of the farmers still plant traditional row crops. The average land quality enrolled in row crops is significantly higher than the land enrolled in bioenergy crop production. The farmers enrolled in a profit sharing contract is significantly more risk loving than the farmers enrolled in leasing contract and fixed price contract. The farmers who choose leasing contract are more risk averse. The land planting bioenergy crops is insufficient to meet the biomass capacity of the biorefinery; 30% of the biomass is purchased from the spot market. The biorefinery's rate of return is 8.7% in the baseline case.

Table 2. Baseline Simulation

	Leasing Contract (Land Rent $/acre)	Fixed Price Contract (Price Rate $/ton)	Sharing Contract (share)	Row Crops
Contract Terms	90	65	0.34	
Profit ($/Acre)	90	125	121	199.75
Signup Rate	30.86%	11.65%	4.86%	52.63%
Land quality (Min, Mean Max)	(0.0, 0.7, 1.7)	(0.0, 0.5, 0.9)	(0.0, 0.6, 1.1)	(0.8, 1.3, 2.0)
Risk aversion coefficient (Min, Mean, Max)	(0.003, 0.007, 0.02)	(-0.002, 0.0008, 0.003)	(-0.02, -0.004, -0.002)	(-0.02, 0.003, 0.02)
Farmer's utility (Min, Mean Max)	(90, 90, 90)	(90, 116, 146)	(146, 179, 370)	(90, 171, 431)
Farmer's net utility[1] (Min, Mean, Max)	(0.004, 64, 264)	(0.006, 45, 125)	(0.05, 50, 146)	
Biomass from spot market (% of total biomass used)	28.95%			
Biorefinery's rate of return	8.68%			

[1] Farmer's net utility is the utility derived from contracting minus the utility they would derive if they plant traditional row crops.

4.2 Effect of Production Risk and Price Uncertainty

We analyze the effect of increasing the riskiness of crop production on the terms of the contracts and land allocation decisions as shown in Figure 3. A reduction in the variance of the biomass yield distribution leads to a x% increase in the percentage of farmers that chose to grow energy crops instead of the traditional crop. Of the total energy crop produced, 80% of the biomass produced is under the fixed price contract with the same fixed price per ton as in the benchmark case. The average land quality enrolled in energy crop production under the leasing contract and the fixed price contract increases significantly while that enrolled in the profit sharing contract decreases compared to the benchmark conditions. As a result, the average leasing rental rate is 33% higher while the profit sharing rate is marginally lower. If the biomass yield risk increases, farmers will switch from contract 2 to contract 1 because contract 1 protects against yield risk. Moreover, farmers will switch from energy crops production to row crop production. Farmers are more likely to choose bioenergy crops production if the yield risk associated with its production is small. Otherwise, farmers will plant traditional row crops.

A 25% increase or decrease in the volatility of biomass price does not affect the contract terms provided by the biorefinery. The only change is reflected in the signup rate. A larger percentage of farmers will choose the leasing contract and a lower percentage will chose contract 3 in the high price volatility case. This is the case because contract 3 links the contract payment with the fuel market while contract 1 is risk-free choice. If the volatility of the fuel market is high relative to other markets, risk averse farmers will be more likely to switch to contract 1 and row crops which are free of fuel market risk. If the biomass price volatility is low, farmers will switch from contract 1 and row crops to contract 3 in order to get higher payoff.

When the row crop profit volatility is 25% lower than the benchmark case, the biorefinery needs to provide a higher land rent to farmers to attract them to sign contracts. Compared with the baseline case, we observe that a larger percentage of farmers grow traditional row crops and the leasing rate required to induce enrollment in Contract 1 is higher. On the other hand, with a high volatility in corn prices, the biorefinery needs to provide a lower land rent to farmers to induce enrollment in Contract 1.

When the ethanol price volatility is 12.5% lower than the benchmark case, there is a significant reduction in the profit sharing rate needed to induce enrollment from 35% to 26%, When the ethanol price volatility is 12.5% higher than the benchmark case, this rate increases ?? The simulation results are also illustrated in the figures below.

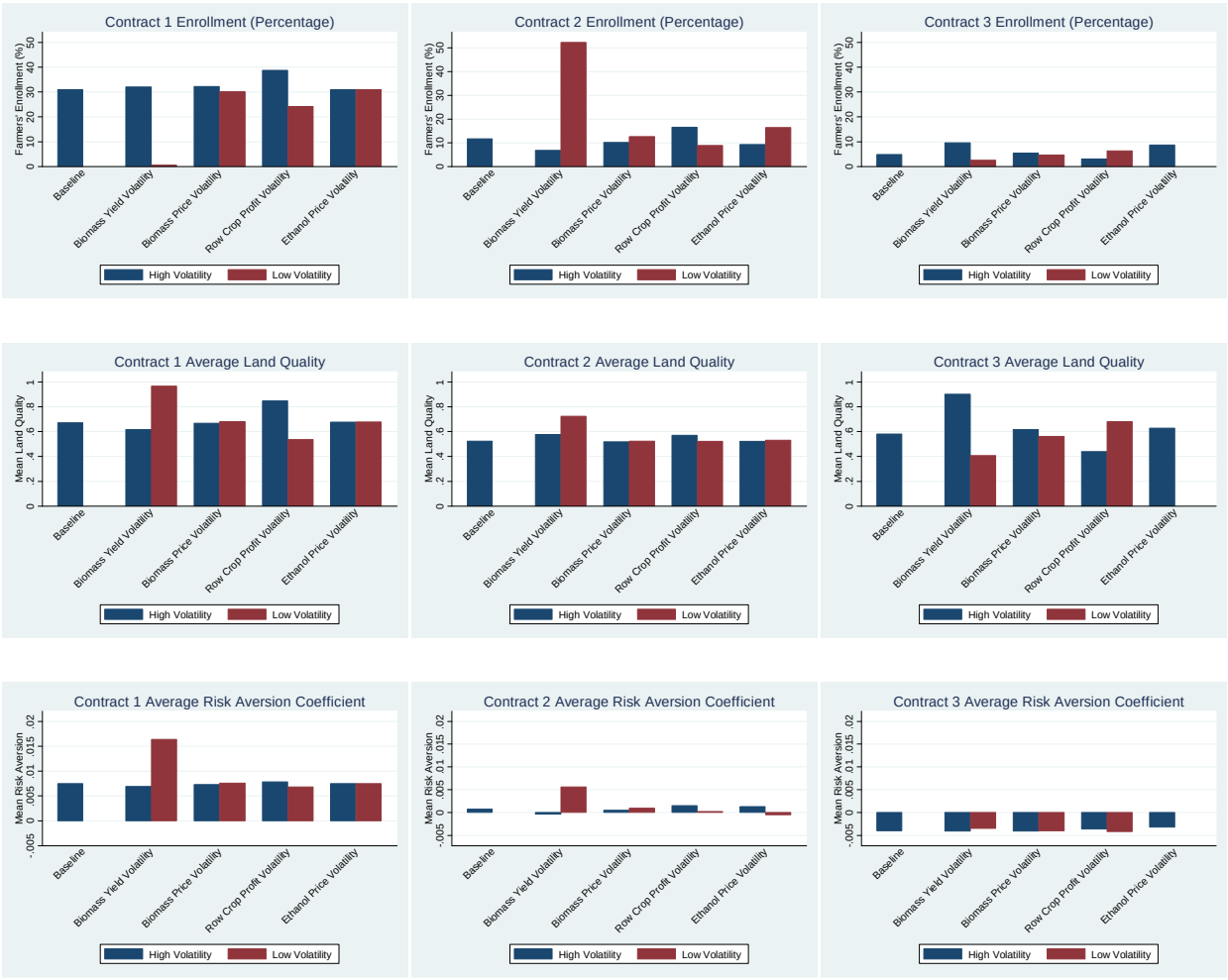

Figure 3. Contract and Farmer Characteristics Across Risk Scenarios

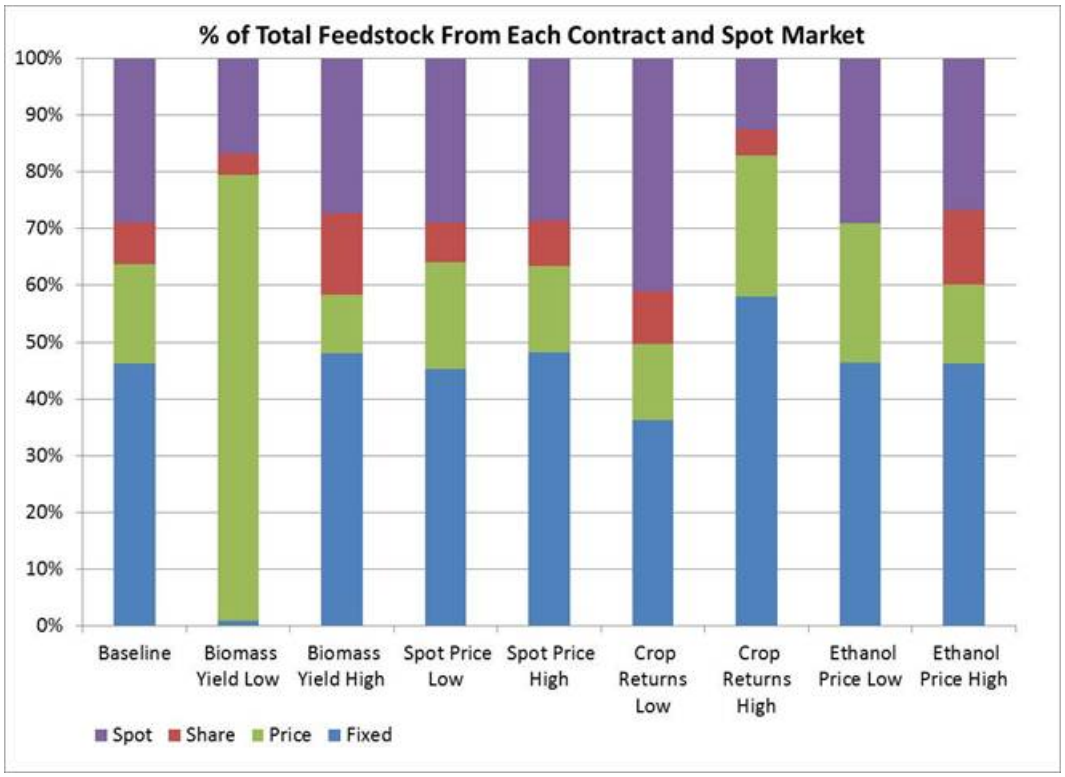

Figure 4: Effect of Risk on Percentage of Total Feedstock from Alternative Contracts

Figure 4 shows that as traditional crop production becomes more risky, farmers are more willing to lease out their land for energy crop production and choose a fixed price contract. When the volatility of biomass yields and ethanol price is high there is greater reliance on biomass produced on land leased from farmers and on the profit sharing contract. On the other hand when these volatilities are low, there is greater reliance on the fixed price contract.

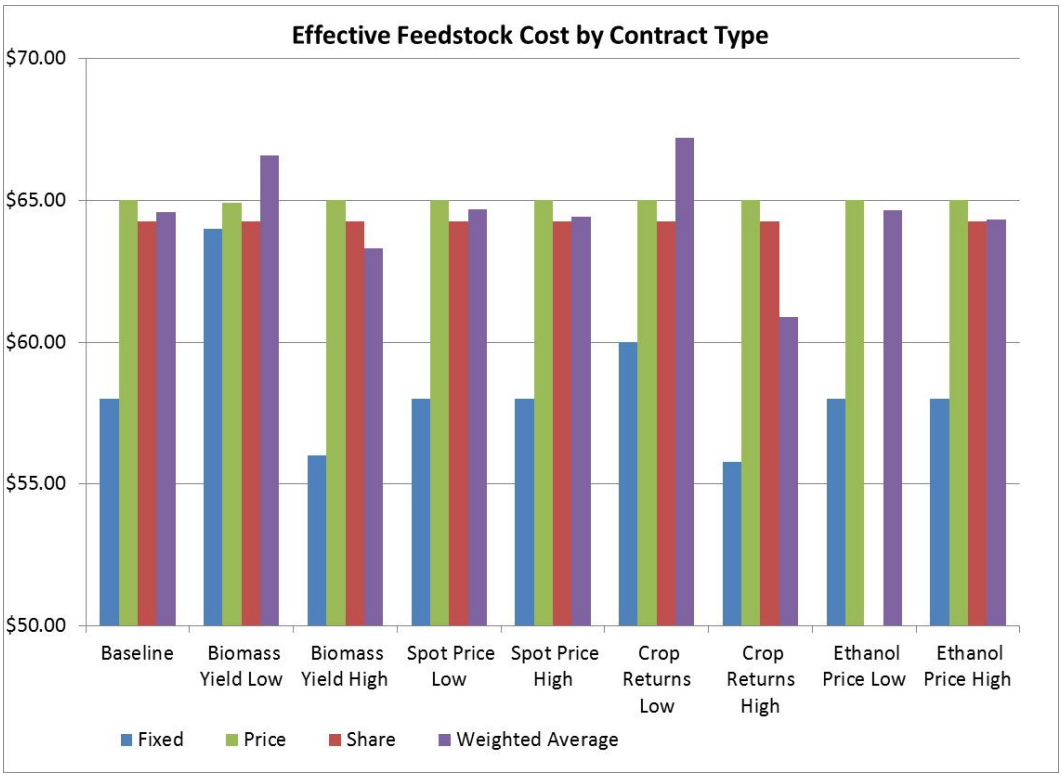

Figure 5. Effective Feedstock Cost by Contract Type Across Risk Scenarios

We illustrate the effects of variations in the riskiness of biomass production and prices on the effective cost of the feedstock grown under different contracts in figure 5. The effective cost of the feedstock under profit sharing contract are very similar to those for the fixed price contract and do not vary significantly across scenarios. A change in the variability of the biomass yields and returns primarily affects the land rent at which farmers are willing to lease their land for biomass production, and the effective cost of feedstock under the fixed lease contract. As compared to the benchmark case, when row crop return variability is low, the biorefinery can offer lower rental rate for land to produce biomass. This results in a relatively low weighted average cost of biomass in this scenario. The scenario with low relative variability in row crop returns results in the highest average cost of feedstock, due mainly to the higher land rent required in this case. Somewhat surprisingly, average feedstock costs are also relatively high when biomass yield variation is low. This is due to the higher rental rate and greater reliance on the fixed price contract in this scenario. Note that while the average feedstock price in the high biomass yield risk scenario is low, the refiner is also facing a considerable amount of feedstock supply risk as more than 70% of their total feedstock supplies are coming from fixed lease contracts and the spot market.

4.3 Effect of Farmers' Risk Preference and Land Quality

We also investigate the relationship between the variation in farmers' risk aversion coefficient and the profitability of the biorefinery. The results are shown in Table 3, and show that the optimal contract terms are affected by the distribution of farmers' risk preferences.

Table 3. Risk Dispersion Coefficient, Land Quality and Optimal Contract

Parameter Values	Contract 1 Rent: $/Acre (Signup Rate)	Contract 2 Price: $/ton (Signup Rate)	Contract 3 Share (Signup Rate)	Percentage of Biomass from Spot Market	Profit (Rate of return)
Baseline($\sigma = 0.0045$) (Average net return = $150/acre)	90 (30.86%)	65 (11.65%)	0.34 (4.86%)	28.95%	$5.47M (8.68%)
Concentrated Risk Averse Case ($\sigma = 0.0015$)	100 (39.61%)	65 (4.92%)	0.34 (0.0006%)	33.20%	$5.22M (8.28%)
Diversified Risk Averse Case ($\sigma = 0.0075$)	70 (27.05%)	65 (11.42%)	0.34 (11.30%)	25.35%	$6.02M (9.55%)
Low Land Quality Case (Average net return = $100/acre)	70 (44.47%)	60 (4.48%)	0.32 (16.60%)	1.7%	$8.21M (13%)
High Land Quality Case (Average net return = $200/acre)	100 (23.60%)	65 (5.62%)	0.34 (3.05%)	51.59%	$4.21M (6.69%)

We examine three levels of dispersion in risk preference level. If the farmers are all concentrated around the mean value of risk preference, the biorefinery needs to pay a higher land rent to farmers to induce them to participate in the bioenergy crop production; this results in lower profits for the biorefinery. If farmers exhibit diversified risk preference, the the land rent required to induce leasing of land for energy crop production is lower because the proportion of risk averse farmers decreases compared with the benchmark case. Farmers' contract choices are illustrated in figure 6. We observe more farmer participation in the diversified case compared with concentrated risk preference case. The biorefinery will achieve the highest rate of return under a high degree of heterogeneity in risk preferences.

Concentrated Case Baseline Case Diversified Case

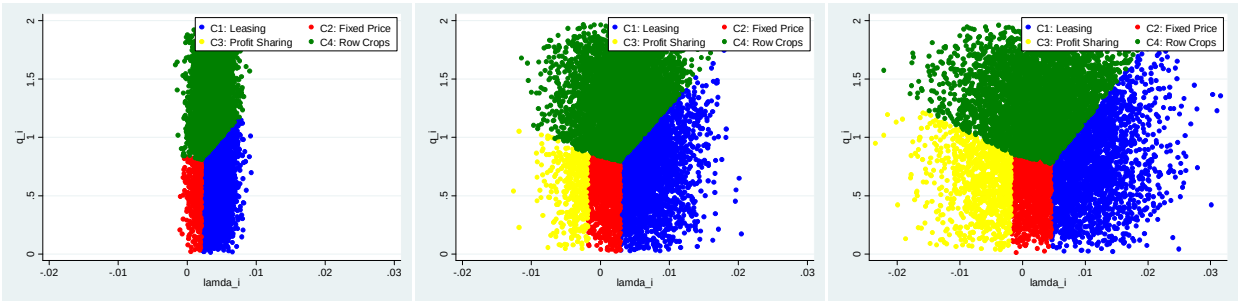

Figure 6. Risk Preference Dispersion and Farmers' Contract Choices

The last two rows in table 3 also show that the optimal contract term is also affected by the distribution of farmers' land quality. If the biorefinery is situated in a region dominated by low land quality, it is able to access biomass at a relatively low cost and earn a higher rate of return as compared to the case where it is located in a high land quality area.

5. Conclusions

This paper undertakes an integrated analysis of the decision of farmers to grow an energy crop and their contract choice simultaneously with a biorefinery's decision about the contract terms they are willing to offer. The joint optimization by farmers and the refinery determines the optimal contract terms and the allocation of land for biomass production under alternative contractual arrangements. We show the impact of risk preferences, land quality and riskiness of biomass production and prices on the optimal contract terms and the effective cost of biomass production. Specifically, we evaluate three types of contract arrangements between biorefinery and farmers: leasing contract, fixed price contract and profit sharing contract. These contract arrangements differ in both profitability and riskiness.

Our findings suggest that farmers' land allocation decisions depend on the joint distribution of their individual land quality and risk preferences. Farmers with a lower land quality and a higher degree of risk aversion are willing to lease their land for biomass production while those with low land quality but low degree of risk aversion are more willing to grow the energy crop themselves under a profit sharing contract. A biorefinery will prefer to be more vertically integrated and grow its own energy crop when biomass yield and price risks are high to

avoid paying a high risk premium to risk averse farmers. It will also prefer to be more vertically integrated when the variability in returns to crop production is high and risk averse farmers are more willing to choose leasing land for energy crop production as a safer option. We also investigated the relationship between the variation in farmers' risk aversion coefficient and regional distribution of land quality and the profitability of the biorefinery. We find that the biorefinery earns a higher profit if there is a big variation in farmers' risk aversion coefficients keeping everything else constant and if the average land quality is lower. This finding suggests that the biorefinery should choose a location where farmers have diverse risk preferences and lower land quality.

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7. Appendix

Proof of Corollary 1:

From Proposition 1-4, the lower limit of the span is determined by the following condition:

$$\frac{\omega_1+\lambda_i{\sigma_C}^2}{\bar{\pi}_C}=\frac{\alpha\bar{P}_E G\bar{Y}_B-C_0\ -\lambda_i\left({\bar{Y}_B}^2G^2{\sigma_E}^2+{\bar{P}_B}^2{\sigma_1}^2+{\sigma_B}^2{\sigma_1}^2-{\sigma_C}^2\right)}{\bar{\pi}_C}$$

$$\lambda_{13}=\frac{\alpha\bar{P}_E G\bar{Y}_B-C_0\ -\omega_1}{{\bar{Y}_B}^2G^2{\sigma_E}^2+{\bar{P}_B}^2{\sigma_1}^2+{\sigma_B}^2{\sigma_1}^2}$$

Hence,

$$q_{13}=\frac{\omega_1}{\bar{\pi}_C}+\frac{{\sigma_C}^2(\alpha\bar{P}_E G\bar{Y}_B-C_0-\omega_1)}{\bar{\pi}_C({\bar{Y}_B}^2G^2{\sigma_E}^2+{\bar{P}_B}^2{\sigma_1}^2+{\sigma_B}^2{\sigma_1}^2)}$$

The upper limit of the span is determined by:

$$\frac{\bar{P}_1\bar{Y}_B-C_0\ -\lambda_i\left({\bar{P}_B}^2{\sigma_1}^2+{\sigma_B}^2{\sigma_1}^2-{\sigma_C}^2\right)}{\bar{\pi}_C}$$
$$=\frac{\alpha\bar{P}_E G\bar{Y}_B-C_0\ -\lambda_i\left({\bar{Y}_B}^2G^2{\sigma_E}^2+{\bar{P}_B}^2{\sigma_1}^2+{\sigma_B}^2{\sigma_1}^2-{\sigma_C}^2\right)}{\bar{\pi}_C}$$

$$\lambda_{23}=\frac{\alpha\bar{P}_E G\bar{Y}_B-\bar{P}_1\bar{Y}_B}{{\bar{Y}_B}^2G^2{\sigma_E}^2}$$

Hence,

$$q_{23}=\frac{\bar{P}_1\bar{Y}_B-C_0}{\bar{\pi}_C}+\frac{({\bar{P}_B}^2{\sigma_1}^2+{\sigma_B}^2{\sigma_1}^2-{\sigma_C}^2)(\alpha\bar{P}_E G\bar{Y}_B-\bar{P}_1\bar{Y}_B)}{\bar{\pi}_C({\bar{Y}_B}^2G^2{\sigma_E}^2)}$$