Mitigating Feedstock Supply Risk in Corn Stover Biofuel Production

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Abstract

We develop an economic model of cellulosic biofuel production under stover supply uncertainty. The model considers three contract arrangements that vary according to risk-sharing between the processor and farmers and allows us to evaluate the processor's choices of plant size and contract terms that acquire corn stover feedstock with relatively low variability. We apply the model to corn stover-based ethanol in U.S. crop reporting districts. A greater quantity of biofuel is supplied at lower cost under right-of-access contracts than a delivered quantity contract. However, the processor bears most of the stover production risk with right-of-access contracts. The processor can lay off some of this risk by contracting excess acreage, and if available, by purchasing deficit stover from a spot market. Contracting excess acreage increases the expected biofuel cost but results in lower uncertainty surrounding cellulosic biofuel supply. A biomass spot market provides a source of biomass during low yielding years, but can also create competition for the processor by providing an alternative outlet for farmers to supply stover. Our results also suggest that farmers' contract preferences are responsive to the basic structure of incentives. As the industry develops and market uncertainties change, rigidity of farmers' contract preferences are not expected to limit the processor's adjustment process.

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I. Introduction

Agricultural producers, biorefiners, and the broader U.S. energy sector have had roughly one decade to adjust to the Renewable Fuel Standard (RFS) legislation passed in 2005. Since the introduction of the RFS and revised RFS (Energy Independence and Security Act of 2007), the U.S. corn ethanol industry expanded rapidly and has been producing 860-930 thousand barrels/day in recent years (EIA, 2015). Despite the considerable expansion in first generation biofuels, advanced biofuels from crop residues, perennial grasses, woody biomass, and municipal waste have not experienced appreciable growth. The U.S. has a significant amount of potential biomass feedstock, in particular corn stover in Midwest and Plains states (Turhollow et al., 2014), but only three commercial-scale cellulosic ethanol plants have opened in the U.S. to date and none are operating at capacity. Policy uncertainty, feedstock acquisition uncertainty, processing technologies and associated costs, biofuel and oil prices, and other risks continue to play an important role in the development of advanced biofuel industries (Alexander et al., 2012; Rosburg and Miranowski, 2011; Yang et al., 2015). In the present study, we focus our attention on feedstock supply risk, in part because this source of economic risk is most directly manageable by individual biorefiners.[2]

With the major gap between U.S. advanced biofuel production and initial policy targets, strategies for identifying sources and magnitudes of feedstock supply uncertainty and risk mitigation are beginning to be rigorously studied. This area of research builds upon the body of literature that uses simulation analysis or non-linear programming models to evaluate farmer willingness to supply biomass at alternative prices (e.g., Egbendewe-Mondzozo et al., 2015; Okwo and Thomas, 2014; Sesmero et al., 2015; Thompson & Tyner, 2014; Vadas & Digman, 2013). Most of these studies, however, do not specify the contract arrangements or the share of biomass supply risk borne by the processor and farmer. The types of contracts, as well as contract terms, are fundamental decisions for processors to lay off biomass supply risk and an important determinant of farmer participation (Alexander et al., 2012; Altman et al., 2008). As a result, a smaller, more recent literature has emerged that evaluates the profitability and risk-mitigation characteristics of pay-for-performance contracts.

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[2] Although important, several other sources of uncertainty are either practically exogenous or only influenced in the very long run. For example, individual biorefiners accept national policy uncertainty as given (although trade associations could have some influence), and oil prices are generally determined on world markets. Improvements in processing technologies require consistent investment in research and development, and private benefits may not be realized until decades after initial conception.

One such study is Yang et al. (2015), who examine farmer's willingness to enter into energy crop contracts when ethanol price, row crop per-acre return, biomass yield and spot market price are uncertain and local farmers differ in land quality, risk preference, and time preference. While the processor can increase expected profits by offering multiple contract types, a majority of contracting farmers select a land-lease contract over a fixed price or revenue-sharing contract. Yoder et al. (2015) also evaluate energy crop contracts (*Miscanthus*) and find that risk is minimized for both the farmer and processor with a contract that provides a per acre base payment combined with a per ton payment. Larson et al. (2008) consider potential corn stover, switchgrass and wheat straw supplies in northwest Tennessee under alternative contract arrangements. With risk averse farmers, a contract with annual payments based on expected yields rather than annual yields leads to the largest biomass supply, which is primarily switchgrass. Using a game-theoretic approach, Golecha & Gan (2016a, 2016b) analyze corn stover contract arrangements under different market structures and year-to-year variation in stover supply. While stover supply risk raises cost and reduces potential supply, selecting the optimal contract arrangement for a given market structure and other strategies such as feedstock diversification and excess contracting can help mitigate risk.

We build on these studies by modeling the processor's cost-minimizing choices of plant size and contract terms to acquire corn stover feedstock with relatively low variability. We consider three contracts that vary according to risk-sharing and which replicate currently-existing contracts or those most likely to develop. Our contributions to the literature include: (i) endogenizing biofuel plant size, (ii) evaluating the processor's potential to lay off risk of operating under capacity through contracting excess acreage or purchasing feedstock deficits in a spot market, (iii) including alternative sources of stover supply uncertainty, (iv) modeling the tradeoff between capture radius and participation rate in feedstock acquisition, and (v) considering multiple plant locations in major corn growing regions of the U.S.

A strength of our empirical investigation is a spatially-disaggregated analysis across 40 high-yielding crop reporting districts (CRDs) in Midwest and Plains states. This is facilitated through the use of two unique datasets. First, we use corn yield data from the only nationally-representative source of farm- and field-level information, the USDA's Agricultural Resource Management Survey (ARMS). Second, parameters related to stover yields and harvest, storage, and nutrient replacement costs are based on five years of data (2011 – 2015) from a commercial-scale corn stover research project (Iowa State University Stover Research Project). To our knowledge, this is the first study to use fine-scale data to jointly model stover contract arrangements and biorefinery plant size decisions.

The paper proceeds as follows. In the next section, we develop the theoretical model under the three contract strategies. Empirical model assumptions and an overview of the data follow. We then present baseline model results and sensitivity analyses to certain model assumptions. We conclude with a discussion of implications for potential growth and development of the stover ethanol industry.

II. Model

Consider a risk-neutral biofuel processor that is building a plant in a region with no biomass spot markets and with heterogeneous farmers that each manage one acre of land in corn production.[3] Farmers are assumed to differ in land quality (i.e., expected corn and stover yield) and will decide whether to enter into a stover contract with the processor. The farmer's decision will depend on his individual characteristics (i.e., land quality, rotation practice) and the contract terms offered by the processor (i.e., contract price, risk sharing). The processor takes the distribution of local farmer characteristics as given and recognizes that farmer participation, and therefore stover supply, will depend on the contract terms offered. The processor's objective is to minimize long-run total cost per gallon of biofuel by choosing the plant size and the stover contract terms.[4]

While there could be many potential contract arrangements between a biofuel processor and farmers, we evaluate three contract arrangements that are similar to currently-existing contracts or those likely to develop. The three contracts vary according to risk-sharing and incidence of harvest, storage, and transportation (HST) costs. The first arrangement is a right of access (ROA) contract where the processor offers the farmer a fixed payment value (P_{ROA_1}) for a contracted acre. The processor then coordinates all aspects of stover HST. Under the ROA contract, the processor bears all stover supply risk except uncertainty in nutrient replacement cost, which is borne by the farmer under all contract arrangements.

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[3] While spot markets for biomass are not common today, they may develop in the future with increased biomass demand. We consider the existence of a developed spot market in the results section.

[4] We minimize long-run average cost rather than maximize long-run profits for two reasons. First, this approach follows previous literature on the optimal biofuel plant size (e.g., Gan & Smith, 2011; Leboriero & Hilaly, 2011, 2013; Searcy & Flynn, 2009). Second, cellulosic biofuel is not likely to achieve long-run breakeven at current oil prices (Rosburg & Miranowski, 2011). Plants would not be built (i.e., the optimal plant size would be zero) without significant fiscal incentives, higher long-run fuel prices, or enforced mandates.

The second arrangement is an ROA contract with two payment components – a small (fixed) per acre payment (P_{ROA_2}) regardless of stover removal and variable payment (P_S) for each ton of stover harvested from the contracted acre. We will refer to this contract as the ROAq contract. Similar to the one-part ROA contract, the processor coordinates all components of HST and bears all HST risk. However, with a variable payment mechanism, the processor and farmer both bear stover yield risk.

The final contract is a delivered quantity (Del Q) contract where the processor contracts with the farmer for a delivered quantity of stover at a per ton price (P_{DS}). The farmer coordinates all components of HST and is assumed to contract his expected harvestable yield. Since stover quality affects the processor's conversion yield or gallons of biofuel per ton of stover (Aden & Foust, 2009; Kenney et al., 2013; Weiss et al., 2010; ISU Stover Research Project, 2011-2015), the processor incentivizes farmers to use HST practices that preserve stover quality by conditioning the per ton price on a minimum quality level. Specifically, the processor imposes a fixed per ton penalty if delivered stover is below a minimum quality level. Further, if the farmer's realized harvestable yield does not cover the contracted quantity, the farmer incurs a penalty or cost per ton unfilled.[5] Sensitivity analysis will consider development of a spot market where the farmer can purchase deficit biomass during low yielding years. Under the Del Q contract, the farmer bears all stover yield and HST risk.

For each contract, the processor's decision is what price to offer under the contract arrangement, and the farmer's decision is whether to accept the offered contract arrangement. The processor does not price discriminate and offers all farmers in the region the same price for each contract type. We formalize the model in two stages. In the first stage, we model the farmer's decision under the three contract designs. Given the distribution of local farmer characteristics, the first stage provides information on the willingness of local farmers to participate under each contract design. The second stage incorporates this participation information into the processor's cost-minimization problem.

II.A Farmer's decision

Consider a corn farmer *j* that decides whether to accept the stover contract arrangements offered by the processor. Farmer *j* makes the decision that maximizes his utility, which is a nonlinear function of profit. Since

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[5] In the equations that follow, we model this as a fee charged by the facility for production underage. Alternatively, this cost could represent the cost to procure additional stover from non-contracted corn acreage in the area.

the outcome of interest is whether the farmer decides to accept the stover contract, we define profit as stover-related profits only. In other words, we model stover supply as a potential value-added enterprise for the farmer and secondary to the corn acreage decision. Implicit in this assumption is that stover contracts will not incentivize a switch in land use towards corn production or change the farmer's rotation practice.[6] We also exclude any profit terms that are independent of the stover contract decision (i.e., costs that a farmer would incur whether he decides to contract or not), such as corn establishment cost or land opportunity cost.[7]

Farmers are assumed to have an established crop rotation practice, either continuous corn (CC) production or a corn-soybean (CS) rotation. If a farmer is in a CS rotation, we assume the farmer has two acres of equivalent quality land and rotates each acre on opposite years such that he always has one acre of corn production. It is generally agreed that CC production incurs a yield penalty (or 'yield drag') relative to a CS rotation (Birrell et al., 2014; Karlen et al., 2014; Sindelar et al., 2013). However, recent agronomic findings also suggest that stover removal on CC production provides a modest corn yield increase (or 'yield bump') in the following year, effectively offsetting some (but not all) of the yield drag (Birrell et al., 2014; Coulter & Nafziger, 2008; Ertl, 2013; Jeschke & Heggenstaller, 2012; Karlen et al., 2014; Pantoja et al., 2015; Sindelar et al., 2013).

Let $\pi_{i,j}$ denote farmer j's realized profit per acre with contract type i. Equations (1) – (3) describe farmer j's profit function for each contract type if the farmer had an expected harvestable stover yield of $\bar{Y}_{HS,j}$ but a realized harvestable stover yield of $Y_{HS,j}$. Farmer j's realized profit if he does not contract with the processor is denoted as $\pi_{NC,j}$ and equals zero in the baseline case where no biomass spot market exists. Table 1 summarizes the notation used.

$$\pi_{ROA,j} = P_{ROA_1} - n + \beta I_{CC} P_C \Delta Y_{C,j} \tag{1}$$

$$\pi_{ROAq,j} = P_{ROA_2} + P_S Y_{HS,j}(r) - n + \beta I_{CC} P_C \Delta Y_{C,j} \tag{2}$$

$$\begin{aligned}\pi_{DQ,j} = {} & P_{DS}\bar{Y}_{HS,j}(r) - (c_H + c_S + c_T + I_{q,j}c_q)\bar{Y}_{HS,j}(r) - n + I_{L,j}(Y_{HS,j}(r) - \bar{Y}_{HS,j}(r))(c_L + P_{DS} - \\ & c_H - c_S - c_T - I_{q,j}c_q) + \beta I_{CC} P_C \Delta Y_{C,j}\end{aligned} \tag{3}$$

$$\pi_{NC,j} = 0 \tag{4}$$

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[6] The potential value-added from supply stover is relatively low such that stover contracts are unlikely to induce large changes in rotation practices, unlike land use change in the Corn Belt induced by corn ethanol (Wallander et al., 2011).

[7] While we do not account for land opportunity cost, we account for stover opportunity cost. The baseline case assumes the next best alternative use for stover is soil nutrient value; however, this value could easily be modified to represent other end use values such as bedding material.

Table 1. Parameters and variables in farmer's problem

Notation	Definition/description
$P_{ROA,1}$	ROA payment per acre offered with ROA contract
n	Nutrient replacement cost per acre
β	Annual discount factor
$I_{CC,j}$	Indicator variable if farmer *j* has land in continuous corn production (i.e., *r* = *CC*)
P_C	Expected corn profit margin per bushel next year
$\Delta Y_{C,j}$	Expected increase in farmer *j*'s next year's corn yield (bu/acre) from stover removal this year
$P_C \Delta Y_{C,j}$	Expected increase in farmer *j*'s next year's corn profits (per acre) due to stover-removal yield bump[8]
$P_{ROA,2}$	ROA payment per acre offered with the ROAq contract
P_S	Per ton stover price offered with the ROAq contract
$Y_{HS,j}(r)$	Farmer *j*'s realized harvestable stover yield with rotation *r*
$\bar{Y}_{HS,j}(r)$	Farmer *j*'s expected harvestable stover yield with rotation *r*
r	Rotation practice (CC or CS)
P_{DS}	Per ton price offered for delivered stover with the Del Q contract
c_H	Harvest cost per ton
c_S	Storage cost per ton
c_T	Transportation cost per ton to the biorefinery
$I_{q,j}$	Indicator variable if farmer *j*'s delivered stover quality is below the acceptable threshold
c_q	Per ton penalty if delivered stover quality is below the acceptable threshold
$I_{L,j}$	Indicator variable if farmer *j*'s realized yield is below the expected yield (i.e., $Y_{HS,j} \leq \bar{Y}_{HS,j}$)
c_L	Per ton penalty if delivered stover is less than quantity contracted (i.e., $Y_{HS,j} \leq \bar{Y}_{HS,j}$) and no spot market exists

We assume the farmer maximizes a second-moment utility function, $U(\bar{\pi}, \sigma_\pi^2) = \bar{\pi} - \gamma_j \sigma_\pi^2$, where $\bar{\pi}$ denotes expected profits, γ_j represents farmer j's degree of risk aversion and σ_π^2 captures the variance of profits. Throughout, overbars will denote expected values. The utility function is assumed to be increasing in expected profits ($U_1 > 0$), decreasing in variance of expected profits ($U_2 < 0$), and separable in expected profit and variance of profit ($U_{12} = 0$). This functional form allows for heterogeneity in attitude toward risk, as indicated by γ_j. However, for simplicity, we assume corn farmers within each region have similar risk preferences and set $\gamma_j = \gamma$ for all *j* and test the sensitivity of results to the assumed γ value. We make this simplifying assumption in preparation for our empirical analysis; data on the variation in risk preferences within local corn markets is not readily available. The assumption that risk preferences are relatively homogenous may best reflect regions where large and relatively homogeneous corn farmers are more likely to contract than smaller farmers.[9]

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[8] The yield bump will vary over time. However, without sufficient data to approximate a distribution, we assume a risk-free expected yield bump, i.e., $var(P_C \Delta Y_{C,j}) = 0$.

[9] This assumption may not hold for dedicated feedstocks that require a shift in land use (e.g., perennial grasses). Yang et al. (2015) consider this issue and evaluate the impact of heterogeneity in risk preferences among potential energy crop suppliers on biorefinery profitability. In the absence of data on farmers' risk preferences, we focus our attention on other factors affecting biomass supply.

We consider four main sources of uncertainty: harvestable stover yield, stover quality, nutrient replacement cost, and harvest cost. Further, we allow uncertainty in harvestable stover yield to stem from two sources – uncertainty in in-field stover production due to weather and uncertainty in collection efficiency. Specifically, we assume that harvestable stover yield takes the form $Y_{HS,j} = cY_{S,j}$ where $c \in (0,1)$ is the collection rate and $Y_{S,j}$ is the realized (in-field) stover yield such that variance in harvestable stover yield is $\sigma_Y^2 = \sigma_W^2 + \sigma_C^2$.[10] For stover quality, we assume $I_{q,j}$ is distributed Bernoulli where $I_{q,j} = 1$ with probability θ. Finally, variance in nutrient replacement cost per acre and harvest cost per ton are denoted as σ_n^2 and σ_H^2, respectively. Sensitivity analysis will also consider existence of a biomass spot market with uncertainty in the spot market price.

Assuming these sources of uncertainty, farmer *j*'s utility for each contract type and for not contracting are expressed in equations (1)' – (4)'. For notational simplicity, we assume independence (i.e., zero correlation) among variables; however, independence could be relaxed without much difficulty in an empirical application. The complete derivation for equation (3)' is provided in Appendix A.

$$U\left(\bar{\pi}_{ROA}, \sigma_{\pi,ROA}^2\right) = P_{ROA_1} - \bar{n} - \gamma\sigma_n^2 + \beta I_{CC} P_C \Delta Y_{C,j} \tag{1'}$$

$$U\left(\bar{\pi}_{ROAq}, \sigma_{\pi,ROAq}^2\right) = P_{ROA_2} + P_S \bar{Y}_{HS,j} - \bar{n} - \gamma[P_S^2\sigma_Y^2 + \sigma_n^2] + \beta I_{CC} P_C \Delta Y_{C,j} \tag{2'}$$

$$\begin{aligned} U\left(\bar{\pi}_{DQ}, \sigma_{\pi,DQ}^2\right) = {} & P_{DS}\bar{Y}_{HS,j} - \left(\bar{c}_H + c_S + c_T + \theta c_q\right)\bar{Y}_{HS,j} - \bar{n} + \beta I_{CC} P_C \Delta Y_{C,j} + \omega\sigma_Y\big(c_L + P_{DS} - \bar{c}_H - \\ & c_S - c_T - \theta c_q\big) - \gamma\big\{\bar{Y}_{HS,j}^2\left(\sigma_H^2 + \sigma_q^2\right) + \sigma_n^2 + 0.5\big(\sigma_Y^2[2 - \omega^2]\left(\sigma_H^2 + \sigma_q^2\right) + \\ & \left(c_L^2 + P_{DS}^2 + \bar{c}_H^2 + c_S^2 + c_T^2 + \theta^2 c_q^2\right)\sigma_Y^2[1 - \omega^2]\big)\big\} \end{aligned} \tag{3'}$$

where $\omega = -\frac{0.399}{0.500}$ and $\sigma_q^2 = \theta(1-\theta)c_q^2$.

$$U(\bar{\pi}_{NC}, \sigma_{NC}^2) = 0 \tag{4'}$$

If farmer *j* is offered contract *i*, he will contract if $U\left(\bar{\pi}_i, \sigma_{\pi,i}^2\right) \geq U(\bar{\pi}_{NC}, \sigma_{NC}^2)$ and not contract otherwise. If farmer *j* is offered multiple contracts and allowed to choose a contract from the set of offered contracts *I*, he will contract if $U\left(\bar{\pi}_i, \sigma_{\pi,i}^2\right) \geq U(\bar{\pi}_{NC}, \sigma_{NC}^2)$ for at least one contract $i \in I$ and will choose the contract option that provides the highest utility, or $\max_{i \in I} U\left(\bar{\pi}_i, \sigma_{\pi,i}^2\right)$. We model a processor that offers all farmers one type of contract and therefore we do not derive explicit decision rules for multiple contract combinations. However, we can

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[10] More specifically, we assume $Y_{HS,j} = cY_{S,j} = \bar{c}\bar{Y}_{S,j} + \sigma_W\varepsilon_W + \sigma_C\varepsilon_C$, where $\varepsilon_W \sim N(0,1)$, $\varepsilon_C \sim N(0,1)$, and $\varepsilon_W \perp \varepsilon_C$ such that $Y_{HS,j} \sim N\left(\bar{c}\bar{Y}_{HS,j}, \sigma_W^2 + \sigma_C^2\right)$ and therefore $\left[Y_{HS,j} - \bar{Y}_{HS,j}\right] \sim N(0, \sigma_W^2 + \sigma_C^2)$.

provide some intuition on how parameter assumptions, risk, and heterogeneity in farmer characteristics will affect farmers' contract decisions.

First, farmers with higher land quality (i.e., higher expected harvestable stover yield) will be more likely to choose contract types with quantity-based payments (e.g., the ROAq and Del Q contract) relative to the ROA contract. Second, all else equal, a higher level of risk aversion (γ) will lower a farmer's utility from contracting and therefore lower the fraction of farmers willing to participate in stover supply at a given price. For a farmer that does contract, a higher level of risk aversion will provide more incentive to choose an ROA contract relative to a Del Q contract. Third, all else equal, a higher mean or variance in the harvest cost (c_H, σ_H^2), a higher penalty for low stover quality (c_q), or higher penalty for supply underage (c_L) will make farmers less likely to choose the Del Q contract and more likely to not contract if this is the only offered contract. Fourth, a decrease in the mean or variance in nutrient replacement cost per acre will increase utility from contracting relative to not contracting; however, the farmer's decision between contract types will not be affected.

Now, consider a processor that intends to offer all farmers one type of contract. For that contract type, each farmer has a minimum price above which he is willing to contract. Consider, for example, the ROA contract. Each farmer j has a "trigger" value of P_{ROA_1} above which they will contract and below which they will not contract. Farmer j's trigger value (i.e., the value of P_{ROA_1} such that $U\left(\bar{\pi}_{ROA}, \sigma_{\pi,ROA}^2\right) = U(\bar{\pi}_{NC}, \sigma_{NC}^2)$) can be determined from equations (1)' and (4)'. A similar approach can be used to determine farmer j's trigger value(s) for the ROAq and Del Q contracts. Therefore, given the distribution of local farmer characteristics, equations (1)' – (4)' identify the fraction of local farmers willing to enter that contract type (i.e., participation rate) as a function of the contract price(s) offered by the processor. The participation rate will be a non-decreasing function of the price offered by the processor. The processor recognizes that farmer participation is a function of the contract price offered and will use the information on local farmer participation when deciding plant size and contract terms.

II.B Processor's problem

The processor's objective is to minimize long-run total cost per gallon biofuel by choosing the plant size (Q) and the stover contract price. Decisions are conditional on plant technology and local stover supply conditions. The processor's cost function has two main components, the stover procurement cost and the biofuel processing cost. Stover procurement costs include all costs of getting stover to the plant. Depending on contract type, procurement costs might include ROA payments, per ton stover payments, and HST costs. For example, the processor will directly incur HST costs under the ROA contracts but will not (directly) incur these costs under the Del Q contract. Stover procurement costs will be an increasing function of plant size because either local farmers will require higher payments to induce larger stover supplies from the local area (i.e., the participation rate is an increasing function of the contract price offered) and/or larger stover supplies will be met by contracting stover from more distant areas. The model accounts for this intensive/extensive procurement tradeoff. Biofuel processing costs include per-gallon costs that are independent of biofuel plant size (i.e., operating costs) and per-gallon costs that depend on plant size and exhibit size economies (i.e., capital costs). We use an engineering power function to model capital cost size economies (Brown, 2003).

The processor minimizes expected long run costs per gallon. Given the sources of uncertainty considered, Equations (5) – (7) describe the processor's expected costs per gallon for each contract type. Table 2 summarizes the notation used.

$$\bar{C}_{ROA}\left(Q, P_{ROA,1}\right) = \min_{Q,P_{ROA,1}} \left[C_O + C_K \left[\frac{Q}{Q_0}\right]^{e-1} + \frac{1}{Y_O}\left[\frac{P_{ROA_1}}{\bar{Y}_{HS}} + \bar{c}_H + c_S + t\rho_D \sqrt{\frac{Q}{Y_O \cdot \bar{Y}_{HS} \cdot d_0 \cdot d(P_{ROA_1})}}\right]\right] \tag{5}$$

$$\bar{C}_{ROAq}(Q, P_S) = \min_{Q,P_S} \left[C_O + C_K \left[\frac{Q}{Q_0}\right]^{e-1} + \frac{1}{Y_O}\left[\frac{P_{ROA_2}}{\bar{Y}_{HS}} + P_S + \bar{c}_H + c_S + t\rho_D \sqrt{\frac{Q}{Y_O \cdot \bar{Y}_{HS} \cdot d_0 \cdot d(P_{ROA_2}, P_S)}}\right]\right] \tag{6}$$

$$\bar{C}_{DQ}(Q, P_{DS}) = \min_{Q,P_{DS}} \left[C_O + C_K \left[\frac{Q}{Q_0}\right]^{e-1} + \frac{P_{DS}}{Y_O}\right] \tag{7}$$

where

$$Q, P_{ROA_1}, P_S, P_{DS} \geq 0 .$$

Table 2. Additional parameters and variables in processor's problem

Notation	Definition/description
$\bar{C}_i(\cdot)$	Minimum long-run expected total cost per gallon biofuel with contract i
Q	Plant size (million gallons per year, mgy)
C_O	Operating costs per gallon
C_K	Per gallon capital costs for a baseline plant with capacity Q_0
e	Scaling factor for economies of size ($e < 1$)
Y_O	Biofuel yield per ton of stover
$\bar{Y}_{HS}$	Expected harvestable stover yield per acre from contracted acres
t	Transportation cost per ton per mile
ρ_D	Conversion factor that depends on the transportation system (e.g., circular capture area vs. square supply plane, road grid pattern)
d_0	Fraction, or density, of land that can potentially be allocated for stover production (i.e., percent of land in corn production)
$d(\cdot)$	Fraction, or density, of potential land (d_0) that contracts to supply stover (i.e., farmer participation rate)
$D = \rho_D \sqrt{\frac{Q}{Y_O \cdot \bar{Y}_{HS} \cdot d_0 \cdot d(\cdot)}}$	Average hauling distance (miles) for a capture region that secures enough stover to operate at capacity Q (French, 1960)[11]

Now, suppose the processor has built plant capacity Q that minimizes expected cost and offers the corresponding cost-minimizing contract prices (i.e., solutions to equations 5 – 7). The processor's actual per gallon cost after stover yields are realized will depend on whether the observed yield is above or below the expected yield. Equations (5)' – (7)' describe the processor's actual costs per gallon, where hat notation denotes realized values.

$$\hat{C}_{ROA} = \begin{cases} C_O + C_K\left[\frac{Q}{Q_0}\right]^{e-1} + \frac{1}{Y_O}\left(\frac{P_{ROA_1}}{\bar{Y}_{HS}} + \hat{c}_H + c_S + t\hat{D}\right), & if\ \hat{Y}_{HS} \geq \bar{Y}_{HS} \\ C_O + C_K\left[\frac{Q}{Q_0}\right]^{e-1}\left(\frac{Q}{\hat{Q}}\right) + \frac{1}{Y_O}\left(\frac{P_{ROA_1}}{\hat{Y}_{HS}} + \hat{c}_H + c_S + tD\right), & if\ \hat{Y}_{HS} < \bar{Y}_{HS} \end{cases} \tag{5'}$$

$$\hat{C}_{ROAq} = \begin{cases} C_O + C_K\left[\frac{Q}{Q_0}\right]^{e-1} + \frac{1}{Y_O}\left(\frac{P_{ROA_2}}{\bar{Y}_{HS}} + P_S + \hat{c}_H + c_S + t\hat{D}\right), & if\ \hat{Y}_{HS} \geq \bar{Y}_{HS} \\ C_O + C_K\left[\frac{Q}{Q_0}\right]^{e-1}\left(\frac{Q}{\hat{Q}}\right) + \frac{1}{Y_O}\left(\frac{P_{ROA_2}}{\hat{Y}_{HS}} + P_S + \hat{c}_H + c_S + tD\right), & if\ \hat{Y}_{HS} < \bar{Y}_{HS} \end{cases} \tag{6'}$$

$$\hat{C}_{DQ} = C_O + C_K\left[\frac{Q}{Q_0}\right]^{e-1} + \frac{P_{DS}}{Y_O} \tag{7'}$$

where

$$\hat{Q} = \left(\frac{r}{\rho_r}\right)^2 \cdot Y_O \cdot \hat{Y}_{HS} \cdot d_0 \cdot d(\cdot) \tag{8}$$

$$D = \rho_D\sqrt{\frac{Q}{Y_O \cdot \bar{Y}_{HS} \cdot d_0 \cdot d(\cdot)}} \tag{9}$$

$$\hat{D} = \rho_D\sqrt{\frac{Q}{Y_O \cdot \hat{Y}_{HS} \cdot d_0 \cdot d(\cdot)}} \tag{10}$$

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[11] French provides a flexible framework for modeling alternate transportation systems. The conversion coefficient, γ, can be adjusted for different transportation systems (i.e., average hauling distance vs. capture radius, circular vs. square supply plane, road grid, etc.). We calculate average hauling distance for a circular capture region with a square road grid. Capture radius can be calculated from the same general formula but with a γ value that reflects capture radius.

In a high yield year ($\hat{Y}_{HS} > \bar{Y}_{HS}$), the processor will have enough stover to operate at capacity under all contract arrangements. With the Del Q contract, farmers will fulfill their quantity contracts and the processor's actual cost will equal the expected cost. With the ROA contracts, stover supply from the contracted acreage will exceed the processor's feedstock demand. We assume the processor will not harvest or transport stover from acreage beyond what is needed to satisfy feedstock demand. Therefore, the processor will observe transportation cost savings from harvesting a smaller capture radius (i.e., average hauling distance of $\hat{D} < D$). The processor will still have to pay ROA fees to acres not harvested.

In a low yield year ($\hat{Y}_{HS} < \bar{Y}_{HS}$), the processor will not have enough stover from contracted acreage to operate at capacity. With the Del Q contract, the processor's actual cost will be unchanged assuming the fee farmer's pay for not satisfying their quantity contract (c_L) offsets the increase in the processor's cost from operating under capacity.[12] Without a spot market to purchase deficit biomass, the processor will be forced to operate under capacity (i.e., $\hat{Q} < Q$) with the ROA and ROAq contracts. Operating under capacity is costly as fixed capital costs and ROA payments are spread over fewer units.

III. Empirical application: assumptions and data

Potential plant locations are based on U.S. crop reporting districts (CRDs). A cost-minimizing biofuel processor will target areas with relatively high density of corn production and historically high corn yields. Therefore, we limit our analysis to CRDs with at least 10% of land area in corn production between 2010 and 2015 and with historical (detrended) average corn yield above 150 bushels per acre.[13] Figure 1 shows the 40 CRDs that satisfy these constraints and maps the mean harvestable stover yield for each CRD. Table 3 summarizes the data, assumptions, and their sources. As with related studies, parameters and assumptions for which data are not available primarily draw from engineering estimates and university crop budgets, e.g., Okwo and Thomas (2014).

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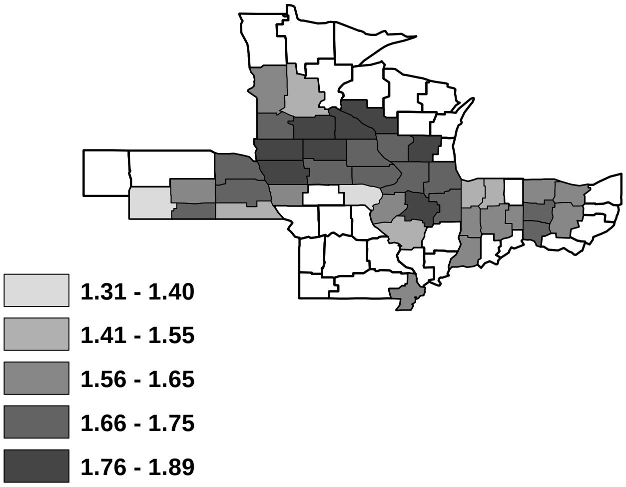
[12] Alternatively, if c_L represents the cost to the farmer to procure additional stover from non-contracted corn acreage in the area (see footnote 5), then farmers will fulfill their contracts and the processor will have sufficient biomass to operate at capacity.

[13] Total land area (including non-agricultural land) in each CRD is derived from the 2007 Agricultural Census. Historical average corn yields are based on detrended corn yields between 1970-2012 (NASS).

Figure 1 – CRD mean harvestable stover yield (tons/acre)



Farm-level expected corn yields are derived from 2009 – 2011 farm-level corn yield data (USDA-ERS ARMS).[14] Specifically, we fit a beta distribution to the pooled dataset of yield observations in each CRD and draw 50,000 observations from the fitted distribution. Data on the proportions of CRD acreage in continuous corn (CC) production are taken from NASS' Cropland Data Layer (CDL). The CDL data depict annual crop cover across the contiguous US at a resolution of 30 meters (m). Satellite imagery from multiple sources, including Landsat, Resourcesat, and the Disaster Monitoring Constellation, are coupled with "ground truth data" (e.g., Farm Service Agency's Common Land Unit data and the US Geological Survey's National Land Cover Dataset data) to produce the final cropland layers. For each 30m grid of agricultural land in a CRD, we first record to which crop (e.g., corn or soybeans) the grid is planted in 2014 and 2015. Among the grids that are planted to corn in 2014, grids that are planted to corn again in 2015 are considered to be in CC production. Our CRD-specific measure of CC acreage is thus the fraction of grids planted to corn in 2015 relative to grids planted to corn in 2014.[15] Land in CC production is assumed to incur a yield penalty (or yield drag) of 8% relative to land in CS rotation (Leibold, 2016) but benefit from a modest corn yield increase in the following year of 4% (synthesis value of findings in Birrell et al., 2014; Ertl, 2013; Jeschke & Heggenstaller, 2012; Karlen et al., 2014; Sindelar et al., 2013). The expected profit margin from the corn yield bump on CC land is assumed $1.00 per bushel.

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[14] To avoid outlier bias, we drop the top and bottom 5% from each CRD prior to fitting the beta distribution.

[15] We choose 2014 and 2015 because they are the most recent two-year sequence for which the CDL data are available. Other recent two-year sequences, such as 2013-2014 or 2012-2013, do not reflect current market conditions, though it is unlikely our baseline results would change substantially by using different reference years or an average across multiple years.

Table 3. Data and parameter assumptions

Parameter	Definition	Value	Level of Aggregation	Data/Source
$\bar{Y}_{HS,j}$	Farmer j's expected stover yield per acre	$0.95 * \frac{\bar{Y}_{C,j}(r)}{35.7} * \bar{c}$	Farmer-specific	ISU Stover Research Project (2011-2015)
$\bar{Y}_{C,j}(r)$	Farmer j's expected corn yield per acre	Farmer-specific	Farmer-specific	2009 – 2011 farm-level corn yields (ARMS)
r	Farmer j's rotation pattern (CC or CS)	Farmer-specific	Farmer-specific	2014-2015 Cropland Data Layer (NASS)
$\bar{c}$	Expected collection rate	39%	All CRDs	ISU Stover Research Project (2011-2015)
σ_C^2	Variance in collection rate	1%	All CRDs	ISU Stover Research Project (2011-2015)
σ_W^2	Stover yield variance due to weather	CRD-specific	CRD-specific	1970 – 2012 CRD average corn yields (NASS)
β	Annual discount factor	0.95	All CRDs	
$\Delta Y_{C,j}$	Increase in farmer j's next year's corn yield (bu/acre) from stover removal (CC only)	0.04*$\bar{Y}_{C,j}(CC)$	Farmer-specific	
P_C	Expected corn profit margin (per bushel) next year	$1	All CRDs	
$\bar{c}_H$	Expected harvest cost per ton	$35	All CRDs	ISU Stover Research Project (2011-2015)
σ_H^2	Variance in harvest cost per ton	$16	All CRDs	ISU Stover Research Project (2011-2015)
c_S	Storage cost per ton (including staging/loading)	$10	All CRDs	ISU Stover Research Project (2011-2015)
t	Transportation cost per ton per mile	$0.71	All CRDs	Wright & Brown (2007)
c_T	Farmer's transportation cost per ton to plant	$t * r$	All CRDs	
c_q	Per ton quality penalty	$10	All CRDs	
θ	Probability farmer believes delivered stover quality will trigger penalty	0.20	All CRDs	
$\bar{n}$	Expected nutrient replacement cost per acre (potassium and phosphorus)	$10*$\bar{Y}_B$	CRD-specific	ISU Stover Research Project (2011-2015), Karlen et al. (2015), Sawyer & Mallarino (2014)[a]
σ_n^2	Variance in nutrient replacement cost per acre	$16*$\bar{Y}_B^2$	CRD-specific	ISU Stover Research Project (2011-2015), Karlen et al. (2015), Sawyer & Mallarino (2014)[a]
γ	Farmer coefficient of risk aversion	0.00375	All CRDs	Yang et al. (2012)
Y_O	Biofuel yield per ton of stover	69.2 gallons/ton	All CRDs	Kazi et al. (2010)
Q_0	Baseline plant size	53.4 mgy	All CRDs	Kazi et al. (2010)
C_K	Per gallon capital costs for a baseline plant of size Q_0	$0.72 per gallon	All CRDs	Kazi et al. (2010)
C_O	Operating costs per gallon	$1.40 per gallon	All CRDs	Kazi et al. (2010)
e	Capital cost size economies factor	0.75	All CRDs	Several[a]
ρ_D	Conversion coefficient for average hauling distance	0.0189	All CRDs	French (1960)
ρ_r	Conversion coefficient for capture radius	0.0223	All CRDs	French (1960)
d_0	CRD harvested corn acreage	CRD-specific	All CRDs	NASS (2010-2015)
c_L	Per ton penalty if realized yield is less than quantity contracted (i.e., $Y_{HS,j} \leq \bar{Y}_{HS,j}$) and no spot market exists.	$20	All CRDs	

[a] Per ton costs provided by data sources and converted to per acre costs.

[b] Cameron et al., 2007; de Wit et al., 2010; Gan, 2007; Kaylen et al., 2000; Kumar et al., 2003; Leboreiro & Hilaly, 2011; Searcy & Flynn, 2009; Wright & Brown, 2007.

Farmer-specific expected harvestable stover yields ($\bar{Y}_{HS,j}$) are derived from the corn yield draws assuming a 0.95 stover-to-grain ratio and 39% collection efficiency (ISU Stover Research Project, 2011-2015). Appendix Figure B.1 maps the variation in expected harvestable stover yield among farmers in each CRD. Variation in harvestable stover yields due to weather uncertainty (σ_W^2) is CRD-specific and derived from the variance in detrended CRD-average corn yields from 1970 – 2012 (NASS). Specifically, for each CRD, we fit a non-parametric function to the detrended CRD-average corn yields and draw 100 observations from the fitted distribution. Assuming the 0.95 stover-to-grain ratio and 39% collection efficiency, the variance in harvestable stover yields due to weather uncertainty (σ_W^2) is the variance over these draws. Appendix Figure B.2 illustrates the CRD-specific variations in harvestable stover yield over time due to weather uncertainty. Variance in stover yields due to uncertainty in collection efficiency is assumed 0.01 for all CRDs (ISU Stover Research Project, 2011-2015).

Parameter assumptions for collection rate, harvest, staging/loading, storage, and nutrient replacement costs are taken from a corn stover research project in central Iowa. Starting in 2008, researchers at Iowa State University, in conjunction with DuPont, collected data on commercial-scale corn stover production from harvest to delivery (ISU Stover Research Project). We use data from the most recent five years of the study (2011-2015) to derive our parameter assumptions. While the project data are from central Iowa only, many of the cost parameters are representative of industrial-level stover HST. Based on these data, the average harvest cost is assumed to be \$35 per ton ($\bar{c}_H$) and the variance in harvest cost per ton to be \$16 (σ_H^2). Staging, loading, and storage costs are assumed \$10 per ton (c_S). The per ton nutrient replacement cost averages \$10 with a variance of \$4 per ton (ISU Stover Research Project, 2011-2015; Karlen et al, 2015; Sawyer & Mallarino, 2014). Nutrient replacement costs per acre are assumed to be CRD-specific but equal for all farmers in each CRD. Per acre nutrient replacement cost is calculated as the per ton nutrient replacement cost (\$10) multiplied by the expected stover yield within the CRD ($\bar{Y}_{HS}$).

Stover transportation cost for the processor is equal to the variable transportation cost (t) times the average hauling distance (D). The variable transportation cost is assumed \$0.71 per ton-mile (Wright & Brown, 2007). Average hauling distance is a function of plant size, biofuel yield, percentage of land in corn production, and the farmer participation rate at the contract price(s) offered. The percentage of land in corn production (d_0) is derived from CRD-level data on harvested corn acreage (2010-2015, NASS). For farmers, we assume that the transportation cost to the plant (c_t) is the same for all farmers and equal to the variable transportation cost times the capture radius (r). Capture radius is calculated using the same formula as average hauling distance (equation 9) but with a γ value that reflects capture radius (γ_r).

Biofuel processing costs are taken from engineering estimates for a 53.4 million gallon per year (mgy) corn stover to ethanol plant using a biochemical process (Kazi et al., 2010). Capital costs for the 53.4 mgy plant (Q_0) are \$376 million (2007\$). Assuming a 20 year plant life, an interest rate of 8%, and a biofuel yield of 69.2 gallons per ton of stover (Y_O), the capital costs for the baseline plant are \$0.72 per gallon (C_K). The capital cost size economies factor (e) is assumed 0.75. Excess electricity from burning lignin (a co-product of processing) is sold to the power grid. After accounting for this co-product credit, operating (processing) costs (C_O) are approximately \$1.40 per gallon.

IV. Results

We first present results for our baseline case and discuss contract structures and institutional arrangements that could mitigate potential biofuel supply risk. This is followed by sensitivity analyses to certain model assumptions. We finish with a discussion of implications for potential growth and development of a stover ethanol industry, assuming current policies and technologies.

IV.A Baseline analysis

For the 40 plant locations considered, Table 4 summarizes the cost-minimizing decisions across contracts. Relative to the Del Q contract, the ROA contracts lead to higher farmer participation and larger optimal plant capacity for most locations. Since the processor bears most of the stover supply risk with the ROA contracts, farmers require a smaller risk premium to contract.[16] However, a benefit of the Del Q contract is that higher-yielding farmers have the greatest incentive to contract which leads to a higher expected stover yield from contracted farmers relative to the ROA contracts. The slightly higher yield, however, does not offset the lower

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[16] Recall that the risk premium is the minimum amount by which the expected return on a risky asset must exceed the known return on a risk-free asset to induce an individual to hold the risky asset. In our case, without a biomass spot market, purchase of the risky asset is analogous to entering into a stover contract, while the risk-free asset is analogous to not contracting.

participation rate and higher risk premium, and as a result, a greater quantity of biofuel is supplied at lower cost under the ROA contracts than the delivered quantity contract.

Table 4 – Summary of cost-minimizing decisions across contract options

(Reported values are median values over the 40 districts; min-max range in parentheses)

	ROA	**ROAq**	**Del Q**
Ethanol cost per gallon, *C* ($/gal)	$3.16 (3.07-3.31)	$3.16 (3.07-3.33)	$3.30 (3.19-3.47)
Plant size, *Q* (mgy)	88 (37-128)	82 (34-121)	71 (29-111)
Capture radius, *r* (miles)	35.9 (29-41)	36.2 (29-42)	35.9 (29-41)
Contracted acreage (%)[a]	30% (13%-48%)	27% (11%-45%)	23% (10%-43%)
Expected yield from contracted farmers (tons/ac)	1.66 (1.3-1.9)	1.73 (1.5-2)	1.76 (1.55-2)

[a]Contracted acreage is the product of CRD corn density (i.e., percentage of corn acreage) and the farmer participation rate.

Figure 2 provides the estimated aggregate biofuel supplies under the three contracts assuming each location builds at their cost-minimizing plant size. Aggregate biofuel production from the 40 CRDS reaches 3.5, 3.25 and 2.9 bgy for the ROA, ROAq, and Del Q contracts. As noted above, if each CRD observes the expected stover yield, biofuel cost is lower and biofuel supply is higher under the ROA contracts relative to the Del Q contract. However, the processor bears a majority of the stover production risk with the ROA contract (farmer bears only nutrient replacement cost risk) and most of the stover production risk with the ROAq contract. The 90% confidence intervals for these contracts in Figure 2 represent biofuel supply if each district builds capacity based on the expected yield but observes the 5th and 95th percentile stover yield draw.[17] When yields are below expectation, the processor operates under capacity which is costly as fixed costs are spread over fewer units. When yields are above expectation, the processor saves on stover transportation cost as a smaller capture radius is needed to satisfy feedstock demand.

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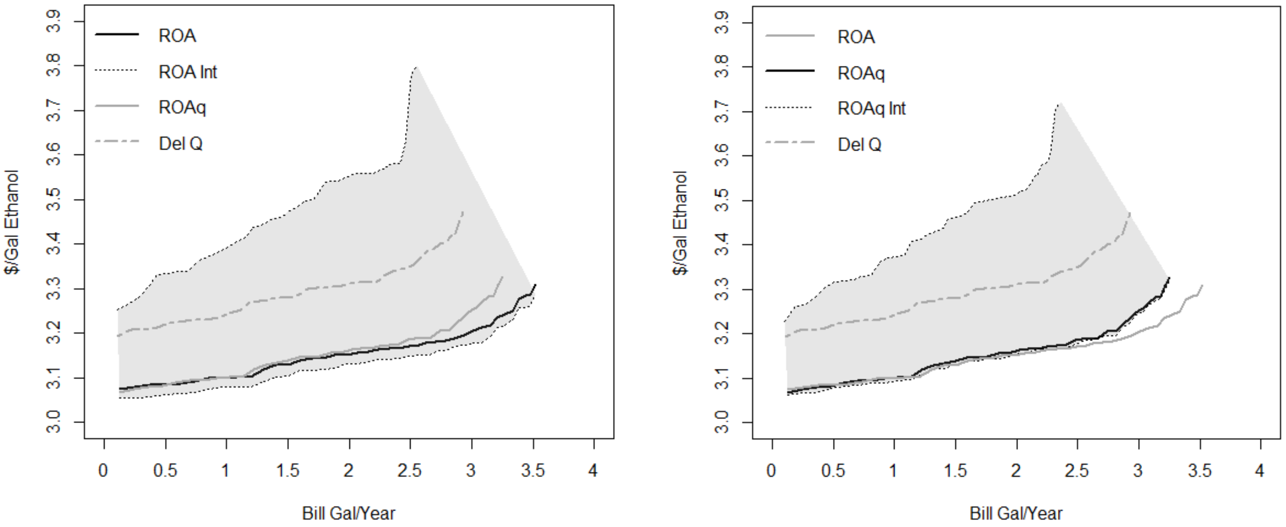
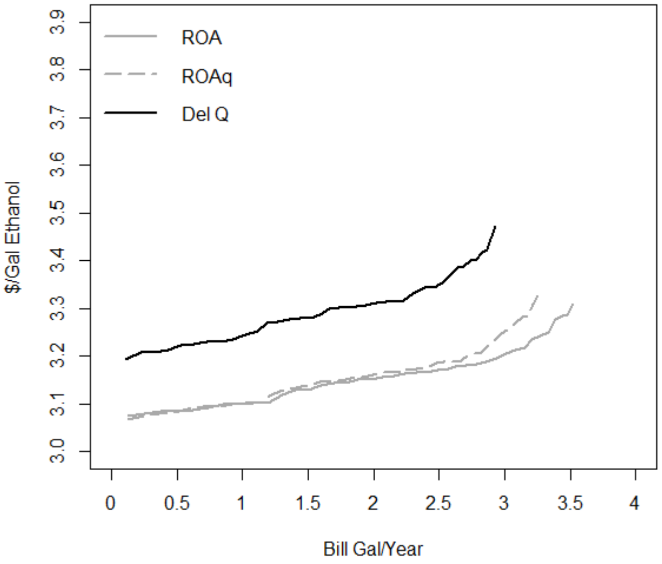
[17] The 90% confidence intervals reported in Figure 2 capture only yield uncertainty and do not account for variability in other sources of uncertainty.

Figure 2 – Supply comparison under the three contract options



a. ROA

b. ROAq



c. Del Q

Table 5 details the stover procurement costs and farmer profits across the three contracts. The mean stover procurement cost per ton increases from the ROA contract to the Del Q contract as farmers bear a greater portion of the stover supply risk. As a result, the expected (or mean) farmer profit for those that contract is highest under the Del Q contract. However, this does not imply that all farmers would prefer the Del Q contract. This contract is most profitable for farmers with relatively high yields. At the per ton delivered price offered by the processor, some lower-yielding farmers would not accept the Del Q contract and therefore would prefer one of the ROA contracts (Table 5, last row). Generally, farmers' preference for the Del Q contract is increasing in mean CRD stover yield (raw correlation 0.25) but decreasing in the variation in expected stover yields among farmers in the CRD (raw correlation of -0.59). Conversely, farmers' preference for the ROAq contract is higher in CRDs with greater variation in expected stover yields among farmers (raw correlation of 0.48).

Table 5 – Summary of stover procurement costs and farmer return across contract options

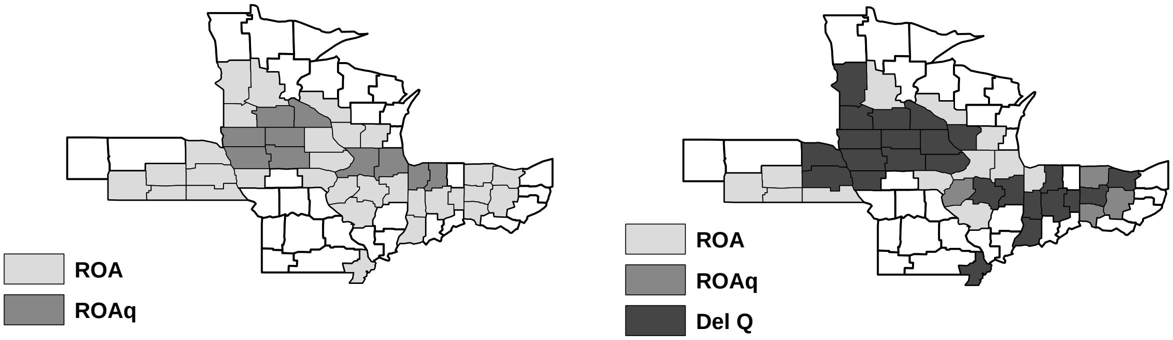
(Reported values are median values over the 40 districts; min-max range in parentheses)

	ROA	ROAq	Del Q
ROA payment ($/acre)	$18.20 (14.2-21)	$2.00 (--)	--
Per ton payment ($/ton)	--	$10.25 (8.7-11.4)	$85.40 (82-89)
Mean stover procurement cost per ton ($/ton)	$81.70 (76.5-85.3)	$82.10 (77-85.7)	$85.40 (82-89)
Mean farmer per acre profit[a]	$3.40 (2.3-5.1)	$4.70 (4 -6.5)	$5.30 (4.5-6.9)
Max farmer per acre profit	$9.20 (8.1-10.9)	$14.20 (11.7-17.9)	$16.20 (12.8-20.6)
Percentage of farmers prefer	40% (28% – 55%)	17% (0% – 60%)	44% (11% – 60%)

[a] Profit is calculated as net expected utility of profits.

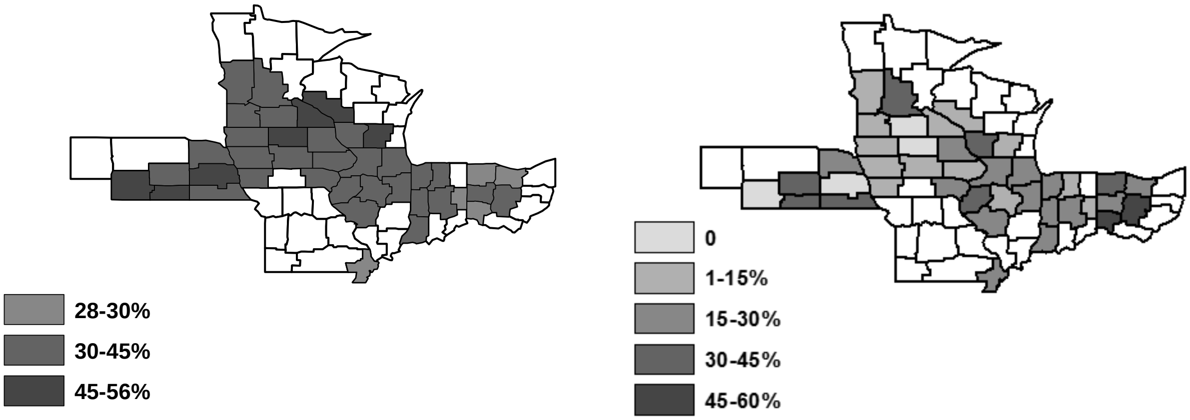
Figures 3 and 4 illustrate the geography of contract preferences. Figure 3a identifies the contract type most preferred by the processor within each CRD, while Figure 3b identifies the contract most preferred by farmers. The contract 'most preferred' by processors is the contract that leads to the lowest expected average cost per gallon biofuel while 'most preferred' by farmers is the contract with the greatest percentage of farmer's getting highest expected profit from that contract. Not surprisingly, the preferences of the processor and farmers do not align in most cases; the processor and a majority of the farmers prefer the same contract in only 9 of the 40 CRDs. The risk premium required by farmers with the Del Q contract (and therefore higher stover procurement cost) makes the Del Q contract least appealing to processors in all regions but most appealing to farmers in several regions. While Figure 3b identifies which contract is 'most preferred' by farmers, Figure 4 shows that the degree to which the identified contract is preferred by farmers varies across CRDs.

Figure 3. Contract type most preferred by processor and farmers


a. Processor preferred

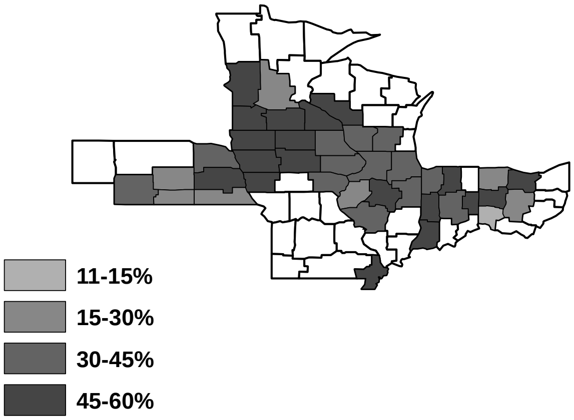
b. Farmer preferred

Figure 4. Percent of farmers that prefer each contract type


a. ROA

b. ROAq

c. Del Q



One pattern exhibited in Figures 3 and 4 is the relationship between yields, corn production practices, and farmers' contract preferences. For example, farmers in central and northern Iowa, southern Minnesota, and central Illinois and Indiana prefer the Del Q contract to the two ROA contracts. The same is true of southern Missouri and southern Indiana, although the former is the highest-cost ($/gallon) CRD in the sample. Farmer preference is nearly evenly divided among the ROA and Del Q contracts for many of the Indiana regions, north central Iowa and southeastern Minnesota.[18]

The choice of the ROAq contract among farmers is more difficult to explain, though the greatest preference for this contract is in CRDs with high variability in land quality (e.g., southern Ohio, southwest Wisconsin, western Nebraska). The median per-ton payment for the ROAq contract is $10.25 (Table 5). This is similar to the findings in Altman et al. (2015) that farmers would need an incentive payment of $8-$10 per dry ton to leave 70% of stover in field. Reasons for the minor discrepancy between our results and those of Altman et al. (2015) include differences in study regions (e.g., we do not consider mid-Missouri) and associated production aspects (e.g., nutrient replacement costs and stover quality).

We also find diverse contract preferences in the Great Lakes region, particularly Ohio and Wisconsin. Unsurprisingly, farmers in two higher-yielding CRDs in northern Ohio – traditionally considered part of the Corn Belt production system – prefer the Del Q contract option. In Wisconsin, multi-output and crop-livestock farming and cross-market linkages may play a greater role than is considered in our analysis (Mooney et al., 2015; Egbendewe-Mondzozo et al., 2015). Egbendewe-Mondzozo et al. (2015) find that Wisconsin corn stover supply begins at $37/dry ton, which is a compromise, on average, between our ROA and Del Q payments (Table 5). If cropland allocated to biofuel feedstocks stays below 30% for a wide range of per-ton biomass prices (Mooney et al., 2015), processors may need to contract excess acreage or increase the capture radius. Consistent with this set of results, we find relatively low optimal plant capacities in Wisconsin. However, the density of stover-supplying farmers could increase in the long run if the presence of a spot market presents a favorable outside option.

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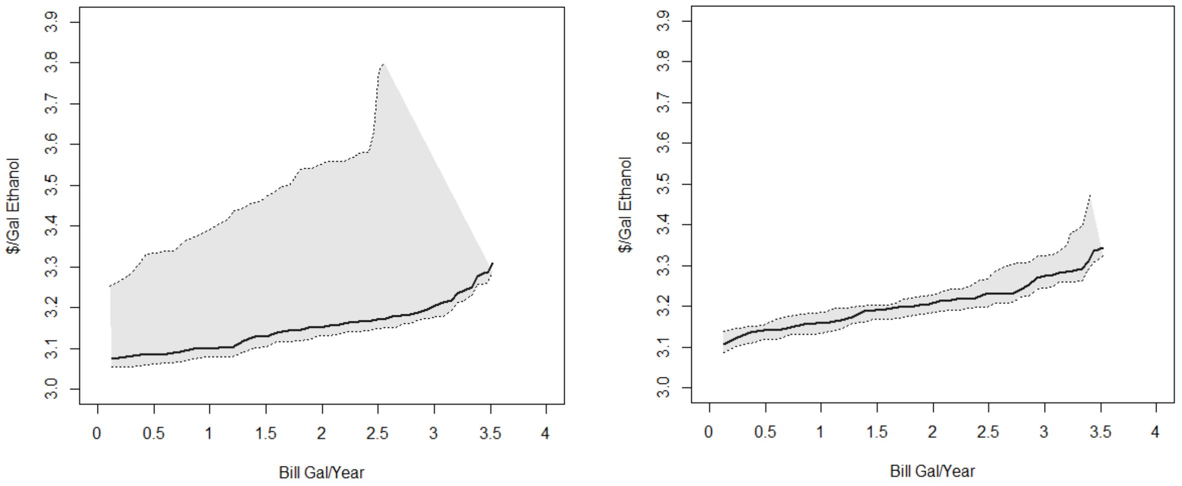
[18] Two corn stover ethanol plants have been commissioned within the regions of our analysis, both located in Iowa. One plant uses a form of the Del Q contract. This is consistent with the contract type identified by our model as most preferred by farmers within that region. The other plant plans to use an ROAq type contract. This is consistent with the contract type identified as most preferred by the processor (i.e., least cost) for CRDs within their practical contracting region.

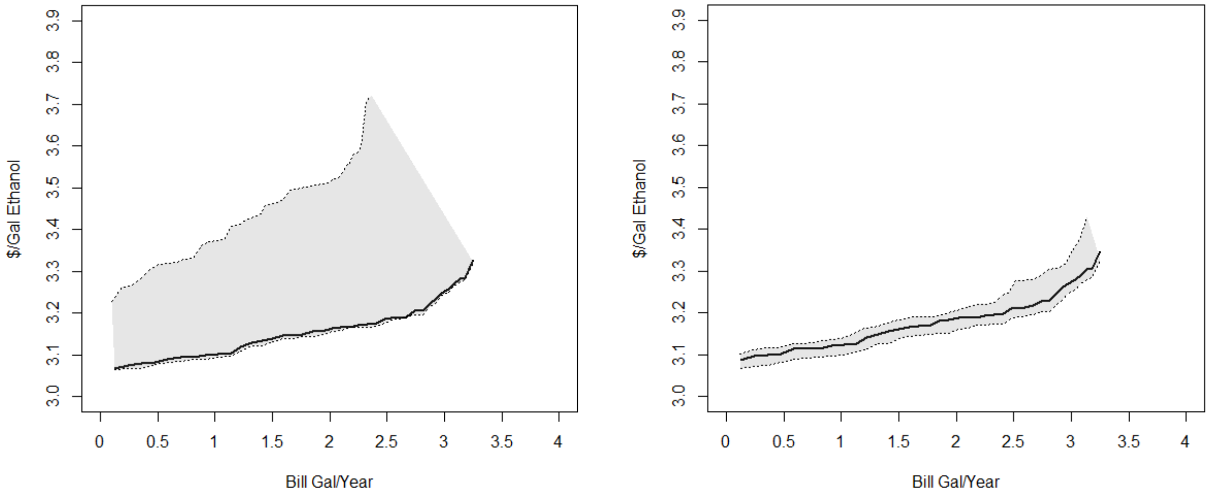
While the ROA contracts lead to the processor's lowest expected average cost per gallon (Figure 3a), the processor also bears more risk. Since a negative yield shock raises cost more than an equally positive yield shock decreases cost, it benefits the processor to mitigate potential losses from a negative yield shock. One potential strategy with ROA contracts is to contract excess acreage. The expected biofuel supply curves and 90% CIs under yield uncertainty for the ROA contracts with and without over-contracting are shown in Figure 5. The amount of over-contracting is CRD-specific and determined based on the excess acreage that minimizes the 90% CI. The added capture radius from over-contracting ranges from 4 to 13 miles. Over-contracting raises the expected biofuel cost but significantly reduces the 90% CI. In this sense, we find that excess contracting reduces the processor's overall production risk.

Figure 5 – ROA contracts with and without excess-contracting

a. ROA – Baseline **b. ROA – Excess Acreage**



c. ROAq – Baseline **d. ROAq – Excess Acreage**



IV.B Spot market analysis

Beyond risk-mitigating contract structures, the existence of a biomass spot market is another institutional arrangement with the potential to reduce the processor's production risk. While spot markets for biomass are not common today, they may develop in the future with increased biomass demand. We consider the case where an established biomass spot market is located a fixed distance from the biorefinery and outside the contracting region. The existence of an established biomass spot market creates an interesting tradeoff. The spot market benefits the processor in that it provides a source of biomass in low-yielding years and can therefore reduce the processor's risk from a negative yield shock: processors with ROA contracts are able to purchase deficit biomass during low-yielding years rather than operate under capacity. However, the existence of an established spot market also provides an alternative outlet for farmers to supply stover and therefore creates competition for the processor, i.e., reduces the pool of potential contractees. Farmers now have the option to sell stover to the spot market rather than contract with the processor.

We assume the biomass spot market price is uncertain with mean $\bar{P}_{Spot}$ of \$85 and variance $\sigma^2_{P_S}$ of \$15.[19] Transportation cost is calculated as the variable transportation cost (t) times the distance from the spot market, assumed to be 60 miles from the biorefinery (D_{SB}) and 30 miles from the farmer (D_{SF}). Additional details and complete model equations for the spot market case are available in Appendix C.

Figure 6 compares the estimated biofuel supply curves with and without the spot market and reports the 90% CI with the spot market. These supply curves illustrate the spot market tradeoff. Given our assumptions, a spot market only provides risk mitigation under certain contract types and/or local yield conditions. Since the option to not contract with the processor and sell to the spot market is most appealing for high-yielding farmers, farmer participation is more costly with the spot market.

However, the degree to which farmer participation is more costly depends on the assumed spot market stover price and distance to the spot market. Competition (and therefore cost of farmer participation) increases with the price paid by the spot market (P_{Spot}) and decreases with the distance to the spot market (D_{SF}). Further, the spot

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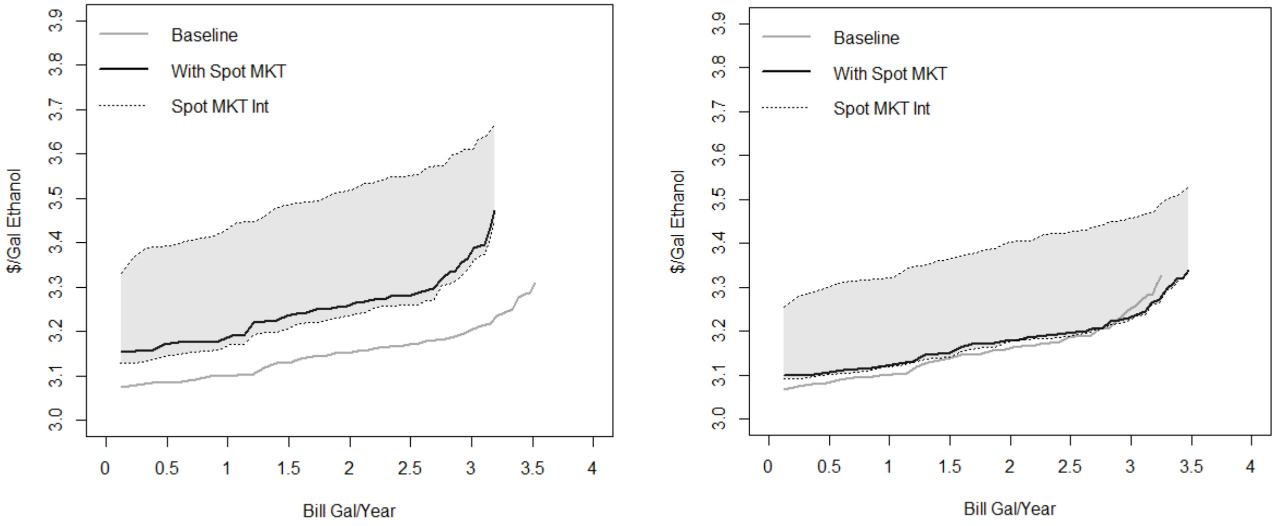
[19] The assumed mean spot market stover price is in line with the median per ton price paid by processors under the baseline Del Q contract (\$85.40 per ton; reported in Table 5). Variance in the stover spot market price is from the Biofuel Breakeven program (BioBreak). BioBreak provides stochastic simulations of long run stover production costs based on observed values in the published literature (Rosburg & Miranowski, 2011).

market tradeoff only occurs if the biomass spot market exists when the farmer is deciding whether to contract with the processor. If the spot market develops after the plant is built such that farmers have already committed to long term contracts with the processor, then the spot market will not influence participation and only provide benefit to the processor through risk mitigation in low-yielding years (i.e., tighten the 90% confidence interval).

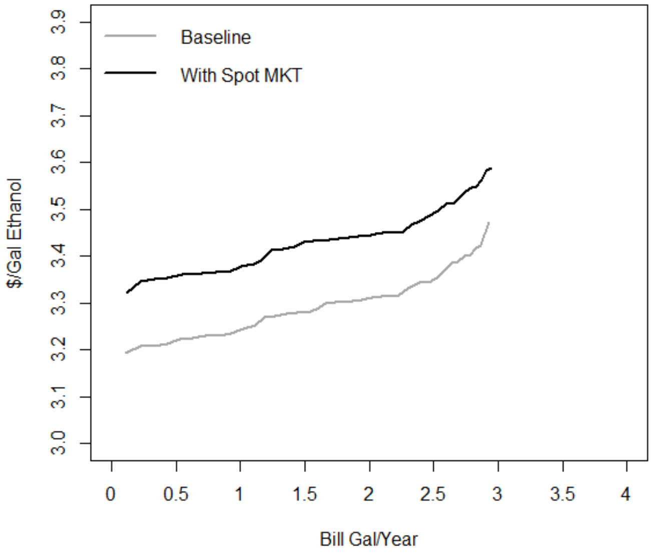
Figure 6 – Existence of a spot market 60 miles from plant



a. ROA Contract

b. ROAq Contract

c. Del Q Contract



IV.C Sensitivity analyses

Results presented thus far are for a baseline scenario and the introduction of a spot market. Table 6 compares the baseline and spot market results to results under a number of sensitivity cases. First, lowering the mean spot market price (P_{spot}) from $85 to $75 reduces the 'competition effect' created by the spot market and therefore reduces the stover procurement cost and resulting cost per gallon biofuel. Although not shown in Table 6, the reduction in the mean spot market price tightens the 90% confidence interval as deficit biomass needed in low yielding years is cheaper to procure than in the baseline scenario.

Second, removing the corn yield bump on CC land takes away a benefit of stover harvest previously received by CC farmers. As a result, CC farmers require a higher price than in the baseline scenario. The higher price per acre has limited effect on processors offering the ROA contract since the processor was already paying an ample amount to incentivize CS farmers to contract. However, without the yield bump, all farmers break even at the contract offer price (i.e., mean farmer profit is zero) and farmer preference shifts towards the ROAq and Del Q contracts. We also consider the case where the corn yield drag on CC is removed along with the yield bump. Removal of the yield drag implies higher expected yields on CC land than under the baseline case, resulting in larger plant sizes producing lower cost ethanol under the ROA contract. However, the effects of removing both the yield drag and yield bump under the ROAq and Del Q contracts are less clear and partially depend on the fraction of CC acreage within the CRD. For example, while the *median* plant size is smaller under the ROAq and Del Q contracts after the yield drag and bump are removed, these directional changes are not uniform across all CRDs.

Third, an increase in the farmers' risk aversion coefficient from γ = 0.004 to $\gamma = 0.01$ increases the risk premium that farmers require to contract. Since farmers incur limited risk with the ROA contract, the increase in the required risk premium is minimal, and the higher farmer risk aversion has negligible effects on the processor's plant size and cost. Farmers bear more risk under the other two contracts resulting in higher risk premiums and biofuel production costs. As a result, the processor's preference for the ROA contract is increasing in farmer risk aversion. We also observe a small shift in farmer preference away from the Del Q contract.

Finally, we consider an increase in the per ton penalty for subpar delivered stover. An increase in the penalty from c_q = \$10 to c_q = \$20 increases the minimum price at which farmers are willing to accept the Del Q contract, thus increasing per gallon biofuel cost. Farmer preferences shift slightly away from the Del Q contract to the ROAq contract.

Table 6 – Comparison of sensitivity analysis results

(Reported values are median values over the 40 districts)

	Ethanol cost ($/gal)	Plant Size (mgy)	Contracted acreage (%)	Expected yield from contracted farmers (tons/ac)	Mean stover procurement cost ($/ton)	Mean farmer per acre profit ($/acre)	Percentage of farmers prefer	Aggregate Supply (bgy)
Baseline								
ROA	$3.16	88	30%	1.66	$81.7	$3.4	40%	3.5
ROAq	$3.16	82	27%	1.73	$82.1	$4.7	17%	3.25
Del Q	$3.30	71	23%	1.76	$85.4	$5.3	44%	2.9
Spot market								
ROA	$3.26	80	29%	1.62	$87	$5.6	56%	3.2
ROAq	$3.19	87	30%	1.69	$84	$0.22	0%	3.5
Del Q	$3.44	74	26%	1.75	$95.3	$4.5	44%	2.95
Low spot market price								
ROA	$3.16	88	30%	1.66	$81.7	$3.4	39%	3.5
ROAq	$3.16	82	27%	1.73	$82.3	$4.7	8%	3.27
Del Q	$3.37	69	23%	1.78	$90.0	$6.4	53%	2.8
No yield bump								
ROA	$3.16	88.5	30%	1.66	$81.7	$0	18%	3.5
ROAq	$3.20	71	25%	1.76	$83.2	$4	24%	3
Del Q	$3.32	70	23%	1.78	$86.5	$5.1	57%	2.9
No yield drag (or bump)								
ROA	$3.14	90	30%	1.70	$80.5	$0	15%	3.6
ROAq	$3.19	72	25%	1.80	$82.6	$4.1	26%	3.0
Del Q	$3.34	69	23%	1.80	$88.2	$6.7	60%	2.8
High risk aversion								
ROA	$3.16	88	30%	1.66	$81.8	$3.4	40%	3.5
ROAq	$3.17	82	26%	1.73	$82.3	$4.7	19%	3.25
Del Q	$3.32	70	23%	1.77	$86	$5.3	42%	2.9
High quality penalty								
ROA	$3.16	88	30%	1.66	$81.7	$3.4	40%	3.5
ROAq	$3.16	82	27%	1.73	$82.1	$4.7	21%	3.25
Del Q	$3.34	70	23%	1.76	$87.7	$5.2	39%	2.8

IV.D Discussion of market implications

Within the context of current policies and technologies surrounding stover ethanol production, our analysis addresses the following four critical questions. What is the market configuration with the least risk to the processor? What is the market configuration most preferred by farmers? What market configuration produces the least-cost gallon of stover ethanol? And what market configuration generates the greatest aggregate supply of stover ethanol?

The processor bears the least risk (has the tightest confidence interval around stover ethanol supply) using ROA contracts with excess contracting and with a spot market, but only if the spot market develops after long-term contracts have been signed so that high-yielding farmers are not induced to substitute from contracting with the processor towards selling stover on ex post profitable spot markets. Interestingly, the least-risk environment for the processor is not the arrangement by which all HST costs are shifted to the farmer (the Del Q contract). Even in a low-yielding year, the cost per gallon is lower under the ROA contract than the Del Q; the 90% confidence interval for biofuel supply with ROA contracts and excess contracting (Figure 5b) lies strictly below the Del Q contract supply curve (Figure 2c). Farmers, on average, tend to prefer the Del Q or ROA contract, but the degree to which each type of contract is preferred by farmers varies across CRDs. Lastly, the ROA contract under a setting in which farmers do not receive a yield drag from CC production is the configuration with the greatest aggregate supply, 3.6 bgy. Under this setting, the median cost of ethanol is also the least expensive of all the cases considered at $3.14 per gallon.

Thus, with respect to the metrics posed by the above questions, the “optimal” contract under several settings and regions is a variation of a flat tariff. However, economic institutional arrangements (e.g., spot markets and excess acreage), crop production, and production practices (e.g., yield, yield variability, yield gains from stover harvest, CC rotations, and yield drag from CC rotations) are key drivers of the location and shape of the stover ethanol supply curve. If risk-averse farmers producing under highly-variable growing conditions are most interested in a flat per-acre payment, then processors with high under-capacity costs should locate in high-yielding regions of ample CC production with the possibility of excess contracting and spot market development.

A potential structural shift not considered in our analysis is the development of third-party consolidators specializing in biomass HST. If the industry matures to an extent that permits capture of scale economies in biomass HST, it is likely that, in a least-cost configuration, large “custom” HST tasks will be contracted to specialized and highly-mobile crews of agricultural laborers. Such specialized, experienced HST crews may benefit the processors by supplying a more uniform quality of biomass (e.g., ash content, density). Further, while our model assumes the processor offers a single contract option to farmers, the optimal contract option may adjust over time as the industry develops (Golecha and Gan, 2016b). With the uncertainty surrounding the cellulosic ethanol industry and the capital investment needed to manage stover HST, some farmers may prefer ROA contracts in the early stages. As the industry further develops and as intermediaries or consolidators arise to provide HST functions, farmers may shift preferences towards quantity-based contracts.

Our analysis suggests three main implications related to the growth and development of stover ethanol markets. First, yield variability (and skewness) is the single-most important determinant of whether or not the stover ethanol plant will operate under capacity, which has the potential to increase processing costs more than any other cost component. As such, the downside yield risk is more detrimental than the downsides for the other three sources of risk we consider – stover quality, nutrient replacement cost, and harvest cost. Since yield risk is a function of underlying weather variability and collection efficiency, the plant can mitigate some of the short-term risk through improvements in collection efficiency. In the long run, plants should consider locating in high-yielding Corn Belt regions that will be more resilient to climate change (e.g., lower implied yield variability).

Second, management practices to reduce yield drag associated with CC production will play a key role in the development of sustainable stover ethanol markets. Improved nutrient management and leguminous cover crops are some options to mitigate this penalty. Processors may want to consider linking payments to these options to the extent this will spur contracting from high-yielding farmers in the supply radius.

Third, farmers’ contract preferences within CRDs are malleable and responsive to the basic structure of incentives. Similar to Yang et al. (2015) who find that the processor should offer a portfolio of contracts because of farmer heterogeneity in yield and risk preferences, we find that a portfolio of contracts may be justified because of underlying yield heterogeneity alone. However, farmer preference for one contract over another is slight in certain CRDs. To the extent that market conditions change such that one contract becomes more costly (to the processor) than another, rigidity of farmers’ contract preferences are not expected to unduly hamper the processor’s adjustment process.

V. Conclusion

The major gap between U.S. advanced biofuel production and initial policy targets has spurred interest in identifying the sources and magnitudes of uncertainty in cellulosic biofuel supply. Towards a goal of better understanding implications for cellulosic ethanol industry development, we analyzed the processor's choices of plant size and contract terms with a focus on mitigating feedstock supply risk. We construct and apply a model that considers three corn stover contracts that vary according to risk-sharing and includes key aspects of potential stover supply systems (e.g., sources of uncertainty, stover quality, yield bump, spot market development).

Three key findings emerge from our baseline analysis of 40 high-yielding CRDs in Midwest and Plains states. First, a greater quantity of biofuel is supplied at lower cost under the ROA contracts than the delivered quantity contract. However, the processor bears most of the stover production risk with the ROA contracts. Second, the processor can lay off some of this risk by contracting excess acreage, and if available, by purchasing deficit biomass from a spot market. Contracting excess acreage increases the expected biofuel cost but results in lower uncertainty surrounding cellulosic biofuel supply (i.e., tightens the 90% confidence interval). A biomass spot market provides a source of biomass during low yielding years, but can also create competition for the processor by providing an alternative outlet for farmers to supply stover. Third, the contract most preferred by farmers, as measured by expected profit per acre, varies both across and within CRDs, and in many cases, does not align with the processor's preferred contract arrangement.

Among the sources of risk considered, we find that yield variability (and skewness) is the key determinant of production risk as it determines whether or not the stover ethanol plant is able to operate at capacity. Therefore, institutional arrangements (e.g., excess acreage and spot markets), technological improvements (e.g., improved collection efficiency), and improved management practices (e.g., reduced yield drag on CC land) that reduce yield uncertainty and/or increase expected yields are potential pathways to mitigate the processor's production risk. Further, with heterogeneity in farmer contract preferences within CRDs, processors may benefit from offering a portfolio of contracts or adjusting contract arrangements over time as the industry develops. Our results suggest that farmers' contract preferences within CRDs are responsive to the basic structure of incentives. Therefore, as the industry develops and market uncertainty changes, rigidity of farmers' contract preferences are not expected to unduly hamper the processors' adjustment process.

The cellulosic biofuel industry currently remains in the research and development phase, with processors continuing to invest substantially in plant capital and conversion technologies and continuing to test new incentives and supply chain management strategies (Jessen & Schill, 2016). As with many other capital-intensive industries, the long-term outcome of this research is expected to be lower per-unit production costs. Reduced ethanol production costs will likely occur with the development of markets for high-value specialty byproducts (Hayes et al., 2016; Rosentrater, 2015). For example, stover ethanol can be used as a substitute for hydrocarbons in the production of high-valued chemicals. In a similar industry, large soybean oil processors co-produce several other liquid byproducts for sale in related intermediate input markets. As such, long-run sustainability and eventual profitability of cellulosic biofuel production will likely be facilitated, in part, through the expansion of markets for valuable byproducts and non-fuel uses.

As these transitions occur, a better understanding of feedstock supply risk and risk mitigation tools can inform processors about promising combinations of risk- and cost-sharing that support industry viability. It can also inform policymakers about aspects of decision making that can lead to a lower-risk business environment. Our results extend the ongoing discussion about the economics of advanced biofuel production and prompt additional research about risk mitigation and contracting in U.S. agriculture.

VI. References

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Appendix A: Derivation of farmer utility with a delivered quantity contract

From equation (3), we have[20]:

$$\pi_{DQ,j} = P_{DS}\bar{Y}_{HS,j} - (c_H + c_S + c_T + I_{q,j}c_q)\bar{Y}_{HS,j} - n - I_{L,j}(\bar{Y}_{HS,j} - Y_{HS,j})(c_L + P_{DS} - c_H - c_S - c_T - I_{q,j}c_q) + \beta I_{CC} P_C \Delta Y_{C,j}$$

Now, assume there are no correlations among σ_Y^2, θ, σ_n^2, and σ_H^2 and that $x_j = \left[Y_{HS,j} - \bar{Y}_{HS,j}\right] \sim N(0, \sigma_Y^2)$. With second-moment utility, we have that:

$$U\left(\bar{\pi}_{DQ}, \sigma_{\pi,DQ}^2\right) = E\left[a_j\right] + E\left[z_j\right] - \gamma\left\{\sigma_a^2 + var\left(\varphi_j\right)\right\}, \text{ where} \tag{A.1}$$

$$E\left[a_j\right] = P_{DS}\bar{Y}_{HS,j} - \left(\bar{c}_H + c_S + c_T + \theta c_q\right)\bar{Y}_{HS,j} - \bar{n} + \beta I_{CC} P_C \Delta Y_{C,j}$$

$$E\left[z_j\right] = 0.5 \int_{-\infty}^{0} 2x_j DF\left(x_j\right)\left(c_L + P_{DS} - \bar{c}_H - c_S - c_T - \theta c_q\right)$$

$$\sigma_a^2 = \bar{Y}_{HS,j}^2\left[\sigma_H^2 + \theta(1-\theta)c_q^2\right] + \sigma_n^2$$

$$var\left(\varphi_j\right) = 0.5\left\{Var\left(x_j \middle| x_j < 0\right)\left(\sigma_H^2 + \theta(1-\theta)c_q^2\right) + E\left[x_j^2 \middle| x_j < 0\right]\left(\sigma_H^2 + \theta(1-\theta)c_q^2\right) + \left(c_L^2 + P_{DS}^2 + \bar{c}_H^2 + c_S^2 + c_T^2 + \theta^2 c_q^2\right)Var\left(x_j \middle| x_j < 0\right)\right\}.$$

The above expressions involve moments of truncated normal distributions. Following Greene (2008), we have that:

$$E\left[x_j \middle| x_j < 0\right] = \mu + \sigma_Y \lambda(\alpha),$$
$$Var\left[x_j \middle| x_j < 0\right] = \sigma_Y^2[1 - \delta(\alpha)],$$

where $\alpha = \frac{a-\mu}{\sigma_Y}$, $\lambda(\alpha) = \frac{-\phi(\alpha)}{\Phi(\alpha)}$ for lower truncation (e.g., $x < a$), and $\delta(\alpha) = \lambda(\alpha)[\lambda(\alpha) - \alpha]$. Since our truncation point is zero (i.e., $a = 0$) and x_j is mean-zero, then $\alpha = 0$. As such, $\lambda(0) = \frac{-\phi(0)}{\Phi(0)} = -\frac{0.399}{0.500}$ and we have:

$$\begin{aligned} E\left[z_j\right] &= 0.5 \int_{-\infty}^{0} 2x_j DF\left(x_j\right)\left(c_L + P_{DS} - \bar{c}_H - c_S - c_T - \theta c_q\right) \\ &= \left(c_L + P_{DS} - \bar{c}_H - c_S - c_T - \theta c_q\right)\int_{-\infty}^{0} x_j f\left(x_j\right)dx_j \\ &= \left(c_L + P_{DS} - \bar{c}_H - c_S - c_T - \theta c_q\right)[0 + \sigma_Y \lambda(0)] \\ &= -\frac{0.399}{0.500}\sigma_Y\left(c_L + P_{DS} - \bar{c}_H - c_S - c_T - \theta c_q\right). \end{aligned} \tag{A.2}$$

The $Var\left(x_j \middle| x_j < 0\right)$ term in the expression for $var\left(\varphi_j\right)$ is evaluated similarly:

$$Var\left(x_j \middle| x_j < 0\right) = \sigma_Y^2[1 - \delta(0)] = \sigma_Y^2\left[1 - \lambda(\alpha)[\lambda(\alpha) - \alpha]\right] = \sigma_Y^2[1 - \lambda(\alpha)^2] = \sigma_Y^2\left[1 - \left(-\frac{0.399}{0.500}\right)^2\right]. \tag{A.3}$$

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[20] To ease the mathematical clutter, we suppress the notation for crop rotation (i.e., $\bar{Y}_{HS,j}(r) = \bar{Y}_{HS,j}$).

Finally, we can use a formula from Dhrymes (2005) to calculate the second moment of the truncated variable. According to Dhrymes (2005),

$$\begin{aligned} E\left[x_j^2|x_j < 0\right] &= \mu^2 + 2\mu\sigma_Y\lambda(\alpha) + \sigma_Y^2[1 + \alpha\lambda(\alpha)] \\ &= 0^2 + 2 * 0\sigma_Y\lambda(0) + \sigma_Y^2[1 + 0 * \lambda(0)] = \sigma_Y^2. \end{aligned}$$

Therefore, we have

$$\begin{aligned} var(\varphi_j) = 0.5\Big\{&\sigma_Y^2\left[1 - \left(-\tfrac{0.399}{0.500}\right)^2\right](\sigma_H^2 + \theta(1-\theta)c_q^2) + \sigma_Y^2(\sigma_H^2 + \theta(1-\theta)c_q^2) + \\ &\left(c_L^2 + P_{DS}^2 + \bar{c}_H^2 + c_S^2 + c_T^2 + \theta^2 c_q^2\right)\sigma_Y^2\left[1 - \left(-\tfrac{0.399}{0.500}\right)^2\right]\Big\} \qquad \textbf{(A.4)} \end{aligned}$$

$$\begin{aligned} = 0.5\Big\{&\sigma_Y^2\left[2 - \left(-\tfrac{0.399}{0.500}\right)^2\right](\sigma_H^2 + \theta(1-\theta)c_q^2) + \left(c_L^2 + P_{DS}^2 + \bar{c}_H^2 + c_S^2 + c_T^2 + \theta^2 c_q^2\right)\sigma_Y^2\Big[1 - \\ &\left(-\tfrac{0.399}{0.500}\right)^2\Big]\Big\}. \end{aligned}$$

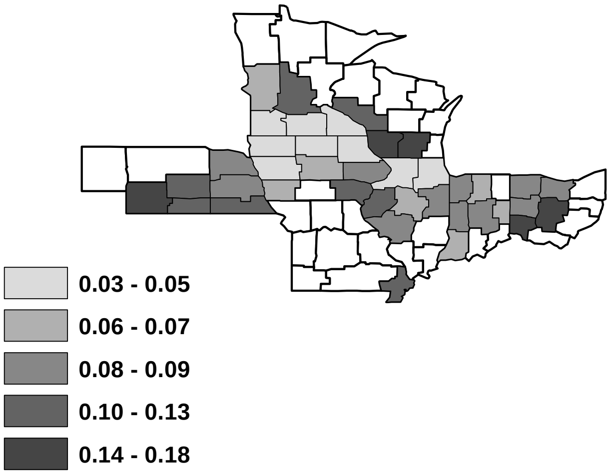
Combining these terms and letting $\omega = -\frac{0.399}{0.500}$ and $\sigma_q^2 = \theta(1-\theta)c_q^2$, we have

$$\begin{aligned} U\left(\bar{\pi}_{DQ}, \sigma_{\pi,DQ}^2\right) = \; &P_{DS}\bar{Y}_{HS,j} - \left(\bar{c}_H + c_S + c_T + \theta c_q\right)\bar{Y}_{HS,j} - \bar{n} + \beta I_{CC}P_C\Delta Y_{C,j} + \omega\sigma_Y\big(c_L + P_{DS} - \bar{c}_H - \\ &c_S - c_T - \theta c_q\big) - \gamma\big\{\bar{Y}_{HS,j}^2\left(\sigma_H^2 + \sigma_q^2\right) + \sigma_n^2 + 0.5\big(\sigma_Y^2[2 - \omega^2]\left(\sigma_H^2 + \sigma_q^2\right) + \\ &\left(c_L^2 + P_{DS}^2 + \bar{c}_H^2 + c_S^2 + c_T^2 + \theta^2 c_q^2\right)\sigma_Y^2[1 - \omega^2]\big)\big\}. \qquad \textbf{(A.5)} \end{aligned}$$

Appendix B: Stover yield maps

Figure B.1 – Variation in expected harvestable stover yields among farmers in each CRD $\left[\boldsymbol{var}\left(\bar{Y}_{HS,j}\right)\right]$

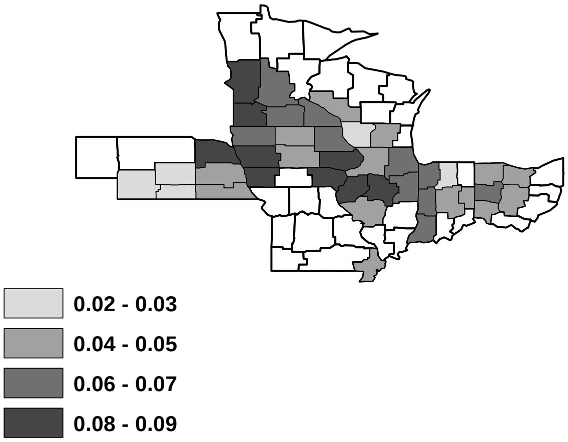
(Based on 2009 – 2011 USDA-ERS ARMS data)



Note: Farmer-specific expected harvestable stover yields are derived from farmer-specific corn yield draws and assuming a 0.95 stover-to-grain ratio and 39% collection efficiency (see discussion in section III and Table 3).

Figure B.2 – Variation in CRD harvestable stover yield due to weather uncertainty $\left(\boldsymbol{\sigma_W^2}\right)$

(Based on 1970 – 2012 NASS CRD average corn yields)



Note: CRD harvestable stover yields are calculated from detrended CRD-average corn yield draws and assuming a 0.95 stover-to-grain ratio and 39% collection efficiency (see discussion in section III).

Appendix C: Model equations with a spot market

Farmer's problem

Existence of a spot market will not affect the farmer's expected profit from the ROA contracts (i.e., equations 1' and 2'). However, with the Del Q contract, the farmer would be required to purchase biomass from the spot market to fulfill his contract in the case of production underage (i.e., realized yield below contracted quantity). Further, the farmer now has the option to sell stover to the spot market rather than contract with the processor, and the farmer's non-contract profit will equal expected profits from selling stover to the spot market (if non-zero and zero otherwise). We assume the biomass spot market price is uncertain with mean $\bar{P}_{spot}$ and variance $\sigma^2_{P_S}$.

Letting $c_{T,SB} = t * D_{SB}$ be the transportation cost per ton from the spot market to the biorefinery and $x_j = [Y_{HS,j} - \bar{Y}_{HS,j}]$, then farmer j's realized profit function under the Del Q contract is expressed as follows[21]:

$$\pi_{DQ,j} = P_{DS}\bar{Y}_{HS,j} - (c_H + c_S + c_T + I_{q,j}c_q)\bar{Y}_{HS,j} - n + \beta I_{CC}P_C\Delta Y_{C,j} + I_{L,j}x_j(\bar{P}_{spot} + c_{T,SB} - c_H - c_S - c_T - I_{q,j}c_q)$$

Now, assume there are no correlations among σ^2_Y, θ, σ^2_n, σ^2_H, and $\sigma^2_{P_S}$ and that $x_j = [Y_{HS,j} - \bar{Y}_{HS,j}] \sim N(0, \sigma^2_Y)$. With second-moment utility, we have that:

$$U(\bar{\pi}_{DQ}, \sigma^2_{\pi,DQ}) = E[a_j] + E[z_j] - \gamma\{\sigma^2_a + var(\varphi_j)\} \qquad \textbf{(C.1)}$$

where

$$E[a_j] = P_{DS}\bar{Y}_{HS,j} - (\bar{c}_H + c_S + c_T + \theta c_q)\bar{Y}_{HS,j} - \bar{n} + \beta I_{CC}P_C\Delta Y_{C,j}$$

$$E[z_j] = 0.5\int_{-\infty}^{0} 2x_j DF(x_j)(\bar{P}_{Spot} + c_{T,SB} - \bar{c}_H - c_S - c_T - \theta c_q)$$

$$\sigma^2_a = \bar{Y}^2_{HS,j}[\sigma^2_H + \theta(1-\theta)c^2_q] + \sigma^2_n$$

$$var(\varphi_j) = 0.5\Big\{Var(x_j|x_j < 0)(\sigma^2_{P_S} + \sigma^2_H + \theta(1-\theta)c^2_q) + E\left[(x_j|x_j < 0)^2\right](\sigma^2_{P_S} + \sigma^2_H + \theta(1-\theta)c^2_q) + (\bar{P}^2_{Spot} + c^2_{T,SB} + \bar{c}^2_H + c^2_S + c^2_T + \theta^2 c^2_q)Var(x_j|x_j < 0)\Big\}$$

Following the derivations and notation from Appendix A, we have:

$$\begin{aligned} E[z_j] &= 0.5\int_{-\infty}^{0} 2x_j DF(x_j)(\bar{P}_{Spot} + c_{T,SB} - \bar{c}_H - c_S - c_T - \theta c_q) \qquad \textbf{(C.2)} \\ &= (\bar{P}_{Spot} + c_{T,SB} - \bar{c}_H - c_S - c_T - \theta c_q)\int_{-\infty}^{0} x_j f(x_j)dx_j \\ &= (\bar{P}_{Spot} + c_{T,SB} - \bar{c}_H - c_S - c_T - \theta c_q)[0 + \sigma_Y\lambda(0)] \end{aligned}$$

---

[21] For notational simplicity, we have suppressed the notation for crop rotation (i.e., $\bar{Y}_{HS,j}(r) = \bar{Y}_{HS,j}$). Also note that when $x_j > 0$, the farmer has the option to sell any excess stover (above that contracted) to the spot market. Since these potential profits would be realized whether the farmer contracted or not, they do not enter in the utility of profits from contracting (i.e., secondary decision to the contract decision).

$$
\begin{aligned}
&= -\tfrac{0.399}{0.500}\sigma_Y\left(\bar{P}_{Spot} + c_{T,SB} - \bar{c}_H - c_S - c_T - \theta c_q\right) \\
&= \omega\sigma_Y\left(\bar{P}_{Spot} + c_{T,SB} - \bar{c}_H - c_S - c_T - \theta c_q\right)
\end{aligned}
$$

and

$$
\begin{aligned}
var(\varphi_j) = 0.5\{&\sigma_Y^2[1-\omega^2](\sigma_{P_S}^2 + \sigma_H^2 + \sigma_q^2) + \sigma_Y^2(\sigma_{P_S}^2 + \sigma_H^2 + \sigma_q^2) + \left(\bar{P}_{Spot}^2 + c_{T,SB}^2 + \bar{c}_H^2 + c_S^2 + c_T^2 + \right. \\
&\left.\theta^2 c_q^2\right)\sigma_Y^2[1-\omega^2]\}. \qquad \textbf{(C.3)} \\
= 0.5\{&\sigma_Y^2[2-\omega^2](\sigma_{P_S}^2 + \sigma_H^2 + \sigma_q^2) + \left(\bar{P}_{Spot}^2 + c_{T,SB}^2 + \bar{c}_H^2 + c_S^2 + c_T^2 + \theta^2 c_q^2\right)\sigma_Y^2[1-\omega^2]\}.
\end{aligned}
$$

Combining these terms, farmer *j*'s utility under contract 3 with a spot market is expressed as follows

$$
\begin{aligned}
U(\bar{\pi}_{DQ}, \sigma_{\pi,DQ}^2) = \; &P_{DS}\bar{Y}_{HS,j} - \left(\bar{c}_H + c_S + c_T + \theta c_q\right)\bar{Y}_{HS,j} - \bar{n} + \beta I_{CC} P_C \Delta Y_{C,j} + \omega\sigma_Y\left(\bar{P}_{Spot} + c_{T,SB} - \right. \\
&\left.\bar{c}_H - c_S - c_T - \theta c_q\right) - \gamma\{\bar{Y}_{HS,j}^2\left(\sigma_H^2 + \sigma_q^2\right) + \sigma_n^2 + 0.5\left(\sigma_Y^2[2-\omega^2](\sigma_{P_S}^2 + \sigma_H^2 + \sigma_q^2) + \right. \\
&\left.\left(\bar{P}_{Spot}^2 + c_{T,SB}^2 + \bar{c}_H^2 + c_S^2 + c_T^2 + \theta^2 c_q^2\right)\sigma_Y^2[1-\omega^2]\right)\}\,. \qquad \textbf{(C.4)}
\end{aligned}
$$

Finally, the farmer's non-contract profit is expected profits from selling stover to the spot market. We assume the spot market imposes a quality penalty equivalent to that which the processor charges if biomass is below the minimum quality threshold. Letting $c_{T,FB} = t * D_{FB}$ be the transportation cost per ton from the farm to the spot market, farmer *j*'s profit from not contracting with the processor and selling stover to the spot market is expressed as follows:

$$
\pi_{NC,j} = \left[P_{Spot} Y_{HS,j} - \left(c_H + c_S + c_{T,FB} + \theta c_q\right) Y_{HS.j} - n + \beta I_{CC} P_C \Delta Y_{C,j}\right]^+ \qquad \textbf{(C.5)}
$$

with corresponding utility function

$$
\begin{aligned}
U(\bar{\pi}_{NC}, \sigma_{NC}^2) = \; &\left[\bar{P}_{Spot}\bar{Y}_{HS,j} - \left(\bar{c}_H + c_S + c_{T,FB} + \theta c_q\right)\bar{Y}_{HSj} - \bar{n} + \beta I_{CC} P_C \Delta Y_{C,j} - \gamma\left[\sigma_Y^2\left(\sigma_{P_S}^2 + \bar{P}_{Spot}^2 + \right.\right.\right. \\
&\left.\left.\left.\sigma_H^2 + \bar{c}_H^2 + c_S^2 + c_{T,SB}^2 + \theta^2 c_q^2 + \sigma_q^2\right) + \bar{Y}_{HS,j}^2\left(\sigma_{P_S}^2 + \sigma_H^2 + \sigma_q^2\right) + \sigma_n^2\right]\right]^+ \qquad \textbf{(C.6)}
\end{aligned}
$$

All else equal, an increase in the expected spot market price and/or decrease in the spot market price variance will lead to less contracting. Utility from contract 3 will increase relative to other contracts with a decrease in the spot market price variance.

Processor's problem:

The processor's expected cost will be the same with and without the spot market (i.e., equations 5-7). Further, the existence of a spot market will not change the processor's costs in a high yield year. In a low yield year, however, the processor will have the option to purchase deficit biomass from the spot market. Equations C.7-C.9 describe the processor's actual costs per gallon under each contract. Hat notation denotes realized values (after harvest). Further, for notational simplicity, let $\hat{c}_{HS} = \hat{c}_H + c_S$.

$$\hat{C}_{ROA} = \begin{cases} C_O + C_K \left[\frac{Q}{Q_0}\right]^{e-1} + \frac{1}{Y_O}\left(\frac{P_{ROA,1}}{\bar{Y}_{HS}} + \hat{c}_{HS} + t\widehat{D}\right), & if\ \hat{Y}_{HS} \geq \bar{Y}_{HS} \\ C_O + min\left[C_K \left[\frac{Q}{Q_0}\right]^{e-1}\left(\frac{Q}{\hat{Q}}\right) + \frac{1}{Y_O}\left(\frac{P_{ROA,1}}{\hat{Y}_{HS}} + \hat{c}_{HS} + tD\right), C_K \left[\frac{Q}{Q_0}\right]^{e-1} + \frac{\hat{Q}}{Y_O Q}\left(\frac{P_{ROA,1}}{\hat{Y}_{HS}} + \hat{c}_{HS} + tD\right) + \left(\frac{Q-\hat{Q}}{Y_O Q}\right)\left(\hat{P}_{Spot} + c_{T,SB}\right)\right], & if\ \hat{Y}_{HS} < \bar{Y}_{HS} \end{cases} \quad \textbf{(C.7)}$$

$$\hat{C}_{ROAq} = \begin{cases} C_O + C_K \left[\frac{Q}{Q_0}\right]^{e-1} + \frac{1}{Y_O}\left(\frac{P_{ROA,2}}{\bar{Y}_{HS}} + P_S + \hat{c}_{HS} + t\widehat{D}\right), & if\ \hat{Y}_{HS} \geq \bar{Y}_{HS} \\ C_O + min\left[C_K \left[\frac{Q}{Q_0}\right]^{e-1}\left(\frac{Q}{\hat{Q}}\right) + \frac{1}{Y_O}\left(\frac{P_{ROA,2}}{\hat{Y}_{HS}} + P_S + \hat{c}_{HS} + tD\right), C_K \left[\frac{Q}{Q_0}\right]^{e-1} + \frac{\hat{Q}}{Y_O Q}\left(\frac{P_{ROA,2}}{\hat{Y}_{HS}} + P_S + \hat{c}_{HS} + tD\right) + \left(\frac{Q-\hat{Q}}{Y_O Q}\right)\left(\hat{P}_{Spot} + c_{T,SB}\right)\right], & if\ \hat{Y}_{HS} < \bar{Y}_{HS} \end{cases} \quad \textbf{(C.8)}$$

$$\hat{C}_{DQ} = C_O + C_K \left[\frac{Q}{Q_0}\right]^{e-1} + \frac{P_{DB}}{Y_O} \quad \textbf{(C.9)}$$

In a low yield year ($\hat{Y}_{HS} < \bar{Y}_{HS}$), the processor will not have enough stover from contracted acreage to operate at capacity. With the ROA contracts, the processor can either operate under capacity (i.e., $\hat{Q} < Q$) or purchase stover from the spot market. Operating under capacity is costly as fixed capital costs and ROA payments are spread over fewer units. The processor will make the least cost decision and only purchase the biomass shortfall from the spot market if the cost to purchase and transport biomass from the spot market is lower than the cost of operating under capacity. With the Del Q contract, the processor's actual cost will be unchanged since farmers are required to procure the stover shortfall from the spot market.