Spatial Competition and Economics of Biofuels from Corn Stover

Juan Sesmero[1], Joseph Balagtas[2], and Michelle Pratt[3]

[1] Assistant Professor of Agricultural Economics, Purdue University
[2] Associate Professor of Agricultural Economics, Purdue University
3 MS in Agricultural Economics, Purdue University

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Juan P. Sesmero

Joseph V. Balagtas

Michelle Pratt

This paper develops a model of spatial competition nesting the classical Zhang and Sexton (2001) duopsony and spatial monopsony in order to evaluate the effects of alternative stover market structures on stover prices, supply of biofuels, and firm profits. We show theoretically, as well as in an empirical implementation calibrated to reflect supply conditions in Indiana, that that spatial competition may significantly increase feedstock cost, reduce profits of biofuels plants, and decrease a plant's optimal scale of production and supply elasticity.

Juan Sesmero is an assistant professor and Joseph Balagtas an associate professor in the Department of Agricultural Economics at Purdue University. Michelle Pratt holds an MS degree from the Department of Agricultural Economics at Purdue University. Sesmero is contact author: jesesmero@purdue.edu, 403 West State Street, West Lafayette, IN 47907-2056, Phone 765.494.7545. This research has been supported in part by the Agricultural Experiment Station at Purdue University.

Cellulosic biofuels can reduce emissions of greenhouse gases (GHG) (Farrell et al., 2006); Wang, 2005) and contribute to energy security (Moschini, Cui, and Lapan, 2012). Moreover some cellulosic sources of biofuels do not compete with food demand for limited land resources and, thus, have limited impact on food prices. Transitioning away from traditional biofuels to cellulosic biofuels is expected to generate social benefits, including reductions in GHG emissions, enhanced energy security, and improved food security. To the extent these are positive externalities, they are not reflected in market prices for cellulosic biofuels. Thus to encourage production, the Energy Independence and Security Act of 2007 (EISA) established specific annual mandates for this fuel source which is expected to reach 16 billion gallons ethanol equivalent by 2022. Corn stover has been identified as one of the most promising feedstocks for cellulosic biofuels (National Research Council, 2011; Downing et al., 2011).

An authoritative study by the US Department of Energy (Downing et al., 2011) estimates that, at a minimum, about a third of total advanced biofuels (5.33 billion gallons) will be produced using corn stover. Assuming 80 gallons of biofuel can be produced with a ton of biomass, five billion gallons of biofuels would require 66 million tons of stover, or approximately 50% of stover currently produced in the four largest corn producing states in the United States (Iowa, Illinois, Nebraska, and Minnesota). Industry sources have stated that plants with a capacity of 25 MGY[1] will target participation rates (i.e., percentage of total stover produced that will be harvested and sold) of 20 to 25%. At these participation rates, plants would need to source stover from a radius of 30 to 50 miles (depending on density of stover production) resulting in procurement areas ranging from 2,830 square miles to 7,854 square miles. Sesmero, Pratt, and Tyner (2013) calculate a stover supply density schedule for Indiana and find that a

[1] Abengoa Bioenergy Plant in Hugoton, KS and POET-DSM facility in Emmetsburg, IA.

monopsonistic, cost-minimizing plant facing this supply will find optimal to search for low cost sources (i.e. keep participation rates low) and incur greater transportation cost. They estimate that a plant producing 25MGY would target a participation rate of about 10% and draw stover form an area of 9,000 square miles.

Under a stover supply density scenario with 25% participation and the 2011 average yield and corn planting density from Iowa (the highest in the Corn Belt with 4.82 tons/acre and 243 acres/mile^2), production of 5.33 billion gallons would require drawing stover from 603,000 square miles if no spatial overlapping of procurement areas is to occur. This amounts to 11 times the area of the State of Iowa. These figures suggest that plants will likely source stover from overlapping areas. Spatial competition may cause higher prices for feedstock, with implications for economic feasibility and aggregate supply of cellulosic biofuels. Yet, the scholarly literature has not examined the effect of alternative input market structures on feedstock price, plant's profitability, and its associated biofuel supply. This study fills this gap.

A number of economic analyses of stover-based biofuels (Petrolia, 2008; Gallagher et al., 2003; Brechbill et al, 2011; Perrin et al., 2012) have considered neither a supply response at the farm level nor optimal pricing or stover demand behavior by the plant. Archer and Johnson (2012) do consider a supply response at the farm level but do not model plant's behavior subject to such supply response. Finally Sesmero and Gramig (2013) consider a supply response and model plant behavior subject to this supply response but assume a monopsonist structure in the feedstock market. Therefore a number of studies have quantified feedstock cost for a biofuel plant but have assumed away competition for feedstock. The assumption of monopsonistic procurement of feedstock may lead to erroneous inference on the economic viability of stover-based biofuels. Our paper evaluates the economic effects of spatial competition in this market: Is

spatial competition likely to have a quantitatively meaningful effect on feedstock cost? If so, how will this affect biofuel supply and the price (or subsidy) required to induce a certain level of biofuel production? How will plant entry affect the overall supply of biofuels?

We shed light on these issues by empirically implementing a model capturing spatial competition for feedstock under typical conditions in Indiana. Our model extends Zhang and Sexton's duopsony model to incorporate the fact that plants may (if optimal) try to draw stover from areas with less intense spatial competition even if that means traveling greater distances. This theoretical extension and its empirical implementation prove useful as it reveals important links between intensity of spatial competition, stover prices, and biofuels supply that are not addressed by the extant literature.

A Model of Spatial Competition for Corn Stover

Following Zhang and Sexton (2001) (ZS from now on) we model spatial competition between biofuel plants located at different points on an unbounded line. Since discussion in policy forums and the scholarly literature has been framed in terms of the price (or subsidy) that would be required to induce certain biofuel volumes we assume these plants are profit maximizers which allows derivation of firm-level biofuel supply under alternative spatial market structures.

A processing plant converts stover (Q) into biofuel (y) according to a fixed proportions technology, $y = min\{\mu Q, h(Z)\}$, where Z is a vector of processing inputs, and μ is the fixed conversion factor (i.e., each dry ton of biomass yields μ gallons of biofuel). Without loss of generality μ is set to one so that biomass quantity is expressed in output-equivalent units and, hence, $Q = y$. The cost of transporting a unit of raw stover to a processing facility is s per unit of

distance. Processors are assumed to be price takers in the product market, selling biofuel at a price of u. Marginal processing cost per gallon is constant and denoted by c. Revenue per ton of biomass net of processing cost is defined by $\rho = (u - c)$, where the finished product price net of per-gallon processing cost is multiplied by the conversion factor. Firms choose the price they pay farmers for stover so as to maximize profits.[2] Profits are defined as the difference between revenue (net of processing cost) and feedstock cost. We consider three market structures here—monopsony, duopsony, and a three-firm oligopsony—in order to focus on the implications of alternative competition scenarios for stover supply and optimal pricing.

Scenario 1: Spatial Monopsonist

For analytical tractability and to facilitate comparison of market structures, we collapse the model of a spatial monopsonist to a one dimension, where the plant is located on a line and can procure stover from farms located continuously along the line. Figure 1 illustrates pricing by a monopsonist. The plant located at *A* offers p_A^M dollars per ton of stover at the plant gate.[3] The downward sloping lines in Figure 1 depict the price received by supply points located along the

[2] The question of the breakeven price for a cellulosic biofuel plant has been addressed elsewhere (Anex et al., 2010; Jones and Male, 2011; Brown and Hu, 2011; Petter and Tyner, 2014). We assume biofuel prices are sufficient to cover costs, and turn our attention to the impact of alternative feedstock market structures on plant behavior.

[3] While an interesting question in and of itself, the choice of pricing strategy (Free on Board –FOB- vs Uniform Delivered Prices –UD-) is not endogenized in this study. FOB pricing is assumed as it is likely to emerge under monopsony (Löfgren, 1986) and competition (Zhang and Sexton, 2001), and it guarantees existence of Nash equilibria in pure strategies (Zhang and Sexton, 2001).

line net of transportation cost. A farmer located at distance r receives a price of $p_A^M - sr$, where s denotes the cost of transporting a ton of stover over a unit of distance.

Stover supply from a farm located at distance r from the processing facility is determined by the product of the maximum biomass production potential of that farm (denoted by $\bar{B}$)[4] and the participation rate (i.e., the fraction of maximum potential that is actually collected, which itself is an increasing function of price). Assuming linearity of the participation rate ($\theta_r^S = \theta_o + \theta_1(p_A^M - sr)$) results in linearity of the stover supply schedule. Naturally, the participation rate cannot be negative or exceed one therefore the stover supply by each supply unit can be denoted by:

$$(1)\ q_r^S = \bar{B} * min\{max[\theta_o + \theta_1(p_A^M - sr), 0], 1\}$$

Where q_r^S denotes tons of stover produced by a supply unit located at a distance r from the plant.

As shown in Figure 1, a plant offering a price of p_A^M draws input from supply units located between A and R_A^E to the East and between A and R_A^W to the West. Assuming transportation costs to the east and west are homogeneous and supply curves at each point on the line are homogeneous,[5] then $R_A^E = R_A^W = R_A^M$; where R_A^M denotes the market boundary on each side of firm A under monopsony. The market boundary R_A^M is defined as the distance at which the price net of transportation cost obtained by the supply unit results in zero supply (i.e., $\bar{B}[\theta_o + \theta_1(p_A^M - sr)] = 0$). Solving this expression for r yields $R_A^M = \frac{\theta_o}{\theta_1}\frac{1}{s} + \frac{p_A^M}{s}$.

The aggregate supply facing firm A is the sum of supply from each location within the market boundaries R_A^M:

[4] Calculation of the empirical analog of this measure will be discussed in the empirical implementation section.

[5] This implies that the same plant-gate price to the supply farms located in either direction.

$$(2)\ Q_A^M = 2\int_0^{R_A^M} \bar{B}\left[\theta_o + \theta_1\left(p_A^M - sr\right)\right]dr = 2\bar{B}\left\{\left[\theta_o + \theta_1 p_A^M\right]R_A^M - \theta_1 \frac{s}{2}(R_A^M)^2\right\}$$

The price p_A^M offered to farmers fully determines the extensive margin, R_A^M, and the intensive margin, $\theta_r^s(p_A^M)$. In this scenario, the plant maximizes profits by choosing the plant-gate stover price:

$$(3)\ \max_{p_A^M} \pi_A^M = [\rho Q_A^M(p_A^M) - p_A^M Q_A^M(p_A^M)],$$

where ρ is revenue per ton of biomass processed (i.e., the product of conversion efficiency and biofuel price) and $Q_A^M(p_A^M)$ is as defined in (2).

Substituting $R_A^M = \frac{\theta_o}{\theta_1}\frac{1}{s} + \frac{p_A^M}{s}$ for the market boundary in $Q_A^M(p_A^M)$ and solving the first order condition for p_A^M yields:

$$(4)\ p_A^{M^*} = \frac{-[\rho\theta_1 - 2\theta_0] \pm \sqrt{(\rho\theta_1 - 2\theta_0)^2 + 6\theta_1\left(\rho\theta_0 - \frac{{\theta_0}^2}{2\theta_1}\right)}}{3\theta_1}.$$

Equation (4) expresses the profit-maximizing price offered by the monopsonist. Substituting this price for p_A^M in (3) yields firm A's profit function. The profit function describes net operating revenues (capital costs are not being considered here) as a function of revenue per ton processed ρ, supply of biomass (θ_0, θ_1, and $\bar{B}$), and transportation cost s.

Scenario 2: Spatial Duopsony

We now consider a scenario in which two plants are located at distance D and compete spatially for the feedstock input. We extend the spatial duopsony model formalized by ZS to incorporate the fact that a plant can procure stover by competing in price with another, or by drawing the feedstock from a region that is not subject to competition, or a combination of both. This market structure is illustrated in Figure 2.

In contrast to the monopsonist scenario, firm A now faces competition for biomass from another plant, firm B. Either plant may procure feedstock from a contested region, an uncontested region, or both. In Figure 2, under price p_B^c, plant B procures feedstock from farms located between B and R^c (i.e. B's boundary in the contested region) and those located between B and R_B^{nc} (i.e. B's boundary in its uncontested region). We are interested in a market structure where both plants coexist so we rule out pricing situations like those depicted by $p_B^{c\prime}$ where one plant outbids the other over all regions.

We have no reason to assume a priori that plants will follow the same pricing strategy in the regions with and without competition. In particular the firm may act as a monopsonist in one region while competing in price in the other, as illustrated in Figure 3. Plant A offers price p_A^{nc} in its uncontested region capturing supply from farmers located between A and R_A^{nc}. Plant B offers price p_B^{nc} in its uncontested region, and is a monopsonist between B and R_B^{nc}. In the contested region, firm A offers price p_A^c and captures supply from farms located between A and R_A^c, while firm B offers p_B^c in the contested region and captures supply farms located between B and R_B^c. Intuition suggests that the price in the contested region should be higher than the price under monoposonized area. Here we formalize such a conjecture.

In a duopsony profits of plant j ($j = A, B$) can be denoted by:

$$(5)\ \max_{\left(p_j^{nca}, p_j^c\right)} \pi_j^d = \left(\rho - p_j^{nc}\right) Q_j^{nc}\left(p_j^{nc}\right) + \left(\rho - p_j^c\right) Q_j^c\left(R_j^c(p_j^c, p_i^c)\right),$$

where p_j^{nc} is the price offered by the plant to suppliers located in the region without competition and $Q_j^{nc}\left(p_j^{nc}\right) = \frac{1}{2} Q_j^M\left(p_j^M\right)$ where $Q_j^M\left(p_j^M\right)$ is as defined in equation (2). Supply from the region subject to competition faced by plant j, $Q_j^c\left(R_j^c(p_j^c, p_i^c)\right)$, is:

$$(6)\ Q_j^c = \int_0^{R_j^c} \left\{\bar{B} * \left[\theta_o + \theta_1\left(p_j^c - sr\right)\right]\right\} dr = \bar{B}\left\{\left[\theta_o + \theta_1 p_j^c\right] R_j^c - \theta_1 \frac{s}{2}\left(R_j^c\right)^2\right\}.$$

Just as in the monopsony case the market boundary in the no competition region is defined as the distance at which the price net of transportation cost obtained by the farm results in zero supply. On the other hand the market boundary between plants in the competition region is determined by the condition:

$$(7)\ \bar{B} * \left[\theta_o + \theta_1\left(p_j^c - sR_j^c\right)\right] = \bar{B} * \left[\theta_o + \theta_1\left(p_i^c - s\left(D - R_j^c\right)\right)\right]$$

This condition results in:

$$(8)\ R_j^c = \frac{p_j^c - p_i^c + sD}{2s}$$

Substituting R_j^{nc} and R_j^c for the market boundary expressions in $Q_j^{nc}\left(p_j^{nc}\right)$ and $Q_j^c\left(p_j^c, p_i^c\right)$ respectively, assuming symmetry ($p_j^c = p_i^c$) and Nash-Bertrand behavior ($\frac{\partial p_j^c}{\partial p_i^c} = 0$), the first order conditions of problem (5) yield:

$$(9)\ p_j^{nc*} = p_j^{M*}$$

Where p_j^{M*} is as defined in (4).

$$(10)\ p_j^{c*} = \begin{cases} p_j^{M*} & if \quad R_j^{nc} = \frac{\theta_o}{\theta_1}\frac{1}{s} + \frac{p_j^{nc*}}{s} \leq \frac{D}{2} \\ p_j^c & otherwise \end{cases},$$

where:

$$(11)\ p_j^c = \frac{-\left[\frac{\rho\theta_1 - \theta_0}{2s} - \frac{3\theta_1 D}{4}\right] \pm \sqrt{\left(\frac{\rho\theta_1 - \theta_0}{2s} - \frac{3\theta_1 D}{4}\right)^2 + 2\left(\frac{\theta_1}{s}\right)\left(\rho\left(\frac{\theta_0}{2s} + \frac{\theta_1 D}{4}\right) - \frac{\theta_0 D}{2} + \frac{\theta_1 s D^2}{8}\right)}}{\left(\frac{\theta_1}{s}\right)}.$$

Substituting these prices into (5) yields duopsonist j's profit function which describes net operating revenues as a function of revenue per ton of biomass processed ρ, and supply density of biomass (θ_0, θ_1, and $\bar{B}$), transportation cost s, and distance between firms D.

Scenario 3: Three-firm Oligopsony

Finally we consider a scenario in which a plant is subject to competition from both sides. Plants are located at distance D from each other and compete spatially for the feedstock supply. Therefore the middle plant will always draw feedstock from a region under competition. We designate this as a "three-firm oligopsony" scenario. This situation is illustrated in Figure 4. In Figure 4, under price p_A^c, plant A procures stover from the region between A and R_A^c on both sides of the plant (i.e., transportation cost, distance to competitors, and technology of those competitors is assumed the same on both sides so prices and procurement boundary to the East and West are the same).[6] Therefore, under this market structure, the profits of the middle plant j can be denoted by:

$$\max_{(p_j^c)} \pi_j^O = 2\left[\rho Q_j^c\left(p_j^c, p_i^c\right) - p_j^c Q_j^c\left(p_j^c, p_i^c\right)\right], \tag{12}$$

where π_j^O denotes profit of the middle plant in the 3-firm oligopsony and the other parameters have been defined before.

If we re-define overall supply faced by the firm as $Q_j^d\left(p_j^d, p_i^d\right) = 2Q_j^c\left(p_j^c, p_i^c\right)$, equation (12) collapses to the ZS duopsony model. The solution of this problem is the same as the solution for p_j^{c*} in scenario 2 (equation (10)). However substituting (10) in (12) results in a profit function π_j^O that is different from that in the duopsony scenario. The two plants located in the extremes operate in a contested market on one side and in an uncontested market on the other. Therefore their profit function is described by equation (5).

Although we have discussed discrete changes in market structure (monopsony, duopsony, and three-firm oligopsony), our model can accommodate varying degrees of competition

[6] Note that the other two plants will act as firms operating under duopsony with non-unique pricing (i.e. monopsony on one side and competition on the other)

intensity. Reductions in supply density (i.e. a reduction in θ_0, θ_1, or $\bar{B}$), distance D, or transportation cost s result in more intense competition. In contrast a large enough increase in θ_1, D, or s results in spatial monopsony.

Comparison of Behavior in Contested and Uncontested Markets

For the remainder of this section and without loss of generality we assume that $\theta_0 = 0$ and $\bar{B} = \theta_1 = D = 1$. These parametric assumptions enhance the tractability of our results and permit focusing on the influence of two key variables on firm behavior, biofuel net price (ρ) and transportation cost (s).

We start by comparing plant-gate price of stover under contested and uncontested markets. Intuition suggests that spatial competition will drive firms to bid each other up thus offering higher prices for feedstock than they would if the market was uncontested. The following proposition addresses the validity of such theoretical prediction over the entire support of ρ and s.

Proposition 1. Let a firm implement FOB pricing in contested and uncontested regions and let our parametric assumptions hold. A firm will always (i.e. over the entire domain of competition intensities) procure more biomass from the uncontested than from the contested region. See proof in Appendix.

The result described in proposition 1 implies that firm entry, if it increases competition, reduces plant-level production and thus contributes progressively smaller amounts to industry-level production. These implications are summarized in the following results.

Corollary 1a. Competition reduces production from the incumbent firm(s).

Corollary 1b. Entry of a firm, if it results in increased competition, contributes less to industry-level production than entry of the previous firm to the market.

Proposition 2. Let a firm implement FOB pricing in contested and uncontested regions and let our parametric assumptions hold. There exists a combination of biofuel price and transportation cost levels that can support competition and for which the price paid for stover in the contested market is lower than the price in the uncontested market. See proof in Appendix.

Proposition 2 reveals that competition in the input market does not necessarily result in higher input prices. The fact that firms may offer a higher price for stover in the uncontested region is rather surprising and deserves further discussion.

The ratio $\frac{\rho}{s}$ can be interpreted as an indicator of profitability and, in contested regions, competition intensity. Numerical simulation of the stover price differential under our parametric assumptions reveals that the plant-gate price of stover in the uncontested region will be higher than that in the contested region as long as competition exists but remains sufficiently mild; i.e. $0.75 < \frac{\rho}{s} < 1.5$.

Increased profitability of biofuel firms (i.e. an increase in the ratio $\frac{\rho}{s}$) promotes a larger scale of production and, thus, higher stover price. This effect takes place in both contested and uncontested regions. In contested regions the intensity of competition also raises, lessening the surge in profitability and consequently the desired increase in production and stover price. It appears as if superior profitability in the absence of competition would always result in higher prices in uncontested regions. However, in uncontested markets, stover supply is more responsive to price due to the contribution of the extensive margin which means that expansions in the scale of production require smaller increments in stover price vis a vis the contested

regions. The difference in biomass supply responsiveness is smaller at low profitability and scale of production. As a result, at sufficiently low profitability and scale of production (i.e. $\frac{\rho}{s} < 1.5$), the difference in biomass supply responsiveness is outweighed by the difference in profitability resulting in higher stover prices in uncontested regions relative to contested ones.

The supply radius of a firm in an uncontested region is, by construction, larger than that in a contested region. Therefore the firm will procure more biomass from the extensive margin in an uncontested region. Moreover, according to our numerical simulations a firm will pay a higher price of stover in the uncontested region when $\frac{\rho}{s} < 1.5$. Since biomass supply responds positively to plant-gate price of stover ($\theta_1 = 1$) a higher price of stover translates into higher amounts of biomass purchased from each supply unit. In other words, firms will also procure more biomass form the intensive margin of uncontested regions if profitability is sufficiently low. These insights are summarized in the following result.

Corollary 2. When profitability is sufficiently low ($\frac{\rho}{s} < 1.5$) a firm will procure more biomass from uncontested regions by drawing greater amounts from both the extensive and the intensive margins.

A lower responsiveness of biomass supply to its price in contested regions implies that, a higher plant-gate price of stover in this region relative to an uncontested one, does not necessarily translate into higher amounts of procured biomass. The following proposition compares total amount of biomass procured from each region over the relevant range of competition intensities.

Propositions 1 and 2 together suggest that the effect of competition on profits is ambiguous. Competition reduces the scale of production (the amount of biomass procured by the

firm) but has an ambiguous effect on the stover price depending on the intensity of competition (i.e., the level of $\frac{\rho}{s}$). The following proposition resolves this apparent ambiguity.

Proposition 3. Let a firm implement FOB pricing in contested and uncontested regions and let our parametric assumptions hold. Profits obtained in an uncontested area are higher than those in a contested area over the entire domain of competition intensities. See derivation in Appendix.

While the propositions and corollaries derived above offer guidance on the qualitative impact of competition on firm behavior the quantitative relevance of such impacts remains an empirical question. We implement this model empirically and try to shed light into these magnitudes.

Empirical Implementation

Empirical implementation of the three scenarios modeled above requires estimation of the stover supply schedule faced by plants. This schedule is in turn a function of maximum biomass production potential and participation rates. Maximum biomass production is defined by $M = p_{den} * D * s_y$, where D represents total distance between the plants, p_{den} represents planting density (acres of cropland per square mile), and s_y is stover yield.

Biomass production parameter values are reported in Table 1. We consider an area comprised of Jasper County and White County in Indiana. This region is considered a good candidate for plant location as it has the highest corn planting densities and yields in the State. Two points at opposing extremes of both counties (North West of Jasper and South East of White) were chosen and the distance between these points was calculated to be 50 miles using google map's distance measuring tools. According to data from USDA NASS Jasper has a total area of 561 square

miles and approximately 445 acres of land per square mile are suitable for corn.[7] White county has 509 square miles and 490 acres per square mile suitable for corn. Jasper's stover yield in 2011 was 4.4 tons per acre and White's yield was 4.7 tons per acre.[8] Previous studies have found that up to 75% of stover produced can be technically recovered. Applying this adjustment factor results in a stover yield of 3.3 tons per acre in Jasper and 3.5 tons per acre in White. Applying the formula for M results in a maximum potential of 1.71 million tons of recoverable stover.

To simplify the spatial dimension of the problem we assume that the maximum potential biomass production is uniformly distributed along the 50-mile line joining the corners of Jasper and White counties in Indiana. Therefore total biomass available from a point on that line can be calculated by the density function of a continuous uniform distribution; i.e. $\bar{B} = \frac{M}{D} = \frac{1{,}710{,}000}{50} = 34{,}200$. Assuming that a given quantity of biomass produced is uniformly distributed along a line between two plants is a simplification of the spatial pattern of biomass production and may result in underestimation of transportation cost. However we make this simplification in order to focus on the implications of alternative market structures.

Since primary data necessary to estimate a participation rate curve are not available we simulate profit-maximizing land allocation decisions (incorporating corn with stover removal as a land use alternative) with the Purdue Crop Linear Programming model (PCLP) (Doster et al., 2009b). This simulation provides a counterfactual scenario (i.e., acres allocated by farmers to

[7] We assume all land planted with corn and soybean in 2011 is suitable for corn. Land planted to other field crops may also be suitable for corn grain but this land was quite small in the area under analysis.

[8] The amount of residue produced is assumed to be the same as grain yields (1:1 ratio of grain and biomass) which is standard in the literature (Perrin et al., 2012).

corn with stover removal at different stover prices) based on which supply density can be estimated.

PCLP calculates the profit-maximizing allocation of acres to alternative crop rotations (Doster et al., 2009b) based on farm-specific data on land, labor, machinery, storage, planting date, crop rotations, crop yields, crop prices, and costs (Doster, Dobbins, and Griffin, 2009a). The farmer information used in PCLP was collected from 24 farms operating in Indiana which reported data during their participation in the Top Farmer Crop Workshops held at Purdue University. The data are from several years of the workshop including 2007, 2008, 2009, and 2010.[9] These farms operated a total of 63,336 acres under commonly observed growing conditions in Indiana. Farm size ranged from 550 acres to 8,200 acres with a mean size of 2,610 acres. Average corn yield in the sample is 174 bushels per acre for corn/soybean rotations and 167 bushels per acre for continuous corn rotations.

Thompson and Tyner (2011) incorporate corn/soybean rotation with stover removal and continuous corn with stover removal as cropping alternatives in PCLP. The estimated cost of stover harvest ($/ton) is subtracted from farm-gate prices for stover ($/ton) to determine net returns from stover collection. The net return per ton is then multiplied by tons harvested per acre to calculate per acre returns from harvesting stover. While cost is calculated, stover price is simulated.

We use PCLP to calculate, based on farm-level data, the profit-maximizing allocation of land to competing crop rotations for a range of stover prices. From this solution the share of land

[9] Some farms do not operate in the two counties considered here but including them provides us with more variability in operating conditions (i.e. a better sample of responses to stover price). Moreover, climatic and soil conditions under which these farms operate are not that dissimilar to those in Jasper and White counties.

allocated to corn with stover removal (i.e., the participation rate) is calculated. Second we conduct a linear approximation to the simulated participation rates as a function of stover price. Figure 5 plots both simulated and predicted participation rates with PCLP. Predicted participation rates are calculated as:[10]

$$\widehat{\theta_r^s} = \underset{(-3.85)}{-0.20} + \underset{(-9.61)}{0.0089}\left(p_j^k - sr\right) \quad (13)$$

Where $\widehat{\theta_r^s}$ represents predicted supply density schedule in the supply unit located at r miles from our representative plant j, and p_j^K is the price offered at the plant gate by plant j operating with competition ($k = c$) and without competition ($k = nc$).

Though a likelihood ratio tests suggests a quadratic specification is statistically superior, we impose linearity to the predicted participation rate. The disadvantage of the linearity assumption is that it overestimates participation at low stover prices and underestimates participation at medium prices. This, in turn, implies that the optimal price with a linear supply density schedule may be lower than that with a quadratic approximation. However, the assumption of linearity of the supply density schedule facilitates comparison of plant profit and biofuel production under alternative market structures.

Substituting $\bar{B}$ and equation (13) in the expression for stover supply (equation (1)) yields the predicted stover supply from each spatial unit:

$$q_r^s = 34{,}200 * min\{max[-0.2 + 0.089(p_A^M - sr), 0], 1\} \quad (14)$$

We now use this stover supply density schedule to quantitatively solve problems (3), (5), and (12), and answer the questions posited at the beginning of this study.

[10] T-ratios are in parentheses. All coefficients are statistically significant at 1% level and R-square is 0.91.

Results

In a situation where two firms are operating on the same line 50 miles away from each other, we find that supplying areas do not overlap until (under our parameter values) the price of biofuel net of processing cost is $0.4/gal. Below this price each firm acts as a monopsonist and the only relevant stover pricing policy is depicted by equation (4). Biofuel prices above this threshold trigger competition (spatial overlapping of supplying areas) and equation (10) becomes the relevant description of the pricing policy. Equation (10) depicts the appropriate stover pricing behavior on the contested side of a firm operating under duopsony or located in one extreme of the three-firm oligopsony. On the other hand equation (10) describes the stover pricing policy on both sides of a firm operating in the middle point of a three-firm oligopsony.

Figure 6 displays solutions for plant-gate stover prices in uncontested markets and contested markets. Biofuel prices above $0.4/gal are reported as only in this range markets can be contested under our parameter values. Optimal prices increase as the biofuel price increases.[11] Increases in biofuel price increase biofuel production which, in turn, increases demand for biomass. Increases in the price paid for stover suggests that part of that additional biomass is obtained through the intensive margin.

The stover price in the contested area is more responsive to output price. An increase in biofuel price increases profitability, biomass demand and, consequently, stover price. However, when the firm operates in a contested market additional biomass can only be procured from the intensive margin which requires larger increases in stover price. Figure 7 depicts firm-level production at different biofuel prices. These production levels are depicted for each of the three

[11] The negative square root in equation (11) was used to depict stover price under competition as it resulted in values above the predicted minimum price for positive participation (i.e. $25/ton).

market structures previously discussed−a firm operating under monopsony (uncontested markets on both sides), a firm operating under duopsony (uncontested market on one side and contested market on the other), and a firm operating in the middle point of a three-firm oligopsony (contested markets on both sides).[12]

Combining results in Figures 6 and 7 reveals that spatial competition increases feedstock cost and reduces firm-level production at all biofuel prices. For instance, at a biofuel price net of processing cost of $0.70/gallon, a monopsonist pays on both sides $2.50 less per ton of stover than the middle point plant in a 3-firm oligopsony (Figure 6). Yet the monopsonist produces almost 23 MGY more of biofuel (i.e. the monopsonist produces close to 49 MGY while the middle plant in a 3-firm oligopsony produces 26MGY).

Figures 8 and 9 illustrate how plants adjust the intensive and extensive margins in response to competition. Participation rates and radii plotted in Figures 8 and 9 respectively reveal that higher prices paid by plants competing spatially for feedstock do not translate into a larger supplying radius but they do result in higher participation rates. Therefore plants operating under spatial competition secure additional amounts of biomass by exploiting the intensive margin. As the price of biofuel increases, a monopsonist also offers a higher price for stover (Figure 6) but in contrast to the case of spatial competition, this translates into both a higher

[12] Firms located on the extremes of a three-firm oligopsony have a contested market on one side and an uncontested on the other thus behaving the same as firms in a duopsony.

participation rate (Figure 8) and a larger supplying radius (Figure 9).[13] In other words a monopsonist can rely both on the intensive and the extensive margin for stover procurement.

The impact of competition on firm-level profits is illustrated in Figure 10. Curves are plotted for the same competition scenarios in Figure 7: monopsonist, duopsonist, and middle plant in a three-firm oligopsony. Figure 10 shows that the effect of competition on plant profits is increasing in biofuel prices. At low biofuel prices, demand for biomass is low resulting in less overlap of procurement regions and less competition. Consequently, at low prices market structure has smaller effects on stover pricing, biofuel production, and plant profits. In contrast high biofuel prices cause large differences in biomass demand and pricing (Figures 6 and 7) which, combined with differences in supply response from the intensive and extensive margins (Figures 8 and 9), results in significant differences in plant profits.

Economic viability of alternative fuel sources can be evaluated based on the price of the fuel that would be required to induce a given level of production and a comparison of this price to that of regular gasoline. Under monopsony, a net price of $0.70 per gallon would be required to induce production of 50MGY.[14] Based on estimates of processing cost reported in Chen, Khanna, and Yeh (2012) this translates into a biofuel price of $3±1 per gallon.[15] The price that

[13] Our calculations also reveal that capacity constraints are never binding in the range of biofuel prices considered here; i.e. at the highest biofuel price considered here, the participation rate at zero distance from the plant (the unit with the highest participation rate) is 41%.

[14] We choose a production volume of 50MGY for illustration. Higher or lower amounts can be chosen and discussed based on our results.

[15] Chen, Khanna, and Yeh (2012) reported estimates of processing costs ranging from $1.3/gal to $3.3/gal depending on the type of conversion process. The average reported processing cost is $2.3/gal

would induce production of 50MGY under duopsony is \$3.08±1 per gallon. [16] The price under a 3-firm oligopsony is \$3.28±1 per gallon. According to the US Energy Information Administration, gasoline rack prices in the US averaged \$2.90/gal in the period 2012-2013 but reached highs of \$3.19/gal. These figures reveal that while gasoline prices at the higher end of this range could have been sufficient to induce an already operating monopsony to produce 50 MGY, they would not have been sufficient to support such production scale under a 3-firm oligopsony.[17] Thus spatial competition may significantly diminish the competitiveness of this fuel source relative to gasoline.

Results in Figure 7 imply that plant entry, if it causes spatial overlapping of supplying areas, reduces production of the incumbent firm (biofuel production is lower in contested areas at all biofuel prices). Moreover the entrant would produce less operating as the middle firm in a three-firm oligopsony that what would produce as a duopsonist. This suggests that the overall impact of entry on aggregate supply depends on its effect on market structure. We now turn our attention to this issue.

Entry of new plants may or may not trigger or intensify spatial competition for feedstock. An entrant may be able to find a location where it can avoid spatial competition for biomass. On the other hand, if such a location strategy is not available, the entrant will (all else constant) try

[16] If biofuels are produced as drop-ins (through a pyrolysis analysis like that evaluated in Anex et al., 2010) they are perfect substitutes to gasoline. We assume biofuels are produced as drop-ins so we compare their prices directly to gasoline rack prices. On the other hand if they are produced as ethanol the above prices should be adjusted upwards to reflect lower energy contents in ethanol.

[17] Since our analysis does not include capital costs, we do not consider here prices that would trigger entry but rather prices that would induce certain level of production after entry absent binding capacity constraints.

to choose a location where competition faced by the plant after entry, is weakest. Finally in certain circumstances it may be impossible for a plant to enter the market without facing strong competition after entry.

We assume in this part of the analysis that firms can locate along a line segment that is 100 miles long. Such an area can support three firms located 50 miles away from each other (i.e., an empirical version of the structure defined above as a 3-firm oligopsony). First, we will consider a situation in which there is a biofuel plant acting as a monopsonist and located at one end of the line segment. Another plant enters the market and locates on the other end of the line segment, presumably trying to avoid competition with the incumbent. These plants will act as spatial monopsonists unless the price of biofuel is high enough to cause a spatial overlapping of procurement areas. Finally we assume a third plant locates exactly halfway between the two incumbents (i.e. 50 miles away from each of the competitors). We calculate the industry-level production corresponding to each case and evaluate the impact of plant entry on total biofuel production. These scenarios, though clearly not exhaustive, are useful to illustrate the link between entry and overall biofuel supply when entry results in more intense spatial competition. Results are displayed in Figure 11.

Entry of the second plant doubles supply for all biofuel prices below $0.525/gal. However if net revenue from biofuel rises above this threshold, spatial overlapping of procurement areas will occur and plant will be subject to spatial competition. Therefore overall supply with two plants is less than twice the supply of a monopsonist at biofuel prices above $0.525/gal (e.g. at a net revenue of $0.8/gal supply with a monopsonist is 75MGY and supply under duopsony is 128MGY). Entry of the third plant (which results in a 3-firm oligopsony) increases biofuel supply by a much smaller amount than entry of the second plant. This is

because the third entrant competes for stover on both sides and, additionally, production by the two incumbents is reduced as they are now subject to competition with the last entrant. These results illustrate the fact that successive entry of plants may provide decreasing marginal contributions to total biofuel production as they generate more competitive market structures.

Conclusions

Previous economic analyses of stover-based biofuels (Petrolia, 2008; Archer and Johnson, 2012; Gallagher et al., 2003; Perrin et al., 2012; Sesmero and Gramig, 2013; Brechbill, Tyner, and Ileleji, 2011) assumed, implicitly or explicitly, a monopsonistic structure in the feedstock market. This study relaxes this assumption to examine the implications of different structures in spatial markets for feedstock on firm behavior and market conduct. Results from our analysis suggest that competition increases feedstock price, reduces firm-level production, and may also curb the effect of entry on industry-level supply which demonstrates the importance of considering alternative input market structures in economic analysis of biofuel plants. Therefore, by ignoring the possibility of spatial competition, previous economic analyses of biofuel plants may have underestimated feedstock cost and, consequently, overstated the economic viability of stover-based biofuels.

A duopsony increases by 7% the biofuel price that induces a plant to produce 50MGY. A three-firm oligopsony, on the other hand, increases such price by 25% (Figure 7). This price differential increases at higher biofuel production levels. Increased competition increases feedstock price which suggests a higher surplus at the farm level relative to a monopsonistic market. While increased competition reduces profits as predicted by economic theory it also lessens the impact of entry on biofuel supply. When entry results in more competitive feedstock

market structure, it reduces production by the incumbents. This effect partially offsets the increase in overall production caused by entry of a new plant.

Several dimensions not considered by our analysis deserve more attention. Our analysis takes entry as exogenous which is an important limitation in this context. In particular, entry in this study is assumed to be consistent with overall profit maximization. Thus, although we examine the link between biofuel prices and behavior by an incumbent firm operating in a given spatial market structure, we refrain from determining whether these biofuel prices are sufficient to trigger entry into the market which is critical for assessment of the overall economic viability of this fuel source. Entry by a biofuel producing plant involves a large and irreversible investment. In these circumstances capital costs and uncertainties are usually important in determining entry decisions (Dixit (1989)).These issues and their potential interaction with spatial competition in the context of dynamic games of entry deserve more attention.

This study also assumes a profit maximizing plant that faces no constraints on the choice of production level. Intuition suggests that if the plant faced capacity constraints and acted as a cost-minimizer, prices chosen in the contested and uncontested areas would be linked; i.e. the marginal cost of stover would have to be equalized in the contested and uncontested areas. Therefore implications of alternative markets structures on plant behavior when the plant is a capacity-constrained cost-minimizer may be different from implications derived in this study. This also seems like an interesting research question. Finally, quantification was conducted based on typical conditions in Indiana. These conditions vary widely across the Corn Belt so, while qualitative insights form this study may still hold in those regions, quantitative aspects will likely vary as well.

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APPENDIX

First note that, under our parametric assumptions, the supply radius in an uncontested region is $R_A^M = \frac{p_A^M}{s} = \frac{2}{3}\frac{\rho}{s}$. For competition to exist, this radius has to be higher than 0.5; i.e. $R_A^M = \frac{2}{3}\frac{\rho}{s} \geq \frac{1}{2}$. Therefore competition occurs if and only if $\frac{\rho}{s} > \frac{3}{4}$.

Proof of Proposition 1.

More biomass will be procured from the uncontested region if and only if:

$$\frac{2}{9}\frac{\rho^2}{s} > \left[\frac{\rho - 1.5s \pm \sqrt{\rho^2 - s\rho + 3.25s^2}}{2}\right] 0.5 - \frac{s}{2}(0.5)^2$$

It can be numerically demonstrated that the above condition holds if and only if $\frac{\rho}{s} > \frac{3}{4}$ which must hold for competition to exist. Therefore the plant always procures more biomass from the uncontested region, concluding the proof.

Proof of Proposition 2.

We prove the proposition by contradiction. Let us assume that the price in the contested region is higher than that in the uncontested region. Therefore:

$$\frac{\rho - 1.5s \pm \sqrt{\rho^2 - s\rho + 3.25s^2}}{2} > \frac{2}{3}\rho$$

Which after some re-arrangements can be expressed as:

$$0.89\left(\frac{\rho}{s}\right)^2 - 2\frac{\rho}{s} + 1 > 0$$

Calculating the first and second order conditions of the expression in the left hand side reveals that the minimum value of this expression occurs at $\frac{\rho}{s} = 1.12$. Evaluating the LHS at $\frac{\rho}{s} = 1.12$ results in a value of -0.12 which is lower than zero contradicting the inequality. Therefore there

is at least one combination of net biofuel price and transportation cost for which input price in the contested region is lower than in the uncontested region, concluding the proof.

Proof of Proposition 3.

A firm would attain higher profits in uncontested markets relative to contested regions if and only if:

$$\pi^M - \pi^c = \left(\rho - \frac{2}{3}\rho\right)\frac{2}{9}\frac{\rho^2}{s} - \left(\rho - \left[\frac{\rho - 1.5s \pm \sqrt{\rho^2 - s\rho + 3.25s^2}}{2}\right]\right)\left(\left[\frac{\rho - 1.5s \pm \sqrt{\rho^2 - s\rho + 3.25s^2}}{2}\right]0.5 - \frac{s}{2}(0.5)^2\right) > 0$$

Solving the above condition numerically reveals that $\pi^M - \pi^c > 0$ if and only if $\frac{\rho}{s} > \frac{3}{4}$ which must hold if competition exists, concluding the proof.

Figure 1. Spatial Monopsonist

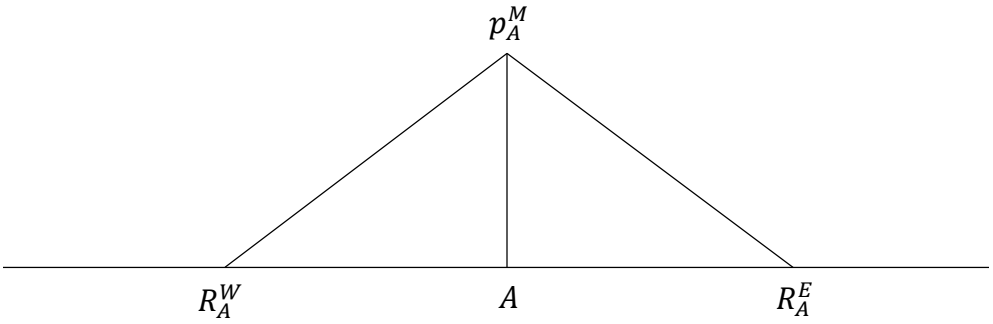

Figure 2. Duopsony with Unique Pricing

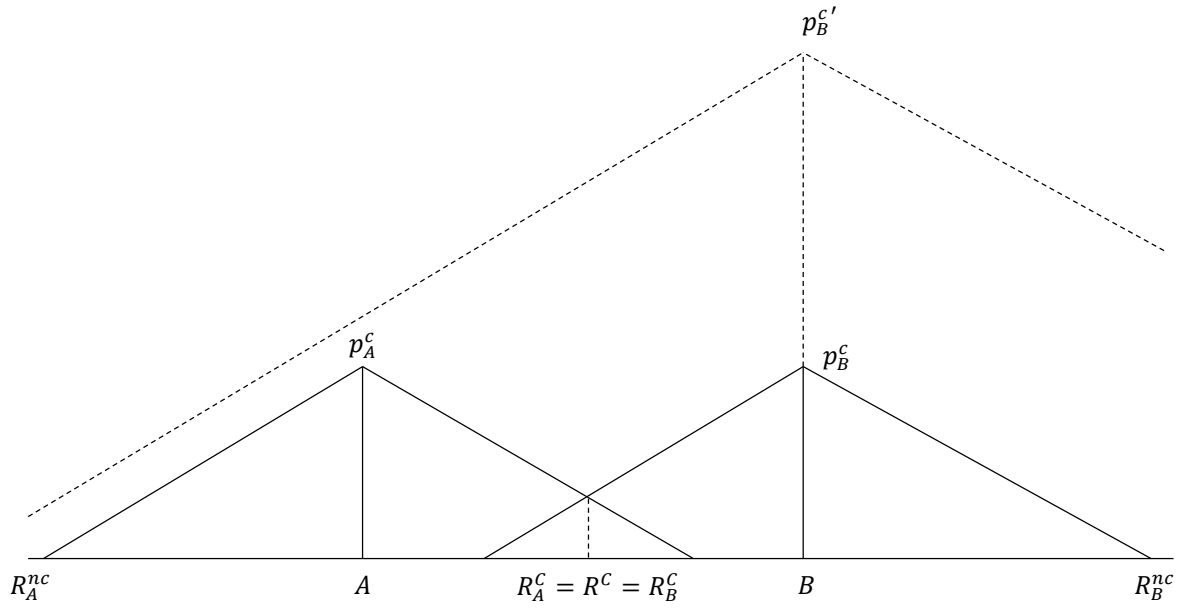

Figure 3. Duopsony with Non-unique Pricing

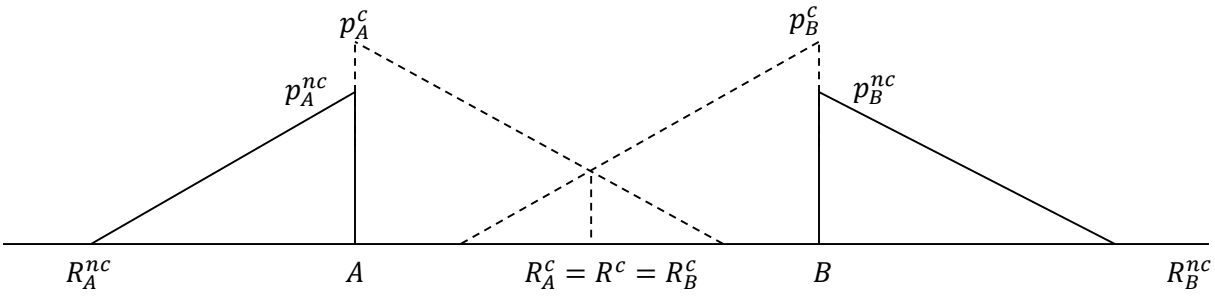

Figure 4. 3-firm oligopsony

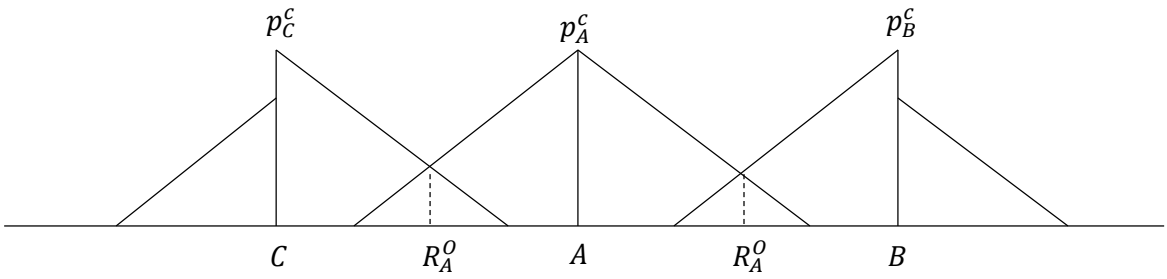

Table 1. Biomass Production Parameters

Measure / County	Area	Land suitable for corn	Recoverable (75%) stover yield	Maximum biomass production
Jasper	561 miles^2	445 acres	3.3 tons/acre	1.71 million tons
White	509 miles^2	490 acres	3.5 tons/acre	

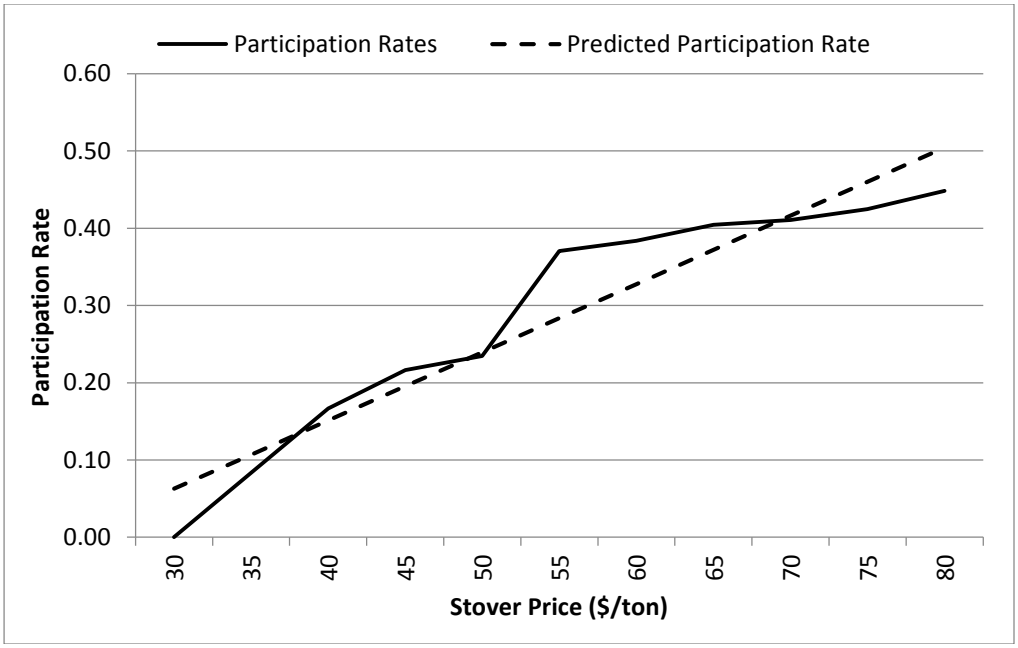

Figure 5. Simulated and Predicted Participation Rates

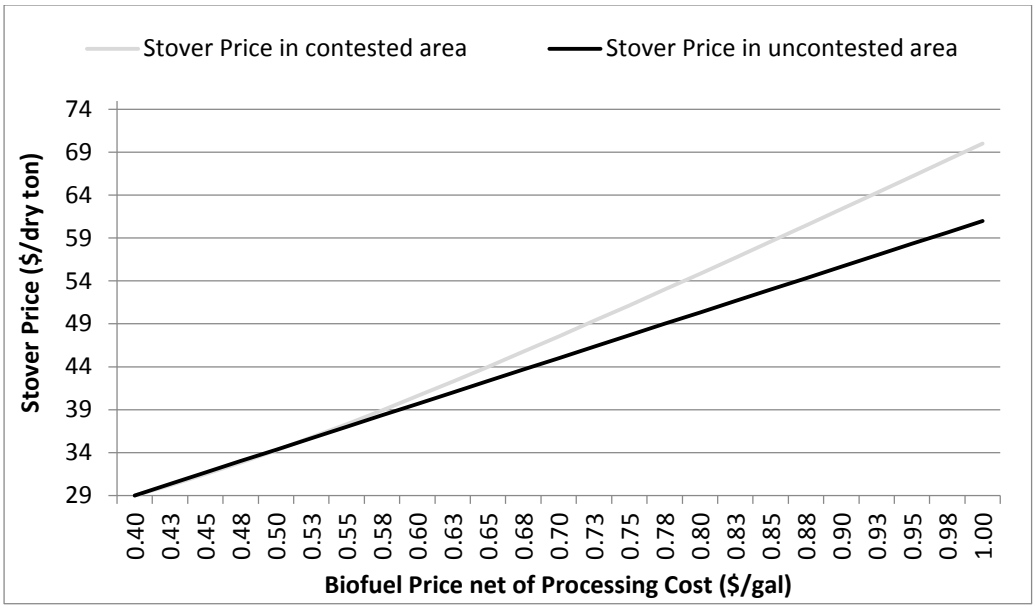

Figure 6. Stover Pricing under Monopsony and Competition

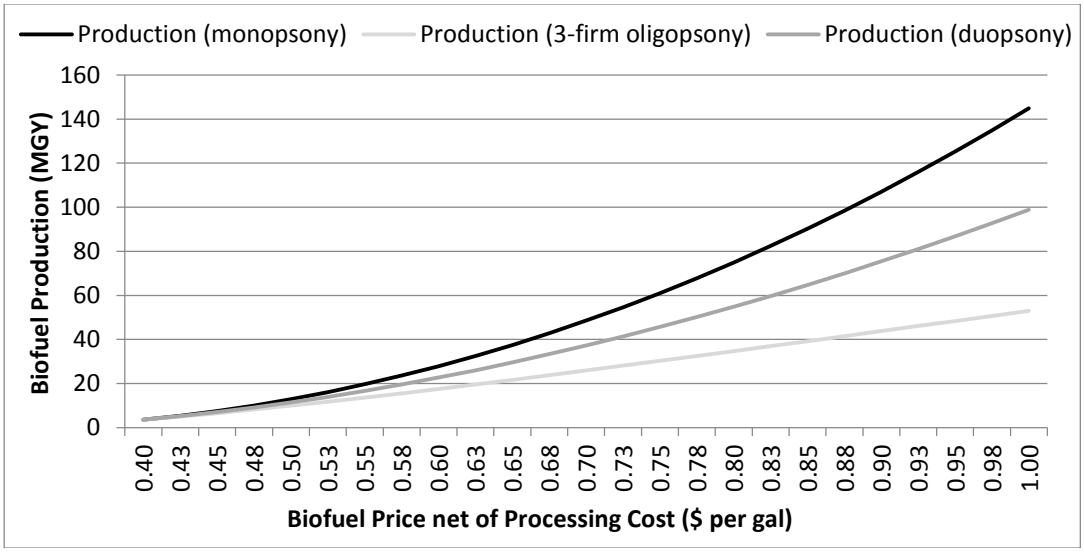

Figure 7. Individual Plant Production

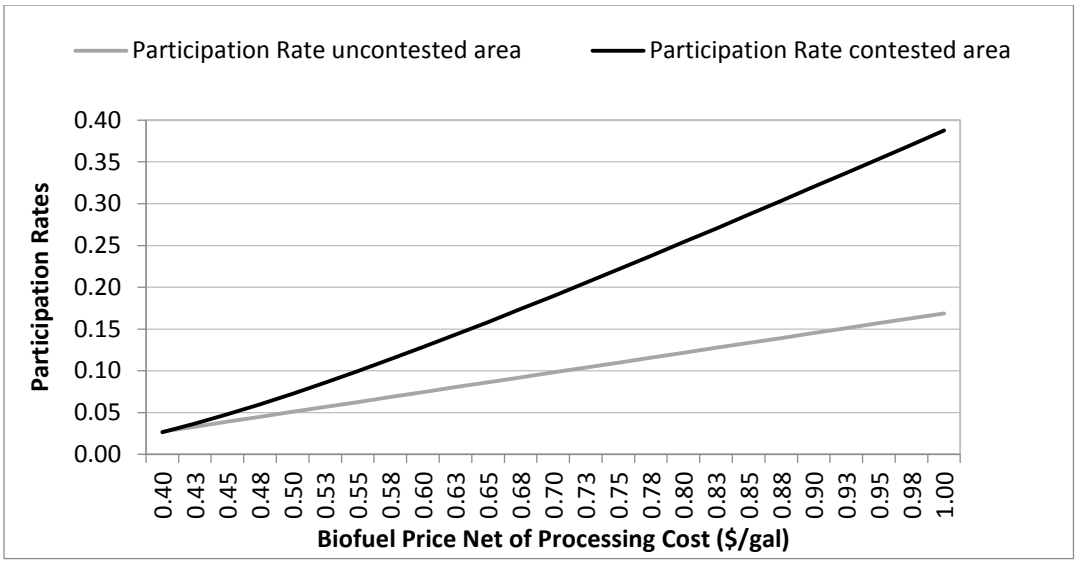

Figure 8. Intensive margin in contested and uncontested markets

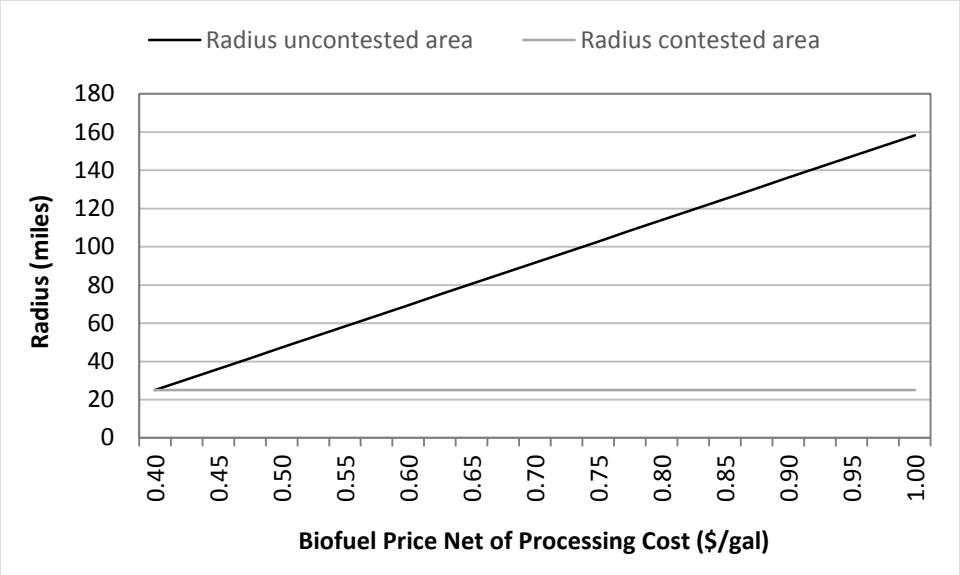

Figure 9. Extensive margin in contested and uncontested markets

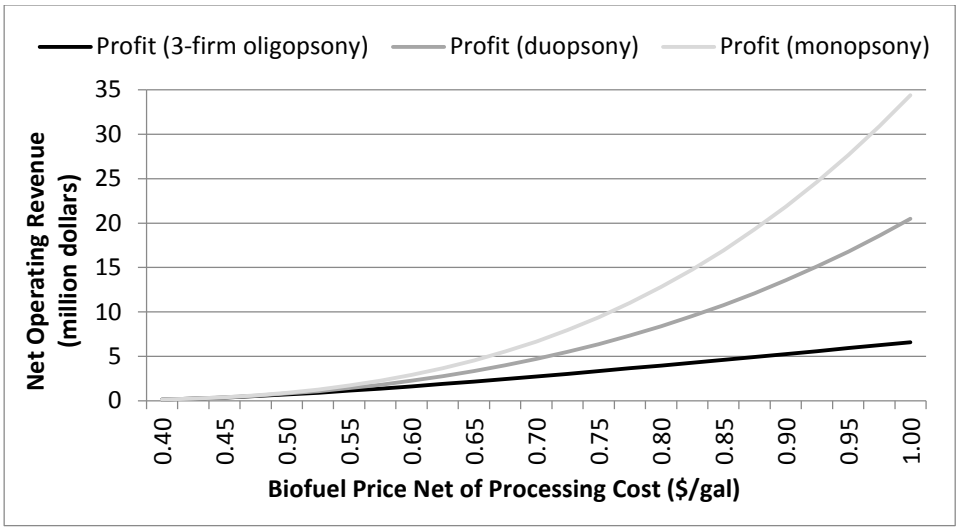

Figure 10. Competition and Plant-Level Profits

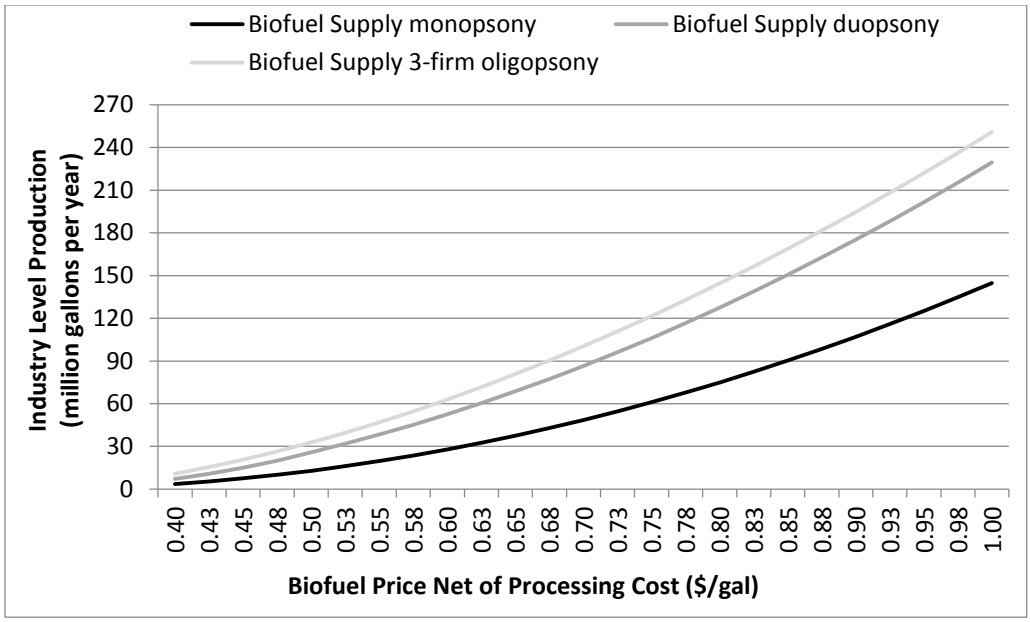

Figure 11. Plant entry and industry-level production