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The Economics of Spatial Competition for Corn Stover

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This paper develops an empirical model of spatial competition in order to evaluate the effects of alternative corn stover market structures on stover prices, supply of cellulosic biofuels, and firm profits. We calibrate the model to market conditions in Indiana and show that spatial competition may significantly increase feedstock cost, reduce profits of biofuels plants, and increase the price of biofuel necessary to induce a given production target. On the other hand, spatial competition causes firms to rely more on the intensive margin, increasing farmers' share of the industry's surplus.

Key words: cellulosic biofuels, comparative statics, corn stover, Nash equilibrium, spatial competition, uncontested markets

Introduction

Cellulosic biofuels can reduce emissions of greenhouse gases (Wang et al., 2011) and contribute to energy security (Moschini, 2012). Moreover, some cellulosic sources of biofuels do not compete with food for limited land resources and thus have a smaller impact on food prices. Transitioning away from traditional biofuels to cellulosic biofuels is expected to generate social benefits, including reductions in greenhouse-gas emissions, enhanced energy security, and improved food security. To the extent that these are positive externalities, they are not reflected in market prices for cellulosic biofuels. 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. Committee on Economic and Environmental Impacts of Increasing Biofuels Production, 2011; Downing et al., 2011).

An authoritative study by the U.S. 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, 5 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) according to data from the United States Department of Agriculture (NASS Quick Stats). Industry sources have stated that plants with a capacity of 25 million gallons per year will target participation rates (i.e., percentage of total stover produced that will be harvested and sold) of 20–25%.[1] At these participation rates, those plants would need to source stover from a thirty- to fifty-mile radius (depending on density of stover production) resulting in procurement areas ranging from

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[1] Plants with a 25 million gallons/year capacity are Abengoa Bioenergy Plant in Hugoton, KS, and POET-DSM facility in Emmetsburg, IA.

2,830 square miles to 7,854 square miles. In contrast, Sesmero, Pratt, and Tyner (2015) calculate a stover supply density schedule for Indiana and find that a monopsonistic, cost-minimizing plant facing this supply would expand on the extensive margin. They estimate that a plant producing 25 million gallons/year 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/square mile), 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 eleven times the area of the state of Iowa. The required area would be even larger if lower participation rates are targeted by plants as suggested by Sesmero, Pratt, and Tyner (2015). 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 profitability, and associated biofuel supply. This study fills this gap.

A number of economic analyses of stover-based biofuels have considered neither a supply response at the farm level nor optimal pricing or stover demand behavior by the plant (Petrolia, 2008; Gallagher et al., 2003; Brechbill, Tyner, and Ileleji, 2011; Perrin et al., 2012). Archer and Johnson (2012) consider a supply response at the farm level but do not model plants' behavior subject to such supply response. Sesmero and Gramig (2013) and Sesmero, Pratt, and Tyner (2015) 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 inferences about 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 within a feedstock supply region affect the overall supply of biofuels?

We shed light on these issues with a model that captures spatial competition for corn stover. First, we modify Zhang and Sexton's duopsony model so that it can be empirically implemented. We then extend this model to analyze competition intensification in the form of a three-firm oligopsony. The analysis reveals important links between intensity of spatial competition, stover prices, and biofuels supply that are not addressed by the extant literature.

A Model of the Biofuel Firm

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 1 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 $\rho = (u - c)$.

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 that biofuel firms are profit maximizers, which allows derivation of firm-level biofuel supply under alternative spatial market structures. Therefore, firms choose the price they pay farmers for stover so as to

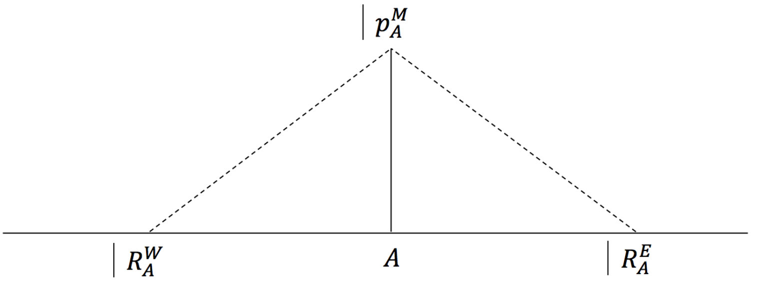

Figure 1. Spatial Monopsonist

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.[3]

Spatial Market for Feedstock

Spatial markets have mainly been formalized through one of two models: Hotelling's line (Hotelling, 1929) and Salop's circle (Salop, 1979). We follow previous analyses of spatial agricultural procurement markets (Zhang and Sexton, 2001; Graubner, Balmann, and Sexton, 2011) and employ a Hotelling's line representation of spatial markets. The Hotelling's line model is a more appropriate empirical representation of most spatial economies (Economides, 1993; Brenner, 2005) due to the existence in reality of central and peripheral operating conditions and the ability of input suppliers to travel direct routes between competitors. This is especially true for an area like the Corn Belt, which has varying corn planting density and dense transportation infrastructure.

Spatial Monopsonist

The monopsonist firm is assumed to be located at the center of a line segment of length D and can procure stover from farms located continuously along the line. Figure 1 illustrates pricing by a monopsonist. The plant offers p_A^M dollars per ton of stover net of breakeven cost (defined as the price of stover at which participation rate is zero) at the plant gate.[4] The downward-sloping lines in figure 1 depict the price received by supply points located along the line net of transportation cost. A farmer located at distance r receives a price of $p_A^M - sr$.

Stover supply from a point located at distance r from the processing facility is determined by the product of the maximum biomass production potential at that point (denoted by $\overline{B}$) and the participation rate (i.e., the fraction of maximum potential that is actually collected, which is itself

[2] The question of the breakeven price for a cellulosic biofuel plant has been addressed elsewhere (Anex et al., 2010; Jones and Male, 2012; Brown and Hu, 2012; 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] Previous work shows that cooperative firms may behave differently than private firms (e.g., Fousekis, 2011). While many corn ethanol plants are operated by farmer cooperatives, the capital costs required to build a stover-ethanol plant are an order of magnitude higher. Thus, existing stover biofuel plants are privately owned, and we believe farmer cooperatives are unlikely to operate stover biofuel plants.

[4] While an interesting question in and of itself, the choice of pricing strategy—Free on Board (FOB) versus Uniform Delivered Prices (UD)—is not endogenized in this study. We assume FOB pricing 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). Moreover it has been suggested as the pricing strategy of choice by both Abengoa (see report at http://www.kcc.state.ks.us/energy/kwrec_09/presentations/B1_Robb.pdf) and Eller and Doering (2014), the only two cellulosic biofuel plants in operation today. It is also the most common strategy for corn ethanol plants, as frequently reported by Hofstrand (2014).

an increasing function of price). We assume a linear participation rate ($\theta_r^s = \theta_1(p_A^M - sr)$), which results in a linear stover supply schedule. Naturally, the participation rate cannot be negative or exceed one, so the stover supply by each supply unit can be denoted by

$$q_r^s = \overline{B} \times min\{max\left[\theta_1\left(p_A^M - sr\right), 0\right], 1\}, \tag{1}$$

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 the plant and R_A^E to the east and between the plant 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, then $R_A^E = R_A^W = R_A$, where R_A denotes the market boundary on each side of firm A under monopsony. The market boundary R_A is defined as the distance at which the price net of transportation cost obtained by the supply unit results in zero supply (i.e., $\overline{B}[\theta_1(p_A^M - sr)] = 0$). Solving this expression for r yields $R_A = \frac{p_A^M}{s}$. On the other hand, the radii on both sides cannot go beyond the boundaries of the line segment that capture the geographical limits to the supply area. Therefore, the market boundary of firm A at each side can be defined as $R_A^M = min[R_A, A]$, where A is the distance between the firm and the boundary.

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

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

The priceoffered to farmers, p_A^M, determines the extensive margin (the size of the supply area), R_A^M, and the intensive margin (the amount of biomass obtained from each supply unit within the supply area), $\theta_r^s(p_A^M)$. In this scenario, the plant maximizes profits by choosing the plant-gate stover price:

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

where ρ is net revenue per ton of biomass (in output-equivalent units) processed and $Q_A^M(p_A^M)$ is as defined in equation (2).

Substituting $R_A^M = min\left[\frac{p_A^M}{s}, \frac{D}{2}\right]$ for the market boundary in $Q_A^M(p_A^M)$ and solving the first-order condition for p_A^M yields

$$p_A^{M*} = \begin{cases} \frac{2}{3}\rho & \text{if } \frac{2}{3}\frac{\rho}{s} < \frac{D}{2} \text{ or, equivalently, } \rho < \frac{3}{4}sD \\ \frac{sD}{8} + \frac{1}{2}\rho & \text{otherwise} \end{cases}. \tag{4}$$ [5]

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

Spatial Competition

Fulfillment of the renewable fuel standards in combination with the size of supplying areas around plants makes the monopsonistic structure implausible. Consequently, we now consider a scenario in which firms compete spatially for the feedstock input. Moreover, given high relocation costs in the biofuels industry and the objective of this paper, we refrain from modeling optimal long-run location decisions by firms. Instead we concentrate on plausible locational configurations and assess the effect of competition on the economics of stover-based biofuel firms.

[5] Zhang (1997) derived a similar version of monopsony pricing on a linear market.

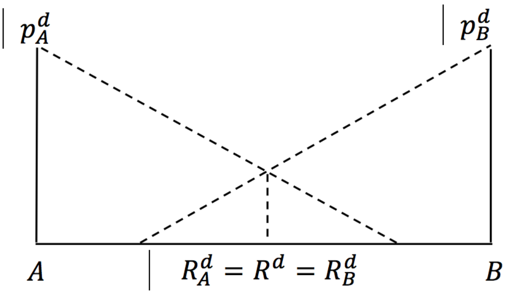

Figure 2. Symmetric Duopsony

Under linear transportation cost, locational symmetry emerges both as a short-run (i.e., high relocation cost) and a long-run (i.e., zero relocation cost) sub-game perfect Nash equilibrium in the Salop's circle (Salop, 1979; Economides, 1989). This analytical tractability of location decisions typically motivates the use of the circle, which is otherwise a poor representation of most empirical situations (Economides, 1993). On the other hand, no locational configuration (symmetric or otherwise) emerges as a long-run sub-game perfect Nash equilibrium (SPNE) in the Hotelling's line model with linear transportation cost (d'Aspremont, Jaskold Gabszewicz, and Thisse, 1979; Economides, 1993).[6] However, it has been proved that symmetric location of firms can emerge as an equilibrium (i.e., support a Nash equilibrium in price competition) in the Hotelling's line with two (d'Aspremont, Jaskold Gabszewicz, and Thisse, 1979) or more firms (Economides, 1993) when relocation costs are high. Relocation costs in the cellulosic biofuels industry are substantial due to high capital investment and large shutdown costs related to asset specificity. Therefore we analyze the case of symmetric locational patterns which, in this case, seem theoretically consistent and empirically relevant.

Spatial Duopsony

In the duopsony case, a symmetrical locational pattern consists of two plants located at the same distance from the boundaries of the line. d'Aspremont, Jaskold Gabszewicz, and Thisse (1979) proved that such symmetrical location patterns can support an equilibrium in a spatial duopoly as long as plants are located at or relatively close to the boundaries of the market. Zhang and Sexton (2001) modeled a spatial duopsony with two firms located at the boundary of a Hotelling's line segment. This model with the same locational pattern was later applied by Graubner, Balmann, and Sexton (2011) to analyze pricing strategies in agricultural procurement markets. We modify the Zhang and Sexton (2001) model slightly to represent a spatial duopsony.

Figure 2 illustrates the duopsonistic market structure considered in this study. In contrast to the monopsonist scenario, firm A now faces competition for biomass from firm B, which is located at the other end of the feedstock supply region at a distance D. In the situation illustrated in figure 2, firm A procures feedstock from farms located between A and R^d (i.e., A's boundary in a contested area); the same radius applies to firm B.

Profits of plant j operating in a symmetric duopsony can be denoted by

$$max_{(p_j^d)} \pi_j^d = \left(\rho - p_j^d\right) Q_j^d \left(R_j^d \left(p_j^d, p_o^d\right)\right), \qquad (5)$$

[6] Diverse equilibrium configurations in the product's market emerge in the Hotelling's model under nonlinear transportation cost, heterogeneous distribution of buyers, random utility models, and demand elasticities. For a review of these issues, see Tabuchi (2012).

where p_j^d is the price offered by the plant to farmers within its supply area. Aggregate supply faced by plant j, $Q_j^d(R_j^d(p_j^d, p_i^d))$, is

$$(6) \qquad Q_j^d = \int_0^{R_j^d} \left\{ \overline{B} \times \left[\theta_1 \left(p_j^d - sr \right) \right] \right\} dr = \overline{B} \left\{ \theta_1 p_j^d R_j^d - \theta_1 \frac{s}{2} \left(R_j^d \right)^2 \right\}.$$

The market boundary between plants operating in a symmetric duopsony is determined by the condition

$$(7) \qquad \overline{B} \times \left[\theta_1 \left(p_j^d - sR_j^d \right) \right] = \overline{B} \times \left[\theta_1 \left(p_i^d - s\left(D - R_j^d \right) \right) \right].$$

This condition results in

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

Substituting R_j^d for the market boundary expression in Q_j^d, assuming symmetry ($p_j^d = p_i^d$) and Nash-Bertrand behavior $\left(\frac{\partial p_j^d}{\partial p_i^d} = 0 \right)$, the first-order condition of problem (5) yields

$$(9) \qquad p_j^{d^*} = \begin{cases} \frac{2}{3}\rho & \text{if } R_J^M = \frac{p^{M^*}}{s} \leq \frac{D}{2} \\ p_j^d & \text{otherwise} \end{cases},$$

where

$$(10) \qquad p_j^d = \left[\frac{\rho}{2} - \frac{3sD}{4} \right] - s\sqrt{\left(\frac{\rho}{2s} - \frac{3D}{4} \right)^2 + \left(\frac{2}{s} \right) \left(\rho \left(\frac{D}{4} \right) + \frac{sD^2}{8} \right)}.$$[7]

Comparing the pricing strategy in equations (9)–(10) with that described by equation (4) reveals that different pricing strategies are implemented by a firm operating under different market structures.

Substituting equation (9) into equation (5) yields duopsonist j's profit function, which describes net operating revenues as a function of net revenue per ton of biomass processed ρ, total biomass produced $\overline{B}$, sensitivity of farmers' participation rate θ_1, transportation cost s, and distance between firms D.

Three-Firm Oligopsony

We now consider the entry of a third firm. Following Economides (1993), we assume that the locational structure remains invariant when the additional firm enters. Therefore firms are assumed to be located at distance $D^o = \frac{D}{2}$ from each other (i.e., peripheral firms are located at the boundaries and the central firm is located in the middle of the line) and compete spatially for the feedstock supply. This situation is illustrated in figure 3. Peripheral firms follow pricing strategy (9)–(10), with D replaced by D^o.

In figure 3, under price p_m^o, the middle plant procures stover from the region between C and R_m^o 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). Therefore, under this market structure, the profits of the middle plant, m, can be denoted by

$$(11) \qquad max_{(p_m^c)} \pi_m^c = 2\left[\rho Q_m^o \left(p_m^o, p_i^o \right) - p_m^o Q_m^o \left(p_m^o, p_i^o \right) \right],$$

[7] The negative square root of the quadratic equation is used in equation (10) as it is later numerically revealed that this is the economically relevant root (i.e., the one that results in positive participation rates).

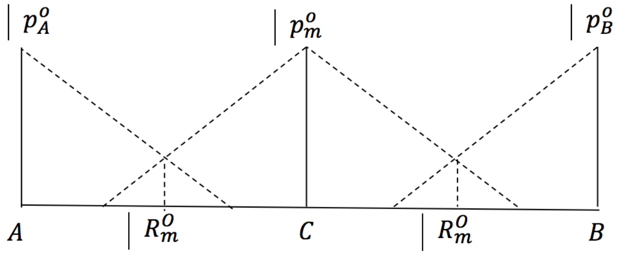

Figure 3. Symmetric Three-Firm Oligopsony

where π_j^m denotes profit of the middle plant in the three-firm oligopsony, $Q_m^o = 2\overline{B}\left\{\theta_1 p_m^o R_m^o - \theta_1 \frac{s}{2}(R_m^o)^2\right\}$ is the supply faced by that firm, p_i^o represents the price of peripheral firms ($p_A^o = p_B^o$), and the other parameters are defined above. The profit-maximizing stover price of this problem is the same as that for peripheral firms (described by equations (9)–(10) with D replaced by D^o). However, under this market structure, the profit of the middle plant is twice that of peripheral firms.

Although we have discussed discrete changes in market structure (monopsony, duopsony, and three-firm oligopsony), our model can accommodate varying degrees of competition intensity. Reductions in supply density (i.e., a reduction in θ_1), 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.

Theoretical Comparison of Plant Behavior and Performance in Contested and Uncontested Markets

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

We start by comparing a plant's biomass demand in contested and uncontested markets over the entire support of ρ and s. Inserting equation (4) and R_A^M into equation (2) yields biomass demand by a monopsonist. Similarly, inserting equations (10) and (8) into equation (6) yields biomass demand by a firm facing competition in a duopsony. Comparison of both expressions reveals that the monopsonist will procure more biomass than the duopsonist as long as $\frac{\rho}{s} > \frac{3}{4}$, which must hold for competition to exist (i.e., for firms' radii to overlap).

Moreover, we find that competition has an ambiguous effect on price. Specifically, there exists a combination of biofuel price and transportation costs 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. We are not the first to explore the non-monotonicity between the farm price and competition or transport costs in Hotelling models. Zhang and Sexton (2001, pp. 204–205) discuss this result, and Mérel and Sexton (2010, pp. 18–19) discuss this phenomenon in detail. Also in line with these studies, we find that the plant's gate price of stover in a duopsony will be lower than that in a monopsony as long as competition exists but remains sufficiently mild (i.e., $0.75 < \frac{\rho}{s} < 1.5$).

Spatial competition for biomass decreases and fixes a plant's procurement radius in a contested region, eliminating the plant's ability to increase harvest on the extensive margin. As a result, spatial competition reduces the supply of biomass faced by a plant and reduces responsiveness of biomass supply to price. This has two effects on input pricing. The reduction in supply increases the price required to purchase a given amount of biomass. However, reduced supply is accompanied by an upward shift in marginal outlay, which causes the plant to reduce quantity demanded and price.

Table 1. Biomass Production Parameters

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	

When competition is sufficiently mild, the price-depressing effect of the upward shift in marginal outlay outweighs the price-enhancing effect of the reduced supply, resulting in net reduction in price.

From these first two results it follows that competition has a potentially ambiguous effect on plant profits. 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 $\frac{\rho}{s}$). However, we confirm that competition in fact reduces firm profits. For firms implementing FOB pricing, profits obtained by a monopsonist are higher than those obtained by a duopsonist over the entire domain of competition intensities.[8]

While the theoretical results 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 Application to Two Corn Belt Counties

Empirical implementation of the three market structures 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 $M = p_{den} \times D \times s_y$, where D represents total length of the supply region, 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 comprising 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 (northwest of Jasper County and southeast of White County) were chosen and the distance between these points was calculated to be fifty miles using Google Maps's distance-measuring tools. According to USDA-NASS, Jasper County has a total area of 561 square miles; approximately 445 acres of land per square mile are suitable for corn.[9] White county has 509 square miles and 490 acres per square mile suitable for corn. Jasper County's stover yield in 2011 was 4.4 tons per acre and White County's yield was 4.7 tons per acre.[10] Previous studies (e.g., Montross et al., 2003) 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 County and 3.5 tons per acre in White County. 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 fifty-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., $\overline{B} = \frac{M}{D} = \frac{1{,}710{,}000}{50} = 34,2000$). Assuming that a given quantity of biomass produced is uniformly distributed along a line between two plants simplifies the spatial pattern of biomass production and may result in

[8] A monopsonist would attain higher profits than a duopsonist if and only if $\pi^M - \pi^c = \frac{2}{27}\frac{\rho^3}{s} - \left(\rho - \left[\frac{\rho - 1.5s \pm \sqrt{\rho^2 - s\rho + 3.25s^2}}{2}\right]\right)\left(\left[\frac{\rho - 1.5s \pm \sqrt{\rho^2 - s\rho + 3.25s^2}}{2}\right]0.5 - \frac{s}{2}(0.5)^2\right) > 0$. 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.

[9] We assume that 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 the area of this land was quite small under analysis.

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

underestimating transportation costs. 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., 2009). This simulation provides a counterfactual scenario (i.e., acres allocated by farmers to 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., 2009) based on farm-specific data on land, labor, machinery, storage, planting date, crop rotations, crop yields, crop prices, and costs (Doster, Dobbins, and Griffin, 2009). The farmer information used in PCLP was collected from twenty-four farms operating in Indiana that 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.[11] 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 (2014) 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.

In PCLP, the cost of harvesting stover is introduced, for each farm, on a weight basis. Therefore, all costs determined on a per acre basis are converted to a weight basis by dividing them by the yield of each farm. So farms with different yields will have different costs of stover removal, which results in different breakeven prices of stover. However, different yields are not the only variables driving heterogeneity of stover breakeven prices. Differences in input availability and size also introduce differences in the prices of stover that induce farmers to choose crop rotations that include stover harvest. Heterogeneity in willingness to accept for stover ultimately shapes participation rates and supply response.

For each farm in the sample, we use PCLP to calculate the profit-maximizing allocation of land to competing crop rotations for a range of stover prices. From this solution the share of land allocated to corn with stover removal (i.e., the participation rate) is calculated. We then conduct a linear approximation to the simulated participation rates as a function of stover price. Figure 4 plots both simulated and predicted participation rates with PCLP. Predicted participation rates are calculated as

$$\widehat{\theta}_r^s = 0.0089(p_j^k - sr), \tag{12}$$

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 net of breakeven cost offered at the plant gate by plant j operating under market structure k ($k = M$ under monopsony, $k = D$ under duopsony, and $k = O$ under three-firm oligoposny).

Though a likelihood ratio test 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

[11] 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.

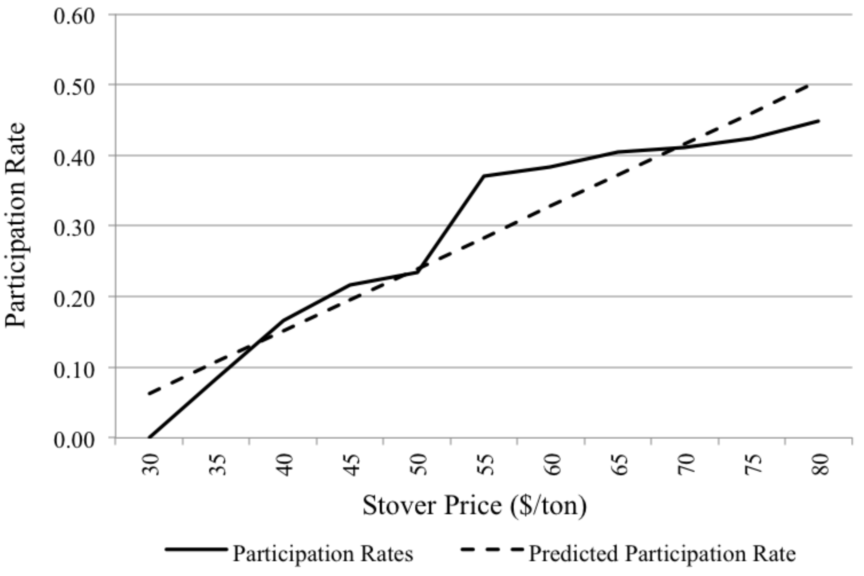

Figure 4. Simulated and Predicted Participation Rates

density schedule facilitates comparison of plant profit and biofuel production under alternative market structures.

Substituting $\overline{B}$ and equation (12) in the expression for stover supply in equation (1) yields the predicted stover supply from each spatial unit:

$$q_r^s = 34,200 \times min\left\{0.089\left(p_A^M - sr\right), 1\right\}. \tag{13}$$

We now use this stover supply density schedule to quantitatively solve problems (3), (5), and (11) and answer the questions posited at the beginning of this study.

Results

When two firms are operating on the same line fifty 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 \$0.40/gallon. When three firms operate in this supply area a biofuel price of \$0.35/gallon triggers competition. Below these prices, each firm acts as a monopsonist and the only relevant stover pricing policy is $p_A^{M*} = \frac{2}{3}\rho$, as described in equation (4). When supply radii overlap, equation (10) depicts the appropriate stover pricing behavior by firms.

Figure 5 compares pricing behavior under alternative market structures and shows gate prices for stover (net of breakeven cost) for a firm operating under monopsony and duopsony market structures. It also shows pricing behavior for a firm operating under a three-firm oligopsony (stover price is the same regardless of the plant being interior or peripheral). Biofuel prices above \$0.40/gallon are reported, as only in this range can markets be contested under our parameter values. These curves reveal that, under plausible stover supply conditions, spatial competition can substantially increase feedstock cost; this issue has received little attention in the extant literature. As competition intensifies, optimal stover prices increase faster in response to rising biofuel prices. This suggests that competition causes farmers to appropriate a higher share of the surplus brought about by increased biofuel demand.

An increase in biofuel price increases profitability, the quantity of biomass demanded and, consequently, stover price. Figure 6 depicts firm-level production at different biofuel prices. These production levels are depicted for each of four scenarios generated by the three market structures

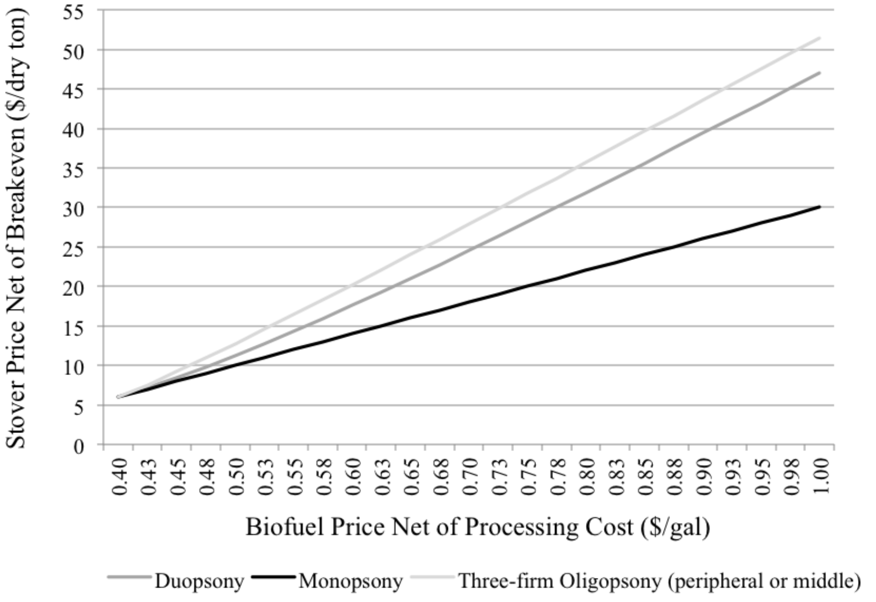

Figure 5. Stover Pricing under Monopsony and Competition

previously discussed: a firm operating under monopsony, a firm operating under duopsony, a peripheral plant in a three-firm oligopsony, and a central plant in a three-firm oligopsony.

Combining results in figures 5 and 6 reveals that spatial competition can adversely impact the economics of biofuel production. For instance, at a biofuel price net of processing cost of $0.70/gallon, a monopsonist pays for stover $6.50/ton and $10/ton less than a duopsonist and a three-firm oligopsonist respectively. Yet the monopsonist produces more than double the amount of biofuel produced by a peripheral plant in a three-firm oligopsony, almost 50% more biofuel than a middle plant in a three-firm oligopsony, and 15% more biofuel than a duopsonist.

Competition fixes supply radii and prevents firms from procuring biomass from the extensive margin. Firms are then forced to rely on the intensive margin for feedstock. Figure 7 illustrates how plants adjust the intensive margin in response to competition. Curves plotted in figure 7 reveal that intensified competition within the supply area greatly increases participation rates (percentage of total biomass produced that is harvested and sold to biofuel firms). For instance, when the biofuel price net of processing cost is $0.70, participation rates are 10%, 19% and 25% under monopsony, duopsony, and three-firm oligopsony, respectively. This also points to the fact that rents appropriated by farmers increase—significantly—with spatial competition intensity.[12]

The impact of competition on firm-level profits is illustrated in figure 8. Curves are plotted for all four scenarios generated by the three market structures considered here. Figure 8 shows that the effect of competition on plant profits is very strong and increasing in biofuel prices. At low biofuel prices, demand for biomass is low, resulting in less overlap of procurement regions and less intensive 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 5 and 6) and, ultimately, 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. We calculate the industry-level production corresponding to monopsony, duopsony, and three-firm oligopsony and report them in figure 9. To illustrate how misleading the

[12] 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 46% in the three-firm oligopsony case).

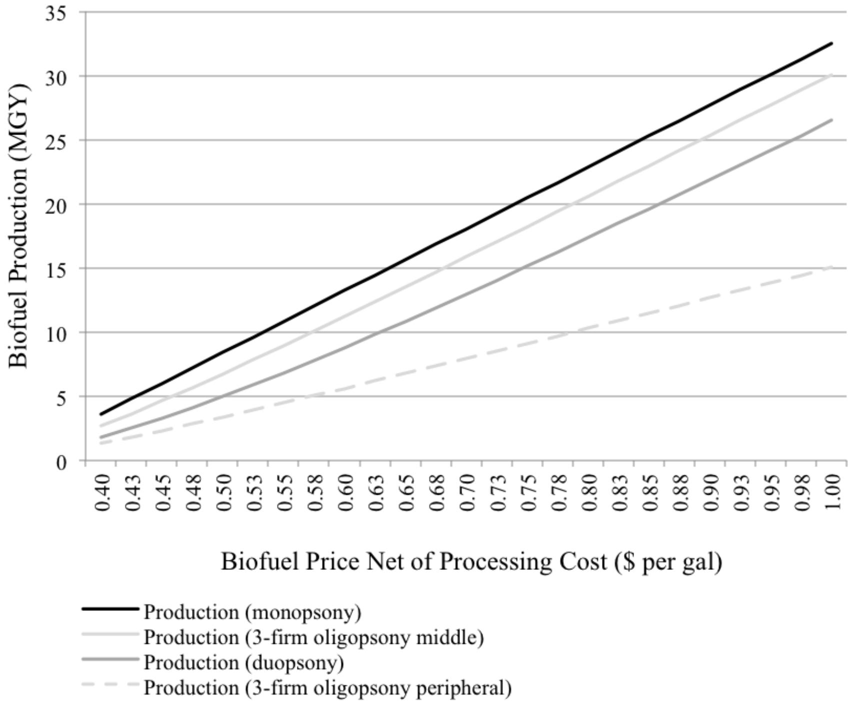

Figure 6. Individual Plant Production

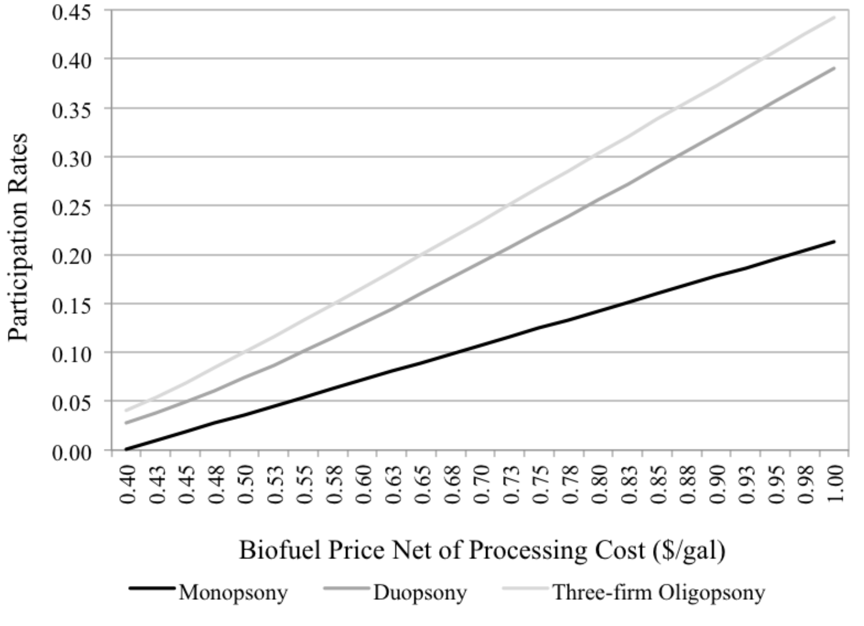

Figure 7. Intensive Margin in Contested and Uncontested Markets

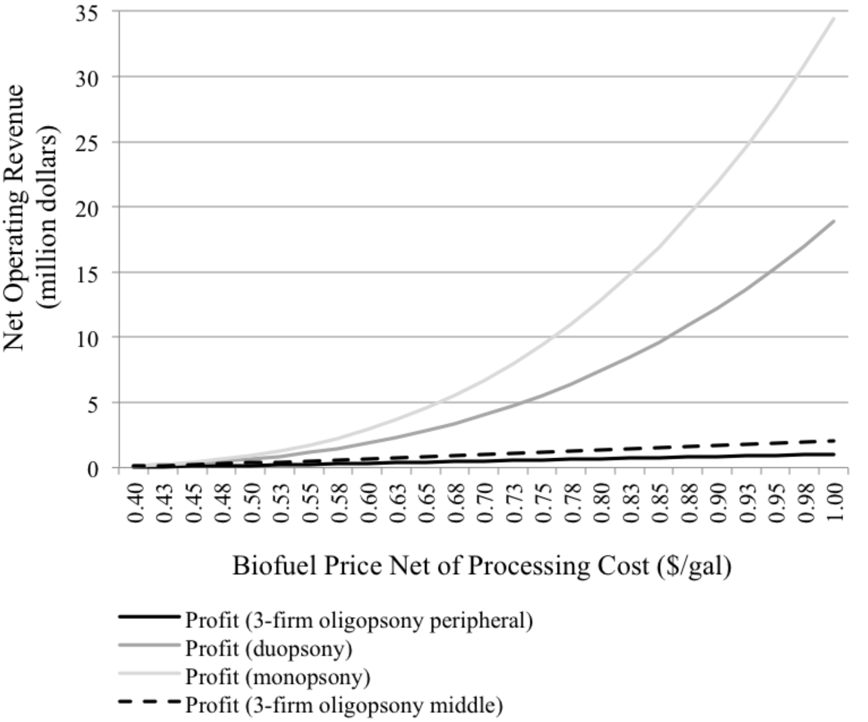

Figure 8. Competition and Plant-Level Profits

monopsony assumption can be, suppose three firms are operating in our supply area. If spatial competition is ignored and all three firms are assumed to operate as monopsonists, a net price of $0.70/gallon would be required to induce production of 50 million gallons/year (such a price would induce each firm to produce 16.66 million gallons/year).[13] Based on estimates of processing cost reported in Chen, Khanna, and Yeh (2012), this translates to a biofuel price of $2/gallon.[14] The price that would induce production of 50 million gallons/year under a three-firm oligopsony structure is approximately $2.60/gallon, 30% higher than the monopsony price. Therefore spatial competition may significantly diminish the competitiveness of this fuel source relative to gasoline.[15]

Results in figure 9 also reveal the link between the number of firms operating within a supplying area and overall biofuel production. For instance, at a biofuel price of $0.70/gal, the existence of two plants in the supply region does not double biofuel production relative to a monopsony but merely increases it by 44% (from 18 million gallons/year to 26 million gallons/year) due to lower firm-level production caused by spatial competition for feedstock. If instead three plants were operating in the supply region under this biofuel price, biofuel production would only be increased by 22% (from 26 million gallons/year to 31.75 million gallons/year) relative to duopsony. These results illustrate the fact that an increase in the number of biofuel firms may provide decreasing marginal contributions to total biofuel production as they generate more competitive market structures.

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[13] We choose a production volume of 50 million gallons/year for illustration purposes. Higher or lower amounts can be chosen and discussed based on our results.

[14] Chen, Khanna, and Yeh (2012) reported estimates of processing costs ranging from $1.3/gallon to $3.3/gallon depending on the type of conversion process. We assume the plant uses the most cost-effective process.

[15] If biofuels are produced as drop-ins (through a pyrolysis process 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.

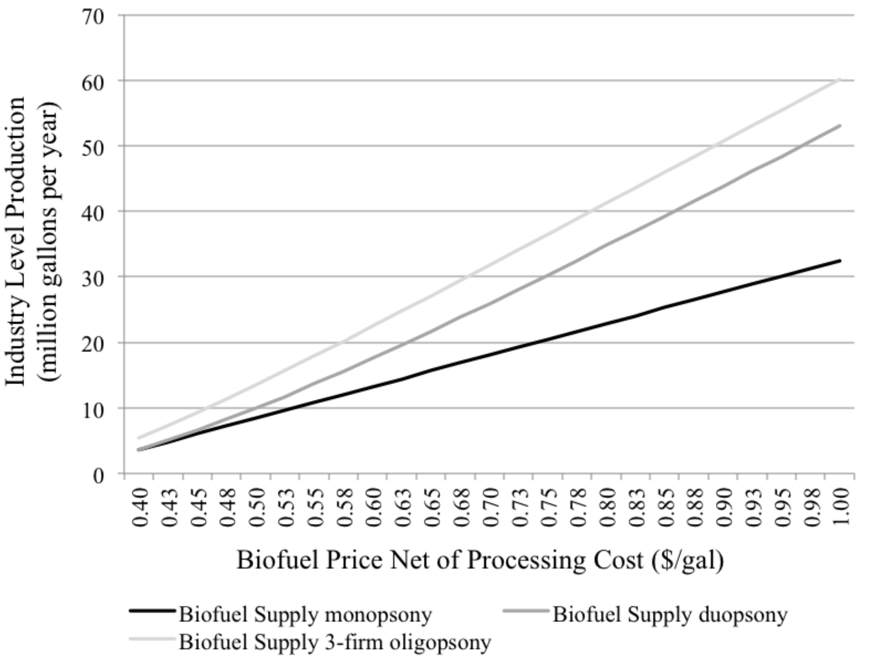

Figure 9. Market Structure and Industry-Level Production

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 empirical analysis indicate that intense competition increases feedstock price and, all else constant, reduces the profit maximizing scale of production and supply elasticity at the plant level. The increase in stover price and participation rates suggests that farmers located within a plant's supply radius attain a higher surplus when biofuel plants face competition relative to a situation in which the market is uncontested.

By ignoring the possibility of spatial competition and the resulting higher feedstock prices, previous economic analyses of biofuel plants may have underestimated feedstock cost and, consequently, overstated the economic viability of stover-based biofuels. The significant and negative impact of competition on net operating revenues (figure 8) may discourage investment in stover-based biofuels by increasing the Marshallian entry price faced by firms (i.e., operating cost plus capital cost per gallon). Moreover, when entry results in a 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, lessening the impact of entry on biofuel supply and increasing the biofuel price necessary to induce certain production targets.

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). We leave for future research these issues and their potential interaction with spatial competition in the context of dynamic games of entry.

This study also assumes a profit-maximizing plant that faces no constraints on the choice of production level. Implications of alternative markets structures on plant behavior when the plants are capacity-constrained cost-minimizers may be different from implications derived in this study. This also seems like an interesting direction for future research. 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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