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Cellulosic biofuel potential under land constraints: locations, plant sizes and feedstock supply costs

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JEL codes: Q16, Q11, Q42, Q41, Q48

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Alicia Rosburg, John Miranowski and Keri Jacobs*

In 2007, the Energy Independence and Security Act (EISA) introduced a revised Renewable Fuels Standard (RFS2). The RFS2 expands the previous Renewable Fuel Standard to include subcategories of renewable fuels with separate sub-mandates. One subcategory is cellulosic biofuel. The volume requirement for cellulosic biofuel increases from 100 million gallons in 2010 to 16 billion gallons in 2022 (U.S. EPA 2012). However, cellulosic biofuel production has not expanded as rapidly as the quantities mandated. Production remains in transition between pilot-scale and commercial-scale operation. The Environmental Protection Agency (EPA) has responded by waiving a majority of the cellulosic biofuel mandates for 2010 through 2013. Even though commercial-scale production has not yet commenced, industry leaders and policymakers remain focused on meeting all or a large portion of future mandate quantities. In an effort to aid industry leaders and policymakers in moving forward, we take a closer look at the feasibility and potential cost of meeting future cellulosic biofuel mandates.

Most efforts to model cellulosic biofuel costs focus on either the cost-minimizing plant size for a specific location or the expected cost to operate a plant of a given size in different locations.

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Instead, we consider several potential plant locations and determine the cost-minimizing plant size and production conditions at each potential location. Some locations will pose significant advantages over others in biomass supply. Further, a common assumption in the literature is that biomass farmers in a local market have identical biomass production conditions (e.g., Brechbill and Tyner 2008; Gustafon et al. 2011; Khanna et al. 2011; Leboreiro and Hilaly 2011; Parker et al. 2011; Popp and Hogan Jr 2007; Rosburg and Miranowski 2011; U.S. DOE 2011). The marginal cost of supplying biomass to the field-side (or field-side biomass price) is therefore assumed constant. We relax this assumption to allow for heterogeneous production conditions within local biomass markets.

We have four main objectives in this article: (1) develop a cost model for commercial-scale cellulosic biofuel production that accounts for locational differences in biomass production conditions; (2) apply the cost model to corn stover and switchgrass production environments existing in alternative US crop reporting districts; (3) identify locations, plant sizes, and biomass supply costs which meet biofuel targets at least cost (e.g., RFS2 mandates); and (4) evaluate policy and biofuel implications of the empirical results.

The remainder of the article is organized as follows. In the next section, we present the cost model. Then we describe the modeling assumptions and database underlying the corn stover and switchgrass biofuel models. A discussion of the empirical results follows. We conclude by highlighting implications of our results for the potential supply, costs, and locations of U.S. cellulosic biofuel production.

Cellulosic biofuel cost model

In this section, we develop a cost model for commercial-scale cellulosic biofuel production. The cost structure for cellulosic biofuel production has two features that motivate our modeling framework. First, a cellulosic biofuel plant will rely on a local market for sufficient biomass supply. This results from the fact that biomass is not a commodity and regional or national biomass markets do not exist. If local feedstock shortfalls occur, the plant will generally find procuring or importing feedstock prohibitively expensive.[1] Potential biofuel plants will therefore make production decisions based on local biomass supply conditions rather than regional or national supplies and prices.

Second, a tradeoff exists between economies of size in biofuel conversion and diseconomies of size in feedstock procurement. As the plant increases in size, the per gallon conversion cost falls but the per gallon delivered feedstock cost increases. Delivered feedstock cost is an increasing function of plant size because either local biomass farmers will require higher payments to induce larger feedstock supplies from the local area and/or larger feedstock supplies will be met by purchasing biomass from more distant areas in the local market.

On the basis of these two features, our model jointly minimizes feedstock procurement and processing costs per gallon while recognizing that feedstock supply conditions are location-specific. Model output consists of location-specific production conditions, including plant size, that minimize per gallon biofuel cost.

Model framework

Let L denote the set of proposed plant locations. All locations $l \in L$ are assumed to have access to the same biofuel conversion technology. Biomass supply conditions, however, are based on local biomass production conditions. Potential biomass suppliers are assumed to vary in biomass production conditions and be uniformly distributed within each local area.

Consider a biofuel processor building a commercial-scale biofuel plant at location l. The processor's objective is to minimize long-run total cost per gallon from biomass production through biofuel conversion.[2] The processor will need to purchase biomass from a large number of biomass farmers in region l. The processor is assumed to pay biomass farmers a fixed value per ton for field-side biomass and coordinate all aspects of storage and transportation.[3] The per ton price paid to local biomass farmers ($P_{B,l}$) is a choice variable for the processor but equal for all units purchased. A potential biomass farmer in region l will supply biomass to the processor if the price $P_{B,l}$ covers all of the costs the farmer incurs in biomass production, including opportunity costs. Since biomass production conditions vary within the region, not all local farmers will be willing to supply biomass at the same price. Local biomass supply is therefore a non-decreasing function of the offer price of biomass. The processor is assumed to know the local biomass supply conditions, including the distribution of biomass production conditions.

For each location $l \in L$, the optimization problem facing the processor is to minimize long-run per gallon biofuel cost (C_l) by choosing plant size (Q_l) and the per ton price paid to local biomass farmers ($P_{B,l}$). The cost minimization problem is expressed as follows:

$$(1) \qquad \min_{Q_l, P_{B,l}} C\left(Q_l, P_{B,l}\right) = \min_{Q_l, P_{B,l}} \underbrace{C_O + C_K(Q_0) \cdot \left[\frac{Q_l}{Q_0}\right]^{k-1}}_{\textit{Biofuel conversion costs}} + \underbrace{\frac{1}{Y_O} \cdot \left[P_{B,l} + S + t \cdot r(Q_l, P_{B,l})\right]}_{\textit{Feedstock procurement costs}}$$

where $k \in [0, 1)$, $\partial r/\partial Q_l > 0$, $\partial r/\partial P_{B,l} \leq 0$, and $Q_l, P_{B,l} \geq 0$.

The processor's cost function has two components: biofuel conversion costs and feedstock procurement costs. Biofuel conversion costs include operating costs and capital costs. Operating costs (C_O) are assumed to be independent of plant size. Capital costs are assumed to exhibit economies of size and are modeled by an engineering power function (Brown 2003). $C_K(Q_0)$ is an engineering estimate for the per gallon capital costs for a plant of size Q_0 and k is an economies of size scaling factor. The value of $k - 1$ represents the rate at which per gallon capital costs change with plant size. C_O, $C_K(Q_0)$, and k are assumed to be known and equal for all locations $l \in L$.

Feedstock procurement cost is the per gallon aggregate cost to acquire, store, and transport enough local biomass feedstock to operate a plant of size Q_l. The calculation within brackets in equation (1) is the per ton feedstock procurement cost. The conversion ratio of gallons produced per ton of biomass, Y_O, converts per ton feedstock costs into per gallon feedstock costs. As previously noted, the processor is assumed to coordinate all aspects of storage and transportation. Storage cost (S) is assumed to be a fixed per ton value and equal for all locations $l \in L$. The feedstock transportation cost equals the per ton-mile transportation cost (t) multiplied by the biomass transportation radius in miles (r).[4] The transportation radius for a plant in location l is a function of the feedstock demand (i.e., plant size) and local biomass supply conditions. We model capture radius using the formulation from French (1960) for a circular biomass supply area with a square road grid:

$$(2) \qquad r(Q_l, P_{B,l}) = 0.0223 \cdot \sqrt{\frac{Q_l}{Y_O \cdot Y_{B,l} \cdot d_{M,l} \cdot d_{S,l}(P_{B,l})}}$$

where Q_l/Y_O is plant feedstock demand in tons, $Y_{B,l}$ is biomass yield per acre in region l, $d_{M,l}$ is the maximum percentage (or density) of land that is available for biomass production in region l, and $d_{S,l}(P_{B,l})$ is the percentage of the maximum available land in location l that will supply biomass at the biomass price $P_{B,l}$. The value for $d_{M,l}$ is assumed to be a known, fixed value based on current land allocation and limited land use change. The function $d_{S,l}(P_{B,l})$ is non-decreasing in the offer price of biomass (i.e., $\partial d_{S,l}/\partial P_{B,l} \geq 0$) and ranges between 0 and 100%. In what follows, we will refer to the function $d_{S,l}(P_{B,l})$ as the local participation rate function.

Since the inclusion of the local participation rate function is a departure from previous literature, it deserves an extended explanation. Previous studies have assumed a fixed biomass price at field-side and a fixed local participation rate. In this case, the processor takes the local field-side biomass price as given and any increase in feedstock demand (i.e., increase in Q_l) would have to be met by purchasing biomass from more distant areas (i.e., increase r). These assumptions are valid if biomass production conditions are locally homogenous such that the marginal cost of supplying biomass to the field-side is equal for all local biomass farmers. An example where these assumptions may apply is for a plant using corn stover feedstock located in an area with uniform and dense corn production such that corn stover producers incur similar stover production costs.

If, however, biomass production conditions are not locally homogeneous, our model approach provides a more flexible framework of the biomass procurement options available to the processor. The local participation function provides an additional option to increase feedstock supply, i.e., increasing the offer price ($P_{B,l}$) increases participation in the immediate area. Depending on local supply conditions, increasing participation may sufficiently increase feedstock supply to meet an increase in feedstock demand without increasing capture radius. Although feedstock procurement cost increases if either $P_{B,l}$ or r increase, the least cost combination of plant size and feedstock procurement conditions will be determined by the model.

Data for corn stover and switchgrass models

The cost model developed in the previous section provides a framework for analyzing the cost of commercial-scale biofuel production at a set of proposed plant locations. In this section, we overview the data and parameter assumptions used to apply the cost model to U.S. corn stover and switchgrass production environments. Potential plant locations are based on U.S. crop reporting districts (CRDs) and potential biomass growing conditions.[5] All plants are assumed to be single-feedstock conversion plants using either corn stover or switchgrass feedstock; we do not consider multiple feedstock conversion. The corn stover model considers districts where at least 10% of total land area is in corn production and enough stover is produced within the district to supply a 10 million gallon per year (mgy) plant. Fifty-one districts satisfy these requirements. The switchgrass model is limited to districts located in rain-fed regions of the United States with available data on switchgrass production costs and land opportunity costs.[6] One hundred and eighty-two districts fit this criteria. For each model, we assume that at most one plant will locate in a district. Each plant is limited to acreage only within the district to avoid double-counting acreage and overestimating potential biofuel supply.

The following subsections overview the data sources, parameter assumptions, and empirical approach used to estimate the corn stover and switchgrass models. Table 1 summarizes the data and the sources from which they come.

[Table 1 about here]

Biofuel processing cost data

Biofuel processing costs for both models are based on engineering cost estimates for a 53.4 mgy corn stover to ethanol plant using a biochemical process (Kazi et al. 2010). We chose biochemical processing because the engineering cost estimates are current (Aden et al. 2002;

Aden 2008; Aden 2009; Kazi et al. 2010) and the biochemical process is approaching commercial production.[7]

Capital costs for the 53.4 mgy plant are $376 million (2007$). Assuming a 20 year plant life, an interest rate of 8%, and an ethanol yield of 69 gallons per ton of biomass (Y_O), the per gallon capital costs [$C_K(Q_0)$] are $0.72. The economies of size factor for capital costs (k) is assumed to be 0.75. Excess electricity from burning lignin (a co-product of processing) is assumed to be sold to the power grid. After accounting for this co-product credit, operating costs (C_O) are $1.40 per gallon.

Feedstock procurement cost data

Corn stover is a co-product of corn grain production that is already produced in large quantities in the United States. Switchgrass is a promising dedicated energy crop that is not yet grown on a commercial scale in the United States. As a result, local biomass production conditions are specified differently in the corn stover and switchgrass models.

For the corn stover model, stover production conditions are assumed to be homogeneous within crop reporting districts. A stover-based processor therefore faces a fixed stover price and fixed local participation rate. While this assumption may be restrictive, it reflects the fact that we limit the corn stover model to districts with relatively uniform and dense corn production. A field-side stover price of $57 per ton and a participation rate of 60% are used based on a review of the literature (Rosburg and Miranowski 2011). We do not include stover establishment or land opportunity costs.[8] Stover yields are derived from district-level corn yield data, a 1:1 stover-to-grain ratio, and 60% collection efficiency. Stover yields average 2.6 tons per acre and range from 2.1 to 3 tons per acre across districts. The maximum percentage of land that is available for stover supply ($d_{M,l}$) is derived from district-level data on harvested corn acreage. For the districts considered, $d_{M,l}$ ranges from 17 to 55% and averages 31% across all districts.

Long-term biomass storage costs (S) for both stover and switchgrass, including loading and unloading costs, are \$15.50 per dry ton based on values reported in Miranowski and Rosburg (2010). The variable transportation cost (t) for both feedstocks in all districts is \$0.71 per dry ton per mile as assumed in Wright and Brown (2007b).

Switchgrass is a dedicated energy crop that is not yet grown on a commercial scale, so we need to make certain assumptions about farmers' decision to allocate land into switchgrass production. We employ assumptions from the existing biomass supply literature that the maximum acreage available for switchgrass production in each district ($d_{M,l}$) is limited to 25% cropland pasture, permanent pasture, failed cropland, and CRP acreage and 10% harvested cropland.[9] The percentage of $d_{M,l}$ that will supply biomass, or the local participation rate [$d_{S,l}(P_{B,l})$], will depend on the fraction of potential switchgrass suppliers for which the biomass price offered by the processor ($P_{B,l}$) covers all of the costs the farmer incurs in switchgrass production, including land opportunity costs. We assume switchgrass production conditions, including yield, establishment costs, and harvest costs, vary between districts but not within districts. The opportunity cost of land, however, is allowed to vary within districts. The basis for this assumption is that switchgrass yields are relatively productive on marginal cropland and exhibit less variance with soil quality than traditional (cash) crops.[10] We assume that the farmer treats all switchgrass production costs as variable (long run). Thus, farmer i in district l is assumed to allocate land into switchgrass production if the following condition holds:

$$(3) \qquad P_{B,l} \geq \frac{P_{Opp,l,i}}{Y_{B,l}} + P_{SG,l}(Y_{B,l}),$$

where $P_{Opp,l,i}$ is farmer *i*'s land opportunity cost per acre, $Y_{B,l}$ is switchgrass yield per acre in district *l*, and $P_{SG,l}$ denotes switchgrass establishment and harvest costs per ton in district *l*. Switchgrass yields for each CRD are assumed to be 75% of the simulated yield values from the crop productivity model MISCANMOD (Khanna et al. 2011). The lower yield assumption reflects recent field and adjusted plot trials and accounts for lower collection efficiency and additional handling losses (Rosburg and Miranowski 2011). Switchgrass yields range from 1.4 – 6 tons per acre with an average 4.2 tons per acre across all districts. Switchgrass establishment and harvest costs per ton for each district are taken from Khanna et al. (2011) and adjusted to reflect the lower per acre yield assumption. Establishment and harvest costs average $50 per ton across all districts and range from $38 – $76 per ton (2007$).

To account for the varying opportunity costs of land within districts, we use offers data from the Conservation Reserve Program (CRP) as a proxy for the opportunity cost of using less productive cropland to produce switchgrass. The CRP offers data include acreage quantity and offered rental rates, for landowners willing to forgo current land use in exchange for a fixed payment. CRP offers data were available from general signup 26 (2003) and updated to 2007$ based on average district CRP rental rate increases from 2003-2007.[11] For each district with at least 20 offers to enroll land, we use a nonparametric kernel density estimator to construct a cumulative distribution function (CDF) of offered rental rates weighted by acreage offered for enrollment.[12] The fitted CDF provides an estimate of the fraction of land available at or below each per acre payment amount. Figure 1 provides an example. We use the fitted CDF of CRP offers for each district together with switchgrass yields, establishment costs, and harvest costs to estimate district-specific switchgrass participation rate functions [$d_{S,l}(P_{B,l})$].

[Figure 1 about here]

Our empirical estimation of participation functions is based on the assumption that CRP offers identify the district distribution of land opportunity cost for switchgrass. We assert this is a reasonable way to proceed because of the similarities between the decisions to enroll in the CRP and produce biomass. The stand length for switchgrass production is approximately 10 years, equivalent to the contract length for the CRP general signup. The offers data contain revealed prices that landowners would remove land from current productive activities in a time frame consistent with the switchgrass production cycle. The CRP also targets erodible and environmentally sensitive cropland and switchgrass provides many of the conservation benefits landowners might seek through CRP participation (Mapemba et al. 2007). Switchgrass is considered a model bioenergy crop because of its relative productivity on marginal cropland (Wright and Turhollow 2010). Finally, switchgrass production may lead to contracts/relationships between a biofuel plant and landowners similar to contracts between the government and CRP enrollees (Epplin 2009).

Empirical approach

For both stover and switchgrass models, the processor's objective function for each district (equation 1) is solved using a non-linear mathematical programming model. Model output consists of district-specific production conditions for the 51 potential stover plants and 182 potential switchgrass plants. The resulting production conditions, including per gallon cost, plant size, and feedstock procurement conditions, are combined to generate feedstock-specific ethanol supply curves as well as an aggregate ethanol supply curve. The model results are then used to identify the locations and specific plant sizes from which stover- and switchgrass-based ethanol can meet cellulosic biofuel targets at least cost (e.g., RFS2 mandates).

Results

This section presents results from the corn stover and switchgrass cost models. We begin with district-level results for both models based on the cost-minimizing plant size and feedstock procurement conditions. Figure 2 illustrates the minimum cost per gallon of stover-based ethanol (C_l) and the minimum efficient plant size (Q_l) for the 51 districts considered in the stover model. Estimated costs range from \$3.34 – \$3.71 per gallon ethanol and plant sizes range from 10 to 113 million gallons per year (mgy).[13] The stover transportation radius is 32 miles on average and ranges between 17 and 37 miles. The lowest cost ethanol is produced in a 113 mgy plant located in north central Iowa with a 29 mile stover transportation radius.

Least cost stover-ethanol production is located primarily in the north and central regions of Iowa and Illinois and southern Minnesota. Relatively low ethanol costs and large plant sizes in these districts result from higher stover yields and a greater percentage of corn acreage. The model results indicate that stover-ethanol production will first develop at these locations and then, if sufficient demand exists, expand into areas with lower stover yields and less corn acreage. This expansion would be characterized by decreasing plant sizes and increasing stover transportation distances.

[Figure 2 about here]

Similar results for the 182 districts considered in the switchgrass model are shown in figure 3. Estimated switchgrass-ethanol costs range from \$3.19 to \$4.57 per gallon and plant sizes range from 10 to 117 mgy. The switchgrass transportation radius is 35 miles on average and ranges between 22 and 37 miles. Land opportunity cost payments average \$18.60 per ton and range between \$4 and \$58. The lowest cost ethanol is produced at a 117 mgy plant in northeast

Texas with a 29 mile switchgrass transportation radius and a land opportunity cost payment of about \$9 per ton.

Least cost switchgrass-ethanol production occurs in northern Texas, Oklahoma, and southern Kansas. Relatively low ethanol costs in these districts result from higher switchgrass yields, lower land opportunity costs, and a greater percentage of land available for switchgrass production. For the locations considered, the model results suggest production of switchgrass-ethanol will first develop at these locations and then shift towards higher cost locations in the Northern and Southern Plains, Delta, and Appalachia regions. This expansion would be characterized by three trends: decreasing plant size, increasing switchgrass transportation distances, and decreasing local participation rates.

Highest cost switchgrass-ethanol production is located in the upper Midwest. High land opportunity costs make switchgrass procurement costly within these districts. For many of the districts with high land opportunity costs, the cost-minimizing feedstock procurement decision is to face a lower participation rate (i.e., lower $d_{S,l}(P_{B,l})$) and increase the transportation distance (i.e., increase r). For example, the cost-minimizing participation rate and transportation distance is 96% and 31 miles for the 25 least cost plant locations (with low land opportunity costs) compared to 77% and 40 miles for the 25 highest cost plant locations (with high land opportunity costs).

[Figure 3 about here]

Combining district-level supplies allows us to construct feedstock-specific ethanol supply curves. These curves are depicted in figure 4. Although the supply curves appear relatively smooth, the estimated functions are stepwise curves with each step corresponding to a different plant location. If each potential district has an ethanol plant at the cost-minimizing plant size, estimated stover-ethanol production is 3.5 billion gallons per year (bgy) and switchgrass-ethanol production is 9.5 bgy. The relatively small variation in stover supply costs ($3.34-3.71/gal) compared to switchgrass supply costs ($3.19-4.57/gal) reflects the differences in biomass supply conditions between the two models. The stover model focuses on dense corn production regions of the United States while the switchgrass model evaluates a wider range of production environments. For example, stover yields range from 2.1 to 3 tons per acre across districts while switchgrass yields range from 1.4 to 6 tons per acre. The switchgrass model also includes variation in local biomass production costs not considered in the stover model. Specifically, variation in land opportunity costs.

[Figure 4 about here]

Aggregation of the stover- and switchgrass-ethanol supply curves results in the aggregate ethanol supply curve in figure 5. Total supply across the 233 plants in our analysis is 13 bgy. Switchgrass-ethanol contributes the first 2 bgy of production. With least-cost expansion, the first stover-based plant would be the 17th plant in the market.

[Figure 5 about here]

The aggregate supply curve identifies the costs or market conditions needed to meet RFS2 cellulosic biofuel mandates and other production targets with stover- and switchgrass-ethanol from these locations. Table 2 provides cost estimates or market conditions for production levels between 2 and 12 bgy. First, the aggregate supply curve provides an estimate of the per gallon (wholesale) breakeven price at each production level (table 2, Row 1). Second, by assuming a simple linear relationship between the price of ethanol and price of oil [$P_{ethanol} = 0.667*(P_{oil}/29)$], the breakeven ethanol price translates into a long-run price of oil needed for markets to support biofuel production (table 2, row 2). Third, if the government covers a portion of the biofuel costs through a tax credit to cellulosic biofuel producers, a lower gasoline price or market price of oil is necessary to support biofuel production. Rows 3 and 4 in table 2 provide the gasoline price and oil price needed, respectively, with the $1.01 per gallon cellulosic biofuel producer credit currently provided by the 2008 Farm Bill.[14]

[Table 2 about here]

A cellulosic ethanol price of $3.42 per gallon ($5.13 per gallon gasoline equivalent) or a long-run oil price above $150 per barrel is needed for stover- and switchgrass-based ethanol within these districts to satisfy the 2016 cellulosic biofuel mandate of 4.25 bgy. The plant locations and feedstocks are mapped in figure 6. With extension of the current cellulosic biofuel producer's tax credit of $1.01 per gallon, the long-run oil price needed for the market to support production of 4.25 bgy reduces to $105 per barrel. The 2012 Annual Energy Outlook forecasts oil prices of $129 per barrel in 2022 and $145 per barrel in 2035 in their reference scenario (2010$) (U.S. EIA 2012).

[Figure 6 about here]

Some limitations of our empirical results should be noted. First, because of data limitations, not all crop reporting districts within the rain-fed regions of the United States were considered in the switchgrass model. The estimated switchgrass-ethanol supply curve therefore may be an underestimate. Second, both the corn stover and switchgrass model were evaluated under deterministic conditions and do not consider potential biofuel production risks such as feedstock supply risk. To the extent that a potential processor may choose to build a smaller plant than the minimum efficient plant size to hedge the financial risk of a biomass shortfall, our model results overestimate plant size and underestimate cost. Third, we only consider two potential biomass feedstocks, stover and switchgrass, and do not consider multiple feedstock conversion. A multiple feedstock plant has the potential to be more economical, especially in areas with low biomass availability or considerable biomass supply risk. Finally, our empirical findings are subject to the data and assumptions on which they were derived. Since neither commercial-scale biomass production nor biofuel processing has been realized, we rely on enterprise budgets and engineering cost estimates. To avoid overestimating biofuel supply, we used conservative assumptions for switchgrass supply conditions (e.g., switchgrass yields, limited land use change). We also made assumptions regarding corn stover collection efficiency (60%) and farmer participation (60%). All else equal, an increase in stover collection efficiency (e.g., crew experience, technology improvements) would increase minimum efficient plant sizes and decrease biofuel supply costs. For example, total stover-ethanol production in the 51 corn-stover districts would increase from 3.5 bgy to 4.1 bgy if stover collection efficiency increases to 75%. On the other hand, improving collection efficiency may lead to soil erosion and runoff on more erodible land. Additional data from current pilot plants and future commercial-scale operations will provide improved biomass production and conversion cost estimates in the near future.

Conclusions

Cost efficient development of the cellulosic biofuel industry will not only require an understanding of the physical potential of biomass for alternative energy production as considered in several recent studies (e.g., Graham et al. 2007; Perlack et al. 2005; U.S. DOE 2011; Walsh et al. 2003), but also a better understanding of the location-specific production decisions and market arrangements to ensure sufficient feedstock supply and least-cost biofuel production (Bergtold, Fewell, and Williams 2011; Rajagopal et al. 2007). While a complete examination of the necessary market conditions for commercial-scale biofuel production fall outside the scope of this article, we take a closer look at the role of local biomass production environments in the potential and cost of U.S. cellulosic biofuel production.

A long-run cost model for commercial-scale cellulosic biofuel production was developed that accounts for locational differences in biomass production conditions. This model expanded on previous cost models by allowing for heterogeneous production conditions within local biomass markets. An application to U.S. corn stover- and switchgrass-based ethanol production showed that cost-minimizing production decisions – including plant size and feedstock procurement conditions – vary significantly across locations. Ethanol from stover and switchgrass feedstock is spatially concentrated, especially at the lower end of the biofuel supply curve. The model results were used to identify the locations and specific plant sizes from which stover- and switchgrass-based ethanol can meet cellulosic biofuel targets at least cost (e.g., RFS2 mandates). Assuming limited land use change, the 2016 RFS2 cellulosic biofuel mandate of 4.25 bgy is costly to meet with stover- and switchgrass-ethanol from the locations considered in our analysis. A wholesale gasoline price of $5.13 per gallon or a long-run oil price above $150 per barrel would be needed to support ethanol production at this level.

Footnotes

[1] This differs from traditional biofuel crops such as corn, soybeans, small grains, etc. Established infrastructure for production, storage, and transportation allows traditional biofuel crops to be commoditized and traded on regional and national markets. While commodity-based biofuel plants get a majority of their feedstock from the local region, additional feedstock can be imported from another region without incurring prohibitively higher short-run feedstock costs. Infrastructure of this type has not yet developed for biomass.

[2] We minimize long-run average cost rather than maximize long-run profits for two reasons. First, this approach follows previous literature on the optimal biofuel plant size. Second, cellulosic biofuels are not likely to achieve long-run breakeven at current fuel prices (Rosburg and Miranowski 2011). The profit-maximizing plant size would be zero without significant fiscal incentives or higher long-run fuel prices. Therefore, our goal is to identify production conditions, including plant locations and sizes, that meet biofuel targets at least cost (e.g., RFS2 mandates).

[3] All per ton values are assumed to be on a dry weight basis.

[4] We use capture radius instead of average hauling distance to account for location or bid rents. In the long-run, assuming the plant does not have monopsony power to price discriminate, biomass suppliers closer to the plant receive location or bid rents regardless of which party is responsible for transportation. Our model mirrors the grain industry and accounts for bid rents by using the capture radius to calculate the transportation cost for each unit of biomass.

[5] County-level land area was frequently insufficient to supply enough biomass for a commercial-scale plant.

[6] Rain-fed regions include the Northern and Southern Plains, Corn Belt, Lake States, Delta States, Southeast, Appalachia, and Northeast. Four districts located in south and east Texas were also removed because of low switchgrass yields and high switchgrass production costs.

[7] Two commercial-scale biochemical conversion plants are under construction and expected to be operational in 2014. POET-DSM Advanced Biofuels, LLC is building a 25 mgy plant in Emmetsburg, Iowa and DuPont Danisco Cellulosic Ethanol (DDCE) is building a 27.5 mgy plant in Nevada, Iowa. Both plants will use corn stover feedstock.

[8] Implicit in this assumption is that a farmer’s stover supply decision is secondary to the corn planting decision and all costs associated with corn planting (including land opportunity costs) would be incurred whether the farmer supplies stover or not.

[9] The updated Billion Ton Report (U.S. DOE 2011) allows up to 50% of permanent pasture, 50% of cropland pasture, and 25% of cropland to switch to biomass production in each county. Khanna et al. (2011) allow 25% of harvested cropland, idle cropland (mostly CRP acreage), and cropland pasture to convert into perennial grass production in each district. De La Torre Ugarte et al. (2003), English et al. (2006), and English et al. (2010) limit the transition of idle cropland and cropland pasture to bioenergy crops to 40% and 25%. Parker et al. (2011) allow 25% and 50% of cropland idle and cropland pasture to convert to energy crop production for low and high assumptions, respectively.

[10] The assumption of fixed switchgrass production costs and yields within districts underestimates the true variation in switchgrass production conditions. While switchgrass production costs and yields may be less dependent on soil quality than traditional crops, variation due to soil quality differences will still occur within districts. However, the data needed to identify variation in switchgrass production costs and yields within districts is not readily available.

[11] General signups are characterized by a competitive enrollment process. An offer submitted by a landowner includes the per-acre rental rate – the bid – at which the landowner is willing to idle his cropland and install one or more conservation practices. General signup enrollments are typically 10-year commitments to establish and maintain whole field establishments of grasses or trees which provide habitats and food plots for wildlife. If the landowner's offer is accepted, he receives the annual rental payment he bid for the contract period. The dataset contains all contracts offered including those not accepted for enrollment.

[12] We use the Epanechnikov kernel function, an efficient (i.e., minimizes the mean integrated square error) and computationally compact kernel function, to derive the fitted distribution functions (Silverman 1986; Cameron and Trivedi 2005). Silverman (1986) argues at least 4 data points are needed for an accurate nonparametric estimate of a one variable distribution. Others have argued Silverman's minimum values may be an underestimate. Therefore, we use a conservative cutoff value of 20 based on the minimum data points Silverman recommends for a two-dimensional distribution. The 53 districts that did not meet this cutoff value were not considered in our analysis.

[13] All per-gallon estimates are reported on a per-gallon ethanol basis unless noted otherwise. Other studies report biofuel cost estimates on a gasoline-equivalent basis. Per-gallon ethanol prices convert into a gasoline-equivalent basis using an energy equivalence factor. One gallon of ethanol provides approximately two-thirds the energy content of one gallon of conventional gasoline. The reported ethanol cost range is equivalent to a range of \$5.00-\$5.56 per gallon gasoline equivalent.

[14] For this illustration, the producer credit is treated as if it were a long-term policy incentive to the processor. The tax credit is currently set to expire on December 31, 2013. This is an extension from the previous expiration date of December 31, 2012.

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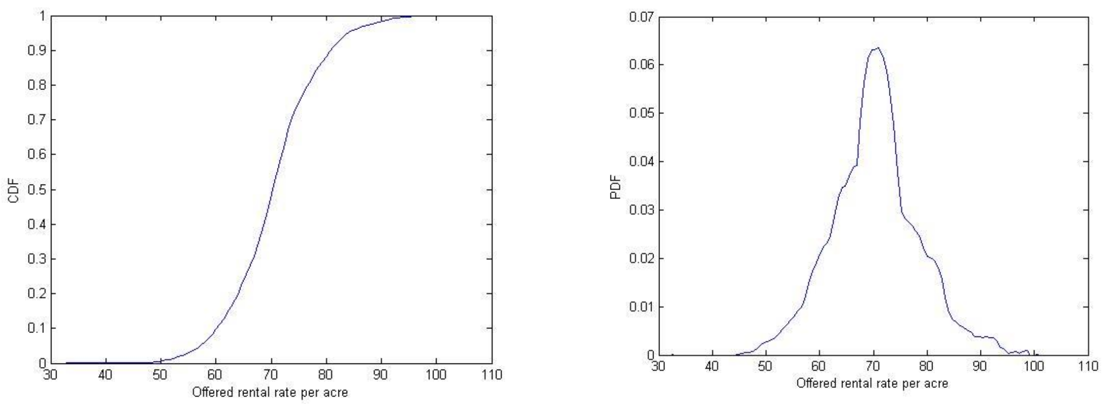
Figures and Tables



CDF PDF

Figure 1. Cumulative and probability density functions of CRP offers from a single district

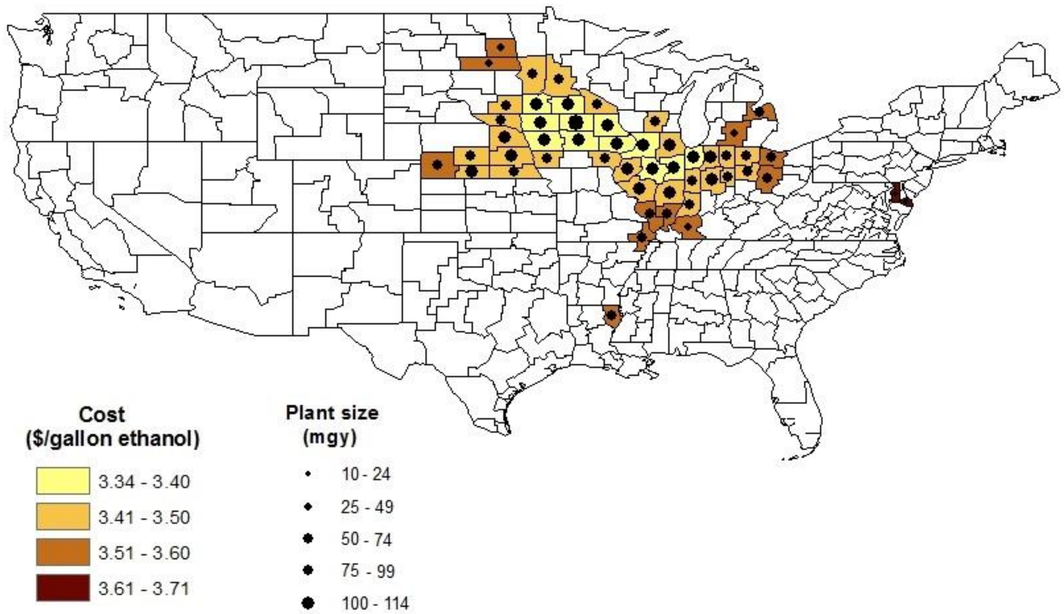


Figure 2. Estimated minimum cost and plant size of stover ethanol by CRD

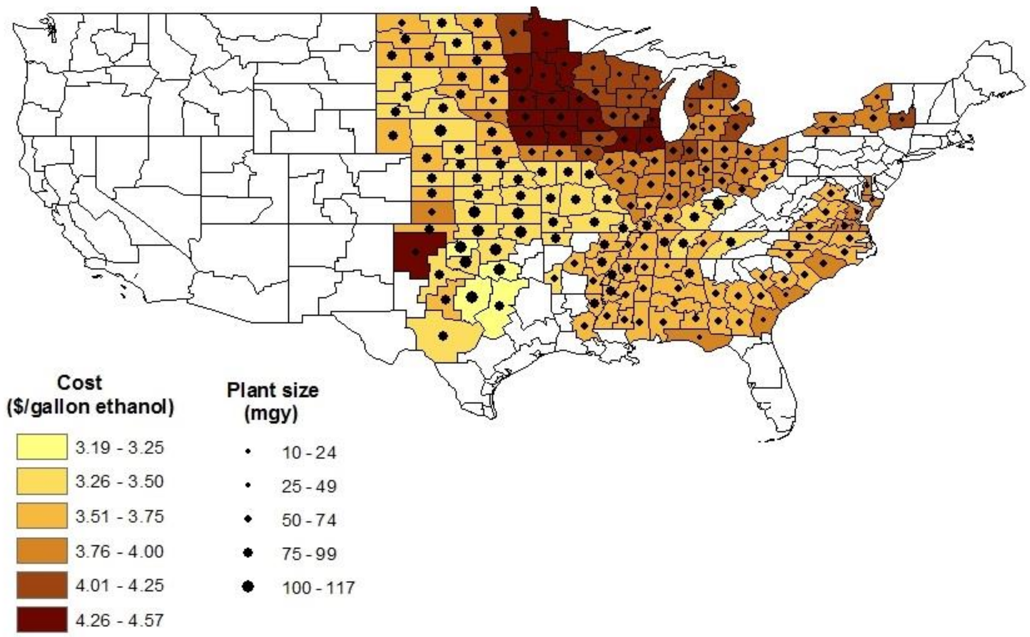


Figure 3. Estimated minimum cost and plant size of switchgrass ethanol by CRD

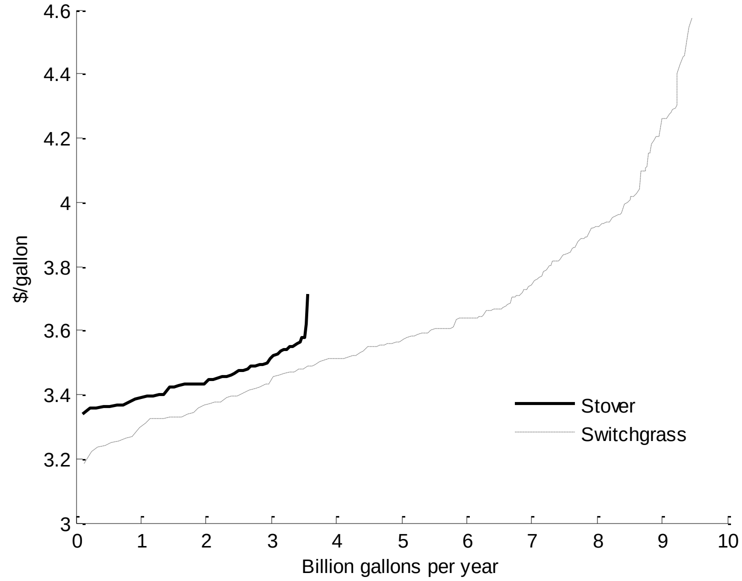


Figure 4. Estimated feedstock-specific ethanol supply curves

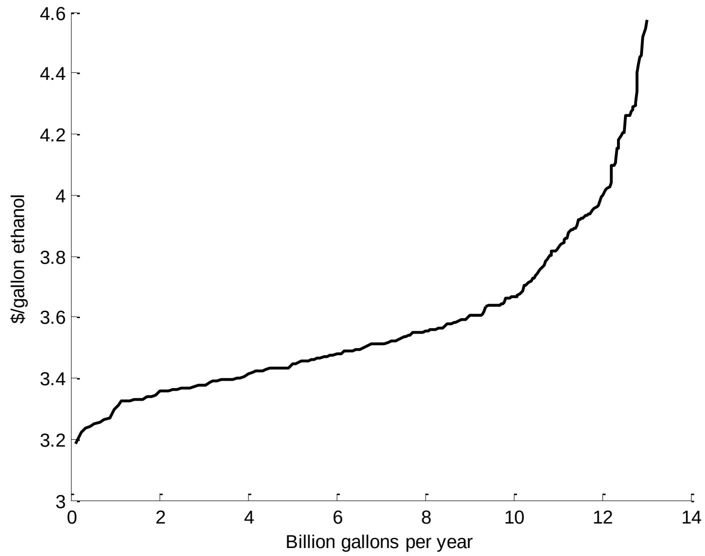


Figure 5. Estimated aggregate ethanol supply curve (stover and switchgrass combined)

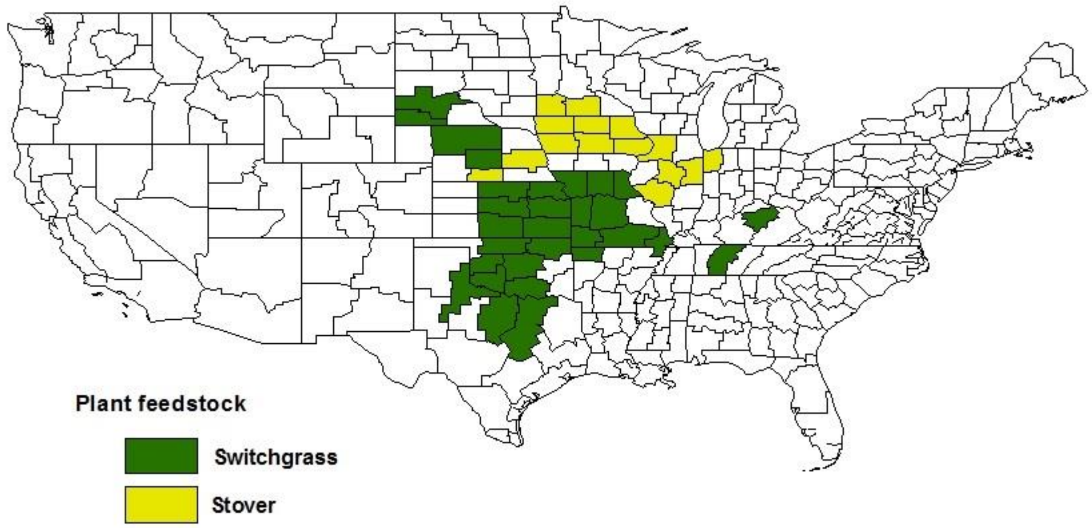


Figure 6. Plant locations and feedstocks that would meet 2016 RFS2 mandate at least-cost

Table 1. Data and Parameter Assumptions

Parameter	Value	Source(s)
Biofuel conversion		
Technology	Biochemical	Kazi et al. (2010)
Q_0	53.4 mgy	Kazi et al. (2010)
$C_K(Q_0)$	\$0.72/gal	
Total cost	\$375.9 million	Kazi et al. (2010)
Debt financing	100%	Wright and Brown (2007b)
Years	20 years	Wright and Brown (2007b)
Interest rate	8%	Wright and Brown (2007b)
C_O	\$1.40/gal	Kazi et al. (2010)[a]
Y_O	69.2 gal/dt[b]	Kazi et al. (2010)
k	0.75	Several[c]
Feedstock procurement		
Biomass production costs		
Stover	\$57/dt	Rosburg and Miranowski (2011)
Switchgrass	CRD-specific (\$38-76/dt)	Khanna et al. (2011)
$Y_{B,l}$		
Stover	CRD-specific; 1:1 stover to grain production with 60% collection (2.1 – 3 dt/acre)	2005-2010 Agricultural Census data (NASS)
Switchgrass	CRD specific (1.4-6 dt/acre)	Khanna et al. (2011)
S	\$15.50/dt	Miranowski and Rosburg (2010)[d]
t	\$0.71/dt/mile	Wright and Brown (2007b)
$d_{M,l}$		
Stover	CRD corn acreage	2007 Agricultural Census data (NASS)
Switchgrass	25% CRD cropland pasture 25% CRD permanent pasture 25% CRD CRP acreage 25% CRD failed cropland 10% CRD harvested cropland	2007 Agricultural Census data (NASS) and CRP enrollment data
$d_{S,l}(P_{B,l})$		
Stover	60%	
Switchgrass	CRD-specific function	CRP offers data (USDA – FSA)

[a] Sum of operating costs reported by Kazi et al. (2010). Includes co-product credit but excludes capital depreciation and average return on investment.
[b]dt denotes dry tons
[c] Cameron, Kumar, and Flynn (2007), De Wit et al. (2010), Gan (2007), Kaylen et al. (2000), Kumar, Cameron, and Flynn (2003), Leboreiro and Hilaly (2011), Searcy and Flynn (2009), and Wright and Brown (2007a).
[d] Reported value includes biomass loading and unloading costs.

Table 2. Cost or Market Conditions to Meet Cellulosic Biofuel Targets

Production (bgy)	**2**	**4.25**	**6**	**8**	**10**	**12**
Ethanol price ($/gallon)	3.36	3.42	3.48	3.55	3.67	4.00
Oil price ($/barrel)	146	149	151	155	159	174
Ethanol price with tax credit ($/gallon)	2.35	2.41	2.47	2.54	2.66	2.99
Oil price with tax credit ($/barrel)	102	105	107	111	116	130

Note: stover and switchgrass models combined; wholesale prices