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by

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Abstract

Advanced biofuels such as cellulosic ethanol are of great interest for their potential to supply a significant portion of U.S. fuel needs plus advantages over corn grain-based ethanol. The sustainability of agriculture-based advanced biofuels depends on how farmers would respond in providing biomass feedstock, yet economic behavior by farmers has been under recognized by the science community. Focusing on markets and policy incentives, this research shows that farmers are unlikely to convert current grain cropland to grow a dedicated cellulosic biomass crop such as switchgrass. However, the financial incentives to harvest cellulosic biomass provided by the 2008 farm bill may stimulate corn production due to demand for corn grain for feed and ethanol and corn residues for advanced biofuels. The prospect of continuous, possibly expanding corn production for advanced biofuels raises the same environmental issues as for corn grain-based ethanol. To assure the environmental sustainability of advanced biofuels production, environmental policies are needed to complement existing bioenergy initiatives.

Keywords: biomass; energy; advanced biofuels; corn; land use; switchgrass; cellulosic ethanol
JEL codes: Q42, Q12

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1. Introduction

While high petroleum prices combined with government supports have stimulated the production of corn grain-based ethanol in the U.S., policy interest has been extending to biofuels that can be made from a broad range of biomass such as grass, wood or municipal wastes (Somerville 2006, Kennedy 2007). Compared to corn grain-based ethanol, biofuels made from cellulosic biomass have many advantages. For example, cellulosic ethanol has lower greenhouse gas emissions and higher energy efficiency than ethanol made from corn grain (Lynd 1996, Farrell et al. 2006, Hill et al. 2006). Being made from a broad range of inedible biomass, cellulosic ethanol does not influence food prices as directly as ethanol made from corn grain. This feature makes cellulosic biofuels socially attractive, especially when a) there is concern over the impact of corn for fuel on food supply (Runge and Senauer 2007) and b) the U.S. policy of promoting corn-based ethanol has been criticized for contributing to the current surge of global food prices. Other considerations motivating cellulosic ethanol include enhanced energy security with reduced dependence on foreign petroleum and the insufficiency of corn-based ethanol alone to reach this goal (Copulos 2003, Greene et al. 2004, Perlack et al. 2005, Copulos 2007, Osborne 2007).

Despite their potential economic, social, and environmental appeal, cellulosic biofuels have not been commercialized. To stimulate the development of cellulosic biofuels, the U.S. government has promulgated a series of policy initiatives. For example, the U.S. Energy Independence and Security Act of 2007 (H.R. 6) has updated the renewable fuel standard (RFS) that mandates 36 billion gallons of biofuel supply in 2022 with 16 billion gallons from cellulosic biomass. More recently, the Food, Conservation, and Energy Act of 2008 (H.R. 2419), the so called farm bill, introduces further support programs to promote advanced biofuels from biomass crops other than corn kernel starch, including a tax credit of $1.01/gallon for cellulosic biofuel refiners (Section 15321) and a cost-sharing program matching up to $45/ton for collection, harvest, storage, and transportation of biomass crops (Section 9011). With agriculture being the current focus of biofuel policy, how farmers would respond to the policy initiatives in providing biofuel feedstock becomes an important policy question.

Farmer choices on which feedstock to produce or which crops to grow -- including dedicated cellulosic energy crops -- directly affect the development and a sustainable supply of agriculture-based advanced biofuels and their environmental sustainability. Their production decisions are largely driven by the markets for agricultural products and associated policy incentives. Farmers face many alternatives for producing cellulosic biofuel feedstocks, including crop residues from current food crops, such as corn, and dedicated energy crops, such as switchgrass, miscanthus, or poplar. Which feedstock will farmers choose to provide to meet the RFS of 16 billion gallons of cellulosic ethanol? How will the economic incentives in the newly enacted farm bill affect farmers' decisions, and thus the supply of cellulosic biomass feedstock? Are any unintended consequences likely to flow from the current policy incentives? All these questions of policy importance are linked to the fundamental problem: how farmers' production decisions will respond to market price and policy initiatives.

Despite its critical importance, the farmers' production choice problem has been under-recognized in the science community. For example, the Billion Ton report asserted that U.S. agricultural and forest lands have the potential to produce over 1.3 billion dry tons of biomass per year to displace 30 percent or more of the country's petroleum consumption by 2030 while still continuing to meet food, feed, and export demands (Perlack et al. 2005). This conclusion is derived largely based on technical feasibility rather than economic behavior needed to supply the target level of biomass. Tillman et al. (2006) show the potential of low-input high-diversity (LIHD) mixtures of native grassland perennials to produce biofuels with desirable properties on agriculturally degraded land. Yet, to what extent farmers would adopt the LIHD production system to produce desirable biofuels is another question without a clear answer. While many studies and research projects exploring the potential and merit of biofuels continuously derive their conclusions based on assumptions that may have no solid economic foundation, an analysis to show how farmers would respond to the market and policy incentives in providing feestock for cellulosic biofuels is urgently needed.

In this paper, we first develop a graphic exposition of the emerging biofuel economy, demonstrating the linkage between energy and agricultural markets. Within this market setting, we show how farmers' production choices between dedicated cellulosic energy crops and food crops (especially crops with residues available for biofuel feedstock) are linked to the potential cellulosic feedstock market and associated policy incentives. To illustrate the farmer's choice problem, we focus on a typical case where farmers can supply cellulosic feedstock by either from switchgrass (a dedicated biomass crop) or from corn (a food crop that produces cellulosic residues). The illustration is built using U.S. market data and production parameters representative of the “Corn Belt” states. This empirical example also allows us to examine the potential effect on the agricultural supply of cellulosic feedstock of the biomass crop assistance program and the tax credit established by the newly enacted farm bill. We conclude by discussing potential environmental impacts and associated policy implications.

2. Market Interactions between Energy and Agricultural Products

The biofuel economy has emerged as markets for petroleum, biofuels and agricultural crops have become linked. Figure 1 shows the emerging correlations among crude oil prices, ethanol production, and corn prices. For example, ethanol production steadily rose from 83 million gallons in 1981 to 1.77 billion gallons in 2001 with an average growth rate at approximately 80 million gallon per year. Since 2001, average growth rate of ethanol production has dramatically increased to approximately 674 million gallons per year over the period of 2001-2007. The expanding production of ethanol since 2001 correlates with the dramatic increase in crude oil price over the same period. As for corn, the average corn price tended to fluctuate around $2.50 per bushel before 2005, and after that suddenly rose up to over $4.00/bushel in 2007.

The correlations between crude oil price, booming ethanol production and corn price are not just random coincidences, but can be attributed to the economic dynamics of markets and their integration. Enabled by the biofuel policy, the rising petroleum prices in the global market triggered a chain of market reactions in the U.S. from gasoline to ethanol and to agricultural products like corn and cellulosic biomass crops (Figure 2). The interaction between the global petroleum market and the U.S. market of agricultural products, corn and dedicated cellulosic energy crops in particular, can explain the current rising corn price, absence of cellulosic ethanol, and farmers' behavior in expanding corn production.

In the global petroleum market (panel A), the recent expansion in petroleum demand from demand curve D_{t1} to demand curve D_{t2} increases international prices, attracting higher cost supplies. The rising petroleum prices induce higher cost gasoline and liquid fuel supplies in the U.S. fuel market (panel B), shifting the supply curve from S_{t1} to S_{t2} such that the same level of fuel supply is only provided at a higher price. With higher fuel prices, more costly substitute fuels, such as corn grain-based or even cellulosic ethanol, become profitable and can supplement the petroleum-based fuel supply. Consequently, even if the demand for fuels in the U.S. does not experience a significant structural change, the higher fuel price makes profitable the production of biofuels that were previously attractive only under government subsidies and protection from the competition of imported biofuels. The U.S. ethanol market (panel C) shows the supply of ethanol coming mainly from corn grain rather than from cellulosic feedstock, due to the high production cost of cellulosic ethanol relative to the current fuel price.

The expanded production of corn grain-based ethanol in turn increases the demand for corn to make biofuels in addition to the traditional demand for livestock feed. In the corn grain market (panel D), the biofuel need creates an epochal kink in the demand for corn grain, which drives prices higher than they otherwise would be with corn being mainly used as livestock feed.

Meanwhile, no market currently exists for cellulosic biomass crops to make advanced ethanol (panel F), because the highest price that biorefiners can afford to pay for biofuel feedstock remains below what even the most efficient farmer needs to earn in order to convert cropland to biomass crops. The market potential of cellulosic biofuel feedstock, however, could improve if new technology were developed that can either reduce the cost of converting cellulosic feedstock to advanced biofuels or increase the yield of biofuel feedstock crops. An advance in the conversion technology would allow biorefiners to pay more for feedstock, while a yield increase would allow farmers to accept less for biofuel feedstock.

3. Farmers' Production Decisions in the Market Economy

What to grow is the most basic question faced by farmers. We assume that farmers decide which crops to grow on their land to maximize their profits, given market prices of agricultural products and their production costs. A simple yet policy-relevant way to examine farmers' response in growing crops for cellulosic biofuel feedstock is the case where a farmer can use available land to grow food or cellulosic biomass crops or a combination of both. A special and interesting case is concerns food crops that also generate crop residues that could serve as cellulosic biofuel feedstocks. Figure 3 illustrates examples of yields per unit land of six crop that produce grain and/or cellulosic feedstock products. Switchgrass, miscanthus and poplar produce only cellulosic feedstock. Soybean produces only food grain. By contrast, corn and wheat are food crops that produce both grain and cellulosic biofuel feedstock products. For profit-maximizing, risk-neutral farmers, the optimal allocation of land between cellulosic biomass and food crops depends on relative earnings per unit land devoted to producing each crop.

3.1 Model Setup

Consider a farmer with a total amount of A units of land available for agricultural production. Suppose the farmer allocates A_{food} units of land to food production and the remaining $(A - A_{food})$ units of land to cellulosic biomass crops. Assume a fixed output production function such that the output per unit land devoted to food production is a with a joint output of residues for cellulosic feedstock at an amount c. Similarly, assume the output per unit land devoted to cellulosic biomass crops is b. Consequently, the total output of food, Q_{food}, is equal to aA_{food}; and the total output of cellulosic feedstock $Q_{cellulose}$ is equal to $b(A - A_{food}) + cQ_{food}$, assuming homogeneous cellulosic feedstock from either cellulosic biomass crops or crop residues associated with food crop production. Assume further that not all cellulosic residues from food production can be sustainably harvested due to conservation concerns, so we introduce a harvesting ratio ε to capture the portion that can be collected sustainably. Therefore, the total output of cellulosic feedstock which farmers can produce based on their land allocation decision can be expressed as $Q_{cellulose} = b(A-A_{food}) + c\varepsilon Q_{food}$.

Based on the model above, we can derive the production possibility frontier (PPF) of corn versus cellulosic feedstock for the total amount of available land, A, as follows

$$\frac{1}{b}Q_{cellulose} + \frac{1}{b}(\frac{b}{a} - c\varepsilon)Q_{foood} = A \tag{1}$$

As demonstrated by Figure 4, more cellulosic feedstock can be produced for given levels of food output than otherwise would be possible if no cellulosic residue were available from food production. As we will see, the potential joint production of both food and cellulosic feedstock from food crops has important implication for farmers' allocation of land between food and cellulosic biomass crops. Note that the straightline PPF is the outcome of the assumption of fixed output production of land, which implies separable crop outputs. The negatively sloped PPF also assumes higher yields of cellulosic feedstock from dedicated energy crops as compared to those from food crop residues (i.e., $b > ac\varepsilon$) per unit land.

3.2 Linking Farmers' Production Decisions to the Markets

With the above setting for agricultural production, the optimal allocation of land between food and cellulosic biomass crops depends on the relative profits per unit land devoted to each crop. Those profits, in turn, are determined by market prices and production costs. Denote P_{food} as the market price of the food product and $P_{cellulose}$ as the market price of cellulosic feedstock. Suppose the production cost per unit crop output is α for food crops and β for cellulosic biomass crops, both of which include harvesting costs. Further, we assume the harvesting cost per unit output of crop residue is γ, which is less than the production cost per unit output, β, of cellulosic biomass crops. Denote h as transportation cost. Mathematically, the farmer attempts to allocate land between both crops so as to maximize profit

$$\pi = P_{food}Q_{food} + P_{cellulose}c\varepsilon Q_{food} - \alpha Q_{food} - (\gamma + h)c\varepsilon Q_{food} + P_{cellulose}Q_{cellulose} - \beta Q_{cellulose} \qquad (2)$$

Collecting items on the right hand side, the profit equation can be reduced to

$$\pi = [P_{food} + P_{cellulose}c\varepsilon - \alpha - (\gamma + h)c\varepsilon]Q_{food} + (P_{cellulose} - \beta)Q_{cellulose} \qquad (3)$$

Without losing generality, assume $P_{food} > \alpha$ and $P_{cellulose} > \beta$. The profit equation (3) represents isoprofit curves with different profit levels π, as demonstrated by Figure 5. The optimal allocation of land that maximizes farmers' profit would be any points on the PPF that are also on the isoprofit curve at the highest possible level of profit π (Figure 5). As a result, the optimal allocation of land between growing dedicated energy crops versus food crops would be: 1) all land allocated to grow food crops with residues available as byproduct for cellulosic feedstock, if $[P_{food} + P_{cellulose}c\varepsilon - \alpha - (\gamma + h)c\varepsilon]/(P_{cellulose} - \beta) > b/a - c\varepsilon$; 2) all land allocated to grow dedicated energy crops, if $[P_{food} + P_{cellulose}c\varepsilon - \alpha - (\gamma + h)c\varepsilon]/(P_{cellulose} - \beta) < b/a - c\varepsilon$; or 3) any points along the PPF as farmers are indifferent on which crop to grow, if $[P_{food} + P_{cellulose}c\varepsilon - \alpha - (\gamma + h)c\varepsilon]/(P_{cellulose} - \beta) = b/a - c\varepsilon$. Figure 5 illustrates case (1), where all land is allocated to the food crop.

The following condition must be satisfied for farmers to grow dedicated energy crops when they could also grow food crops:

$$[P_{food} + P_{cellulose}c\varepsilon - \alpha - (\gamma + h)c\varepsilon]/(P_{cellulose} - \beta) \leq b/a - c\varepsilon \qquad (4)$$

That is, the slope of the isoprofit curve should be less than or equal to the slope of the PPF. This economic condition can further be reduced as

$$P_{cellulose} \geq \{a/[b - 2ac\varepsilon]\}[P_{food} - \alpha - (\gamma + h)c\varepsilon + (b/a - c\varepsilon)\beta], \text{ if } b/a > 2c\varepsilon \qquad (5)$$

Note that if $b/a < 2c\varepsilon$, $P_{cellulose} \leq \{a/[b - 2ac\varepsilon]\}[P_{food} - \alpha - (\gamma + h)c\varepsilon + (b/a - c\varepsilon)\beta] < 0$, which can be ruled out because it would contradict with the assumptions $P_{cellulose} > \beta$, $P_{food} > \alpha$, and $\beta > (\gamma + h)$. Consequently, conditional on the production constraint of both crops ($b/a > 2c\varepsilon$), the minimum price acceptable for the farmer to grow dedicated energy crops when he could also grow food crops would be

$$P_{cellulose}^{farmer} = \{a/[b - 2ac\varepsilon]\}[P_{food} - \alpha - (\gamma + h)c\varepsilon + (b/a - c\varepsilon)\beta] \qquad (6)$$

Further, the farmers' minimum acceptable price (MinAP) for growing cellulosic biomass crops can be decomposed into different cost components as follows

$$P_{cellulose}^{farmer} = \beta + \frac{1}{b/a - 2c\varepsilon}(P_{food} - \alpha) + \frac{1}{b/a - 2c\varepsilon}(\beta - \gamma - h)c\varepsilon \qquad (7)$$

This equation shows that the market price of cellulosic feedstock needs to cover at least the production cost of the dedicated energy crops, the forgone profit associated with food crops, and the saving in production cost attributable to crop residues as a byproduct for feedstock compared to growing dedicated energy crops. If we ignore the residues from food crops as a potential source of cellulosic feedstock, the corresponding farmers' MinAP would be artificially low at

$$P_{cellulose}^{farmer\,\prime} = \beta + \frac{1}{b/a}(P_{food} - \alpha) \qquad \text{for } c = 0 \qquad (8)$$

3.3 The Cellulosic Feedstock Market

The above section establishes the minimum feedstock price acceptable for farmers to grow cellulosic biomass crops when they could also grow food crops with a cellulosic crop residue byproduct. Farmers can increase their profits by dedicating their cropland to cellulosic biomass crops rather than food crops only if the market price for cellulosic feedstock is greater than the MinAP. However, the market price for cellulosic feedstock also depends on how much biorefiners can afford to pay for the cellulosic feedstock. To biorefiners, the maximum price affordable for feedstock is determined by the market prices of biofuels and related biorefinery costs.

Suppose the market price of biofuels such as ethanol is $P_{biofuels}$. This is the price that cellulosic biofuels need to compete with in order to be economically viable, especially when other biofuels from starch or sugar, such as corn grain-based ethanol, are relatively more cost-competitive and have not reached market saturation. Take corn grain-based ethanol as an example. The current market value for corn grain-based ethanol is largely determined by its energy content relative to exogenous crude oil or gasoline prices, government subsidies, and its premium as a fuel additive.

Denote the market price of cellulosic feedstock $P_{cellulose}$, the biofuel yield of cellulosic feedstock r, capital cost k, and cash operating cost m. All the costs are measured as costs per unit volume of cellulosic biofuels produced. Biorefiners are willing to produce cellulosic biofuels only if

$$P_{biofuel} - k - m - P_{cellulose}/r \geq 0 \tag{9}$$

That is,

$$P_{cellulose} \le r(P_{biofuel} - k - m) \tag{10}$$

So biorefiners' maximum affordable price (MaxAP) for cellulosic feedstock is

$$P_{cellulose}^{biorefiner} = r(P_{biofuel} - k - m) \tag{11}$$

As we can see, an increase in the biofuel price can raise biorefiners' MaxAP for cellulosic feedstock, while a decrease in the production and transportation costs can also boost biorefiners' MaxAP for cellulosic feedstock. By determining the price and production costs of biofuels, respectively, crude oil prices and fuel processing technology can affect the maximum price of cellulosic feedstock that biorefiners can offer in the feedstock market.

Figure 6 depicts the relationship between crude oil price and cellulosic feedstock prices. The area above the farmers' MinAP curve represents all cellulosic feedstock prices for each given crude oil price that are acceptable to farmers; while the area below the biorefiners' MaxAP curve represents all cellulosic feedstock prices for each given crude oil price that biorefiners can afford to pay. So to the lower left of the intersection of the two curves, there are no cellulosic feedstock prices that are acceptable for both farmers and biorefiners, because there is no overlap between the domains defined by farmers' MinAP and biorefiners' MaxAP. To the upper right of the intersection of the two curves, the acceptable regions overlap, indicating that cellulosic feedstock prices are acceptable to both parties at these (high) crude oil prices.

4. An Empirical Illustration: Switchgrass *versus* Corn

To illustrate how farmers' production decisions affect the supply of cellulosic feedstock, we apply the decision model above using market data and production parameters from the literature. Specifically, we compare the empirical estimates of both farmers' MinAP and biorefiners' MaxAP for cellulosic feedstock in order to evaluate to what extent farmers and biorefiners can reach an agreement on the feedstock price such that farmers would choose to grow dedicated cellulosic energy crops when they could also grow food crops. We also use this empirical model to evaluate the effect on farmers' production choices of the biomass assistance program and the new tax credit in the 2008 farm bill.

4.1 Model Crops

In this empirical illustration, we focus on switchgrass (*Pancium virgatum*) as a dedicated cellulosic biomass crop to compete with corn (*Zea mays*). A 10-year research program sponsored by the U.S. Department of Energy has identified switchgrass as a model energy crop that not only is compatible with existing farming systems but also could generate annual cash flows while providing many environmental benefits (McLaughlin and Kszos 2005). Life cycle analyses also suggest that switchgrass produced for energy could compete favorably both as an agricultural crop and as fuel for industry (McLaughlin and Kszos 2005). In contrast, corn is the food crop most widely grown in the U.S. and will continue to be one of the major cash crops that farmers would consider growing where possible. Our quantitative analysis of farmers' decisions on allocating land to grow switchgrass versus corn is relevant to the corn-growing areas (such as the "Corn Belt" States) and to the environmental sustainability issues associated with corn.

Given that corn residues (stover and cob) could also be harvested as cellulosic feedstock for biofuels, farmers' production choices between switchgrass and corn could have strong implications for how the U.S. Renewable Fuel Standards are met with attendant consequences for environmental sustainability.

4.2 Empirical Equations and Parameters

To highlight the linkage between the global petroleum market and both the U.S. domestic ethanol market and the cellulosic feedstock market, we can estimate biorefiners' MaxAP for cellulosic feedstock as a function of crude oil prices via the relationship between ethanol and crude oil prices.

Based on monthly market data over the period of 2000-2006, Hurt et al. (2006) empirically identified the wholesale gasoline prices as a function of crude oil prices

$$P_{gasoline}(\$/gal) = 0.3064 + 0.03038P_{crude\ oil}(\$/bbl) \qquad (\text{adjusted } R^2{=}0.93) \qquad (12)$$

The market value of ethanol is composed of its gasoline energy equivalent value, a government subsidy, and a premium from ethanol as a fuel additive. At an additive premium of \$0.25/gal, we can derive

$$P_{ethanol}(\$/gal) = (2/3)P_{gasoline}(\$/gal) + 0.51 + 0.25 \qquad (13)$$

Substituting (12) into (13) in place of $P_{gasoline}$ yields

$$P_{ethanol}(\$/gal) = 0.9643 + 0.02025P_{crude\ oil}\,(\$/bbl) \qquad (14)$$

With the above ethanol price $P_{ethanol}$, we can derive biorefiners' MaxAP for cellulosic feedstock as a function of crude oil prices and the production costs of cellulosic ethanol

$$P_{cellulose}^{biorefiner} = r(0.9643 + 0.02025P_{crude\ oil}\ (\$/bbl) - k - m) \quad (15)$$

From Equation (6), farmers' MinAP for switchgrass as the cellulosic feedstock when corn as the competing food crop is

$$P_{cellulose}^{farmer} = \{a/[b - 2ac\varepsilon]\}[P_{corn} - \alpha - (\gamma + h)c\varepsilon + (b/a - c\varepsilon)\beta] \quad (16)$$

Table 1 summarizes the parameters to be used for estimating farmers' MinAP for cellulosic feedstock at the current technology and market conditions.

4.3 Results of the Empirical Model

Using 2007-08 U.S. market data on crude oil and average corn prices, we calculated the maximum price that biorefiners can afford to pay for cellulosic feedstock and the minimum price required for farmers to grow switchgrass rather than corn (Table 2). Over the period of January 2007 to February 2008, farmers' MinAP for growing switchgrass rose from \$250/Mg to \$536/Mg (column 4) as the U.S. average corn price rose from \$119.96/Mg to \$178.18/Mg. If we ignore the potential profit from corn residues as feedstock, farmers' MinAP for growing switchgrass would drop to \$91-147/Mg. In both cases, farmers' MinAP were greater than biorefiners' MaxAP for feedstock, although the rising crude oil price from \$0.31/L to \$0.54/L raised biorefiners' MaxAP from \$19/Mg to \$63/Mg (column 6). This price gap illustrates that at the current conversion technology and market conditions, switchgrass as a cellulosic biomass crop cannot compete with corn for cropland in biofuel production, and cellulosic biofuels cannot be profitably produced from switchgrass grown on cropland that can also grow corn at the typical yields and prices used here.

To compete with corn, the single biggest cost that farmers' MinAP needed to cover for producing switchgrass was the profit forgone from selling corn grain (column 3), which accounted for over 45% of farmers' MinAP and increased to 75% when corn price rose to its February 2008 maximum. The overall profit available from growing corn ranged from approximately 2.5 to7 times the production cost of switchgrass. Even if we assume away the profit of corn production at low corn prices, the potential profit from corn residues as a byproduct for feedstock still remains an important cost component compared to the production cost of switchgrass. In contrast, what biorefiners could afford to pay for cellulosic feedstocks at the current conversion technology could not even cover the production cost of switchgrass, which was only a small portion of the farmers' MinAP. The comparison between the cost components of farmers' MinAP and biorefiners' MaxAP strongly favor of production of corn over switchgrass on cropland.

4.4 The Effect of the 2008 Farm Bill

The farm bill introduces policy incentives to both biorefiners and farmers that could change the calculations above. This analysis only considered a tax credit of $1.01/gallon for cellulosic ethanol refiners (Section 15321) and an cost-sharing program matching $1 for each $1 per ton provided by biorefiners up to $45/ton for collection, harvest, storage, and transportation of biomass crops (Section 9011). With the incentive from the crop assistance program, the harvesting and transportation costs were fully covered for corn residues because the total cost was less than \$45/ton; for switchgrass, the maximum limit of \$45/ton was applied to the total of transportation and production costs.

Results show that the cost-sharing program could reduce farmers' MinAP to \$189-475/Mg for growing switchgrass instead of corn (column 6). The tax credit of \$1.01/gallon for biorefiners could raise biorefiners' MaxAP from \$19-63/Mg to \$80-124/Mg for the same range of crude oil prices (column 7). Together, the tax credit coupled with the cost sharing could reduce the gap between biorefiners' MaxAP and farmers' MinAP for cellulosic feedstock.

Figures 7 and 8 graphically show changes of farmers' MinAP and biorefiners' MaxAP with the prices of corn and crude oil. In Figure 7, when crude oil price went up and drove up corn price via increased demand for corn to make ethanol from January 2007 to February 2008, both farmers' MinAP and biorefiners' MaxAP for cellulosic feedstock increased as well. These results can be attributed to the increased profits of growing corn and producing ethanol due to increased prices for corn and crude oil. While a higher price could be offered by biorefiners for feedstock, farmers' MinAP increased more quickly (Figure 8). Consequently, the gap widened between the prices that farmers would accept and what biorefiners could afford to pay for cellulosic feedstock. This wider gap implies that for farmers voluntarily to grow switchgrass instead of corn would require dramatic technological advances to reduce the cost of cellulosic ethanol production and/or the cost of switchgrass production.

5. Conclusion

This analysis has important policy implications. While agriculture holds the promise to supply sufficient feedstock for producing advanced biofuels, how farmers would respond to the biofuel policy in providing the feedstock becomes critical. The importance of the issue is justified by its relevance to two inversely related policy questions. If dedicated energy crops compete with food crops for farmland, how will devoting more land to energy crops affect food availability and the current ecosystem services from food crop land? On the other hand, if dedicated energy crops cannot compete at all with food crops for cropland, where will energy crops be grown? Is it feasible to produce the 998 million dry tons of agricultural biomass estimated by the Billion-Ton report using marginal lands that do not currently grow crops? The answers to these questions hinge on how farmers would choose to use their existing cropland, yet how farmers' decisions driven by the markets would affect biofuel supply has received scant attention from the science community.

In this study, we showed how the biofuel economy links the global petroleum market to the U.S. ethanol market and from there to agricultural markets for corn and dedicated energy crops in particular. We developed an economic model of farmers' production decisions and how those decisions are driven by markets and market integration from petroleum to agricultural products. The economic model showed that for cropland currently in food production, the minimum price required to compensate farmers for growing dedicated energy crops rather than food crops should cover at least three cost components: the production cost of the dedicated energy crops, the forgone profit otherwise available by growing food crops, and the forgone profit in providing cellulosic feedstock when producing food crops also generates cellulosic feedstock as a byproduct. The model established that dedicated energy crops could compete with food crops only if the maximum price that biorefiners could afford to pay is greater than the minimum price that farmers would accept to grow dedicated energy crops rather than food crops. The biorefiners' maximum affordable price is chiefly affected by the petroleum price, while the farmers' minimum acceptable price is chiefly affected by the price of competing food crops. For simplicity, the model assumes profit-maximizing, risk-neutral behavior. A model that included risk averse behavior would likely find a that farmers' minimum acceptable price of cellulosic biomass was higher and biorefiners' maximum affordable price was lower, strengthening the risk-neutral results shown.

An empirical illustration of farmer and biorefiner decisions regarding switchgrass and corn production was constructed using parameters from "Corn Belt" States and price data from 2007-08. While actual U.S. production conditions are heterogeneous, this representative analysis reflects typical conditions. The analysis showed that without policy incentives, farmers were unlikely to grow switchgrass for biofuel when they could also grow corn. Indeed, the empirical example demonstrated that the maximum price that biorefiners can afford for cellulosic feedstock only covered a portion of the estimated production cost of switchgrass, not beginning to cover the 2.5-7 times larger opportunity cost of giving up corn production. Apart from prices, these results are driven by the underlying technologies for producing crops and converting biomass to ethanol.

This study contributes a multi-market framework conceptual model and empirical illustration of how farmer decisions about whether to produce energy crops are linked to other food and fuel markets. Our analysis of the farmer's minimum acceptable payment and biorefiner's maximum affordable payment complement recent technical and budgeting studies of the potential supply of cellulosic feedstock (Duffy and Nanhou 2002, Hipple and Duffy 2002, Perlack et al. 2005, Khanna et al. 2007). Our finding on the importance to farmers of opportunity cost from foregone crop income is borne out by Jensen et al. (2007), whose survey of Tennessee farmers found that higher net farm income per acre reduced farmers' willingness to convert the land to switchgrass as an energy crop.

The 2008 farm bill has introduced new subsidies that could increase farmers' incentives to produce cellulosic biomass crops. Nonetheless, corn likely remains an economically attractive crop because corn grain can be used both as feed and as grain based-ethanol, which implies a high opportunity cost of growing other crops, including dedicated energy crops. Even if advanced biofuels become economically competitive within the next 10 to 15 years (Stephanopoulos 2007), corn would be one source, because corn residues are a byproduct of grain production and federal policy does not discriminate among different cellulosic biofuel feedstocks. Indeed, the empirical example showed that farmers' MinAP for growing switchgrass would 2.5-5 times higher with corn residue economically usable as feedstock to make cellulosic biofuels. This high economic threshold would further discourage growing switchgrass instead of corn on cropland. In future, sustained or rising demand for both grain-based and advanced biofuels in addition to feed demand could lead to expanding corn acreage. Such an expansion would raise similar issues to those surrounding corn grain-based ethanol expansion: the food versus fuel competition for cropland (Runge and Senauer 2007), the indirect land use effect on greenhouse gas emissions and wildlife habitat (Fargione et al. 2008, Searchinger et al. 2008), and other environmental concerns associated with producing corn, such as water pollution and soil erosion.

If switchgrass does not readily compete with corn for cropland, then it becomes critical to identify where switchgrass or other energy crops could be grown to meet future U.S. fuel needs. Producing cellulosic biomass crops may be economically attractive on marginal lands that have lower opportunity costs than prime cropland. Future research is needed to identify those lands where growing energy crops might be attractive. One important consideration, however, is that marginal lands are often vulnerable to soil erosion and actively providing ecosystem services such as wildlife habitat and carbon sequestration, so the environmental impact of developing marginal lands deserves scrutiny. To ensure that agricultural biofuel production is environmentally sustainable, further research is needed into the likely environmental effects of land use change and the design of policies that provide incentives for sustained provision of rural ecosystem services alongside biofuel incentive policy.

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Table 1. Parameters for estimating farmers' and biorefiners' compensated prices for cellulosic feedstocks

Parameters	Unit[1]	Value	Year	Source/justification
Corn				
yield, a	Mg/ha (Bushel/acre)	9.42 (150)	2007	Corn yield has been increasing continuously at an annual rate of approximately 1.7 bushel/acre on overage (Doberman et al. 2002). Since 2004, the U.S. average annual corn yield has reached around 150 bushel/acre (USDA National Agricultural Statistics Service 2008).
Production cost, α	\$/Mg (\$/bushel)	96.37 (2.45)	2000-2007	Multiple year average of costs, including land rent, of corn production in Northern Illinois (Schnitkey and Lattz, 2008).
Residue yield, c	Mg/Mg (Mg/bushel)	0.8457 (0.0215)	2002	Graham et al. used a stover mass to grain mass ratio of 1:1, or a dry weight harvest index (HI) of 0.5 reported by (Gupta et al. 1979), and a dry mass of 21.5 kg per bushel of corn assumed by Wilcke and Wyatt (2002). Sheehan et al.(2004) used a dry mass of 25.4 kg per bushel of corn for yield estimates in Iowa.

Residue harvesting ratio, ε	N/A	50%	2004, 2007	Sheehan et al. (2004) estimated 70% of the corn residue can be collected under continuous corn production and no-tillage, taking into account soil erosion restriction in Iowa. Graham et al. (2007) assumed no more than 75% of the stover could be collected due to equipment constraints.
Residue harvesting cost, γ	\$/Mg	28.74	2002	Graham et al. (2007) estimated corn stover collection cost as a function of stover collected in the field, including \$7.17/Mg nutrient replacement cost: $y(\$/Mg)=50.65x(Mg/ha)^{-0.41}$ for collected stover $x > 3.3$Mg/ha.
Transportation cost, h	\$/l (\$/gal)	0.04 (0.14)	2007	Duffy (2008) estimated transportation to plant cost at \$8.65/ton in Iowa, which translates into \$0.14/gal assuming an ethanol yield of 60 gal/ton.

Switchgrass				
yield, b	Mg/ha (Mg/acre)	9.9 (4)	2001	Duffy (2008) assumed switchgrass yield of 4 ton/acre in Iowa; Perrin et al. (2008) summarized alternative estimates of switchgrass yield, including 6.4 Mg DM/ha (2.59 dry ton/acre) based on commercial-scale field data from North Dakota to Nebraska, 7.6 Mg DM/ha (3.08 dry ton/acre) (Duffy and Nanhou 2001), 9.0 Mg DM/ha (3.65 dry ton/acre) (Epplin 1996), 11.1 Mg DM/ha (4.50 dry ton/acre) (Hallam et al. 2001).
Production cost, β	\$/Mg	60	2007	Collins (2007); Perrin et al. (2008) summarized alternative estimates of the production cost of switchgrass in 2003 dollars, including \$63.83/Mg DM, \$95.90/Mg DM (Duffy and Nanhou 2001), \$29.35 (Epplin 1996), and \$72.52/Mg DM (Hallam et al. 2001)
Capital cost, k	\$/l (\$/gal)	0.15 (0.55)	2007	Collins (2007)

Cash operating cost, m	$/l ($/gal)	0.29 (1.1)	2007	Collins (2007)
Ethanol yield, r	L/Mg (Gal/Mg)	227 (60)	2007	Collins (2007). Ethanol yield demonstrated at bench scale or higher was 255 liters/Mg, or 66.3 gallon/Mg (Sheehan et al. 2004)

[1]Unit conversion is based on the following conversion factors: 1 acre = 0.405 hectare, 1 bushel = 0.0254 Mg for corn, and 1 gallon = 3.7854 liter for liquid in the U.S.

Table 2. Farmers' minimum acceptable prices (MinAP) and biorefiners' maximum affordable prices (MaxAP) for cellulosic feedstock with and without farm bill subsidies.

Time	1. Crude oil price[a], $/L ($/bbl)	2. Corn price[b], $/Mg ($/bushel)	3. Forgone profit of corn grain, $/Mg	4. Farmers' MinAP[c], $/Mg	5. Farmers' MinAP with corn residues unavailable, $/Mg	6. Biorefiners' MaxAP, $/Mg	7. Farmers' MinAP with farm bill subsidies[d], $/Mg	8. Farmers' MinAP with corn residues unavailable and farm bill subsidies, $/Mg	9. Biorefiners' MaxAP with farm bill subsidies, $/Mg
01/07	0.31 (49.51)	119.97 (3.05)	116.13	249.82	91.15	19.02	188.99	46.15	79.62
03/07	0.35 (56.26)	134.91 (3.43)	189.68	323.37	105.40	27.23	262.53	60.40	87.82

05/07	0.39	137.27	201.29	334.98	107.65	33.52	274.15	62.65	94.12
	(61.44)	(3.49)							
07/07	0.44	130.59	168.39	302.08	101.28	44.80	241.24	56.28	105.40
	(70.72)	(3.32)							
09/07	0.46	129.41	162.58	296.27	100.15	47.29	235.44	55.15	107.89
	(72.77)	(3.29)							
11/07	0.54	134.91	189.68	323.37	105.40	62.78	262.53	60.40	123.38
	(85.52)	(3.43)							
02/08	0.54	178.18	402.58	536.27	146.65	63.12	475.44	101.65	123.72
	(85.80)	(4.53)							

a. Crude oil price is measured by the U.S. refiners' acquisition cost of imported crude oil in unit of $/barrel, which is from the U.S. Energy Information Administration (2008); crude oil prices are converted to SI unit with 1 barrel = 158.99 liter in the U.S. for petroleum.
b. Corn price is from USDA National Agricultural Statistics Service (2008), which is in the unit of $/bushel; corn prices are converted to SI unit $/Mg with 1 bushel = 0.0254 Mg.
c. Farmers' MinAP for growing switchgrass instead of corn needs to cover production cost of switchgrass, forgone profit from corn grain, and forgone profit from corn residues as cellulosic feedstock. Production cost of switchgrass including transportation cost is estimated around $68/Mg dry matter without farm bill subsidy and $24/Mg dry matter with farm bill subsidy; forgone profit of corn grain depends on market prices of corn grain, and is calculated in column 4; and forgone profit of corn residue is estimated at around $65/Mg dry matter without farm bill subsidy and $49/Mg dry matter with farm bill subsidy.

d. This analysis only considers a tax credit of \$1.01/gallon for cellulosic ethanol refiners (Section 15321) and an assistance program matching \$1 for each \$1 per ton provided by biorefiners up to \$45/ton for costs of collection, harvest, storage, and transportation (Section 9011) in the 2007 Farm Bill (H.R. 2419).

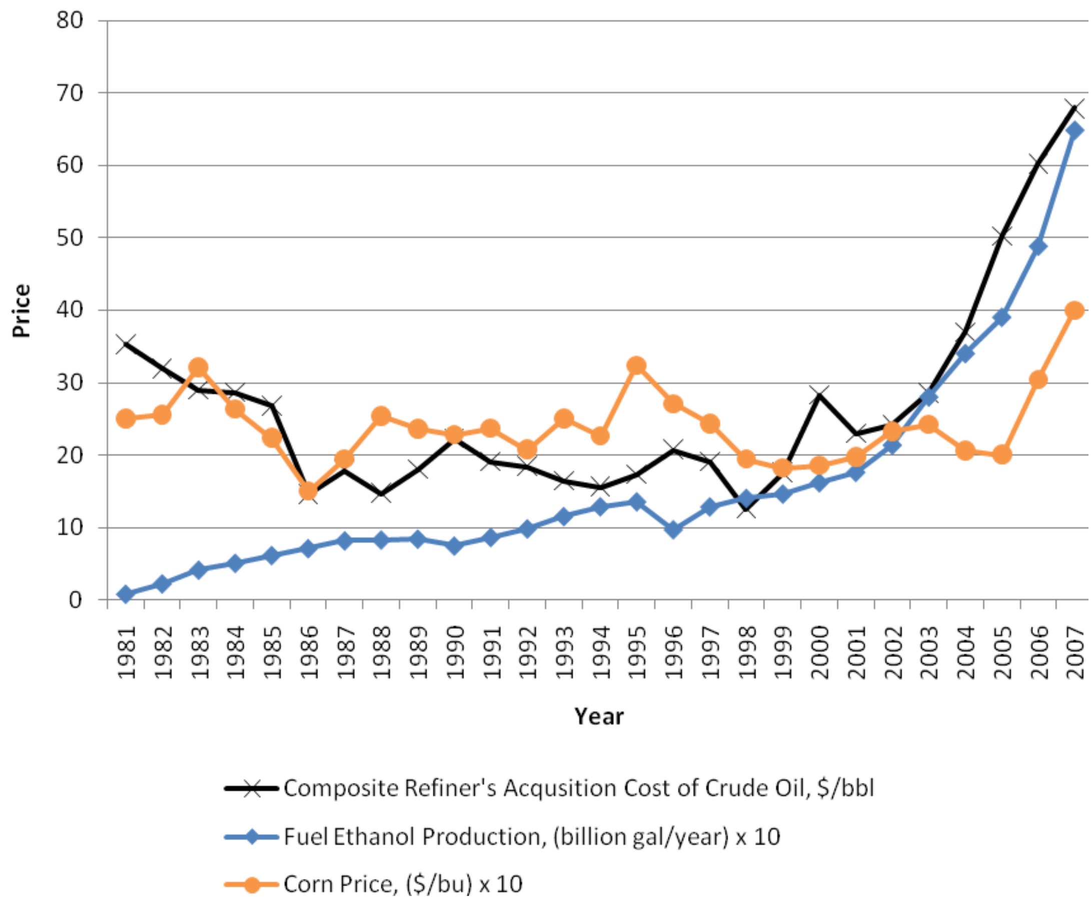

Figure 1. Trends of composite refiner's acquisition cost of crude oil, fuel ethanol production, and corn price over the period of 1981-2007.

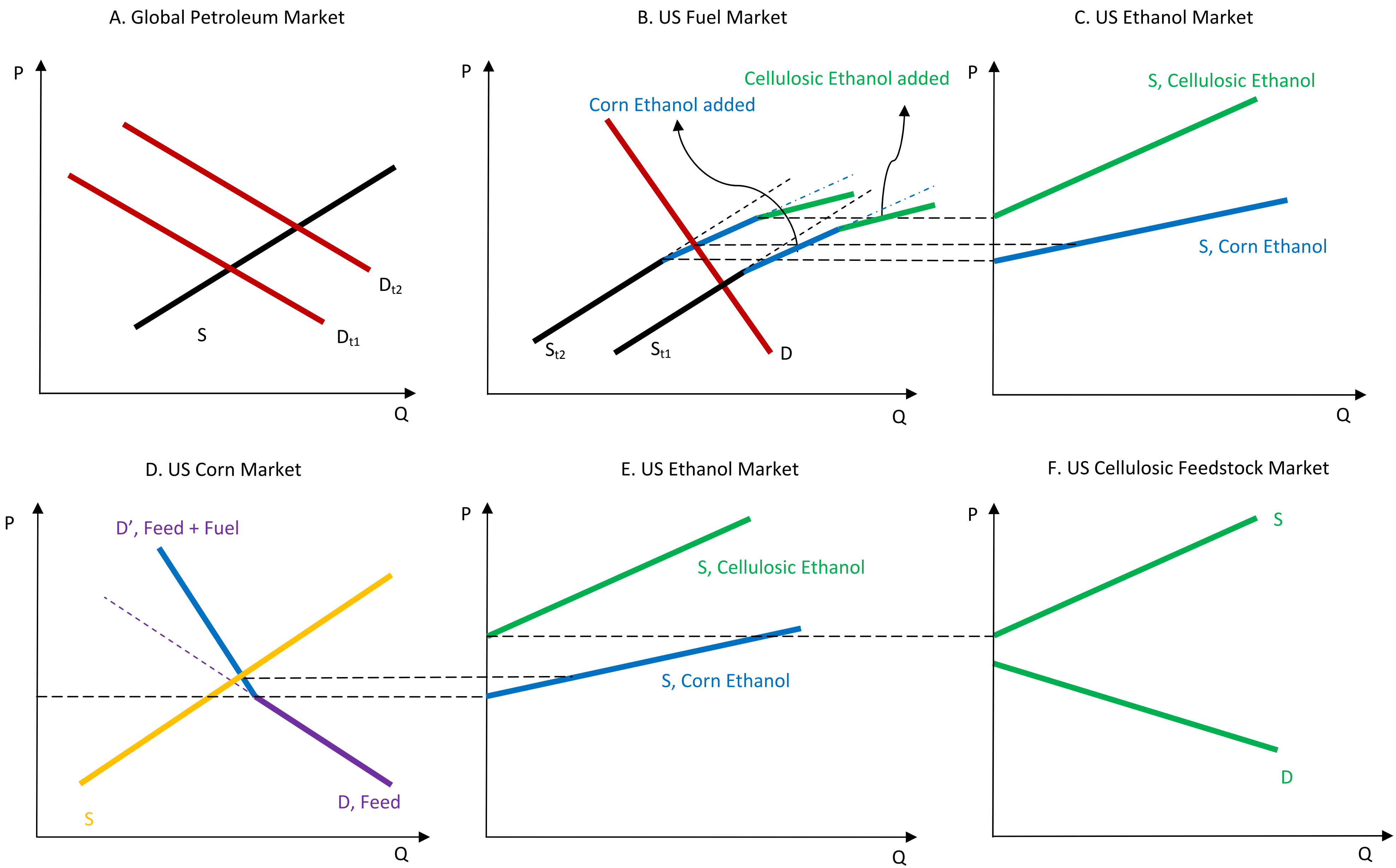

Figure 2. Interaction of Commodity Markets: Petroleum, Fuels, Ethanol, Corn, and Cellulosic Biomass Crops. A. global petroleum market. B. U.S. fuel market. C. U.S. ethanol market. D. U.S. corn market. E. U.S. ethanol market. F. U.S. cellulosic feedstock market

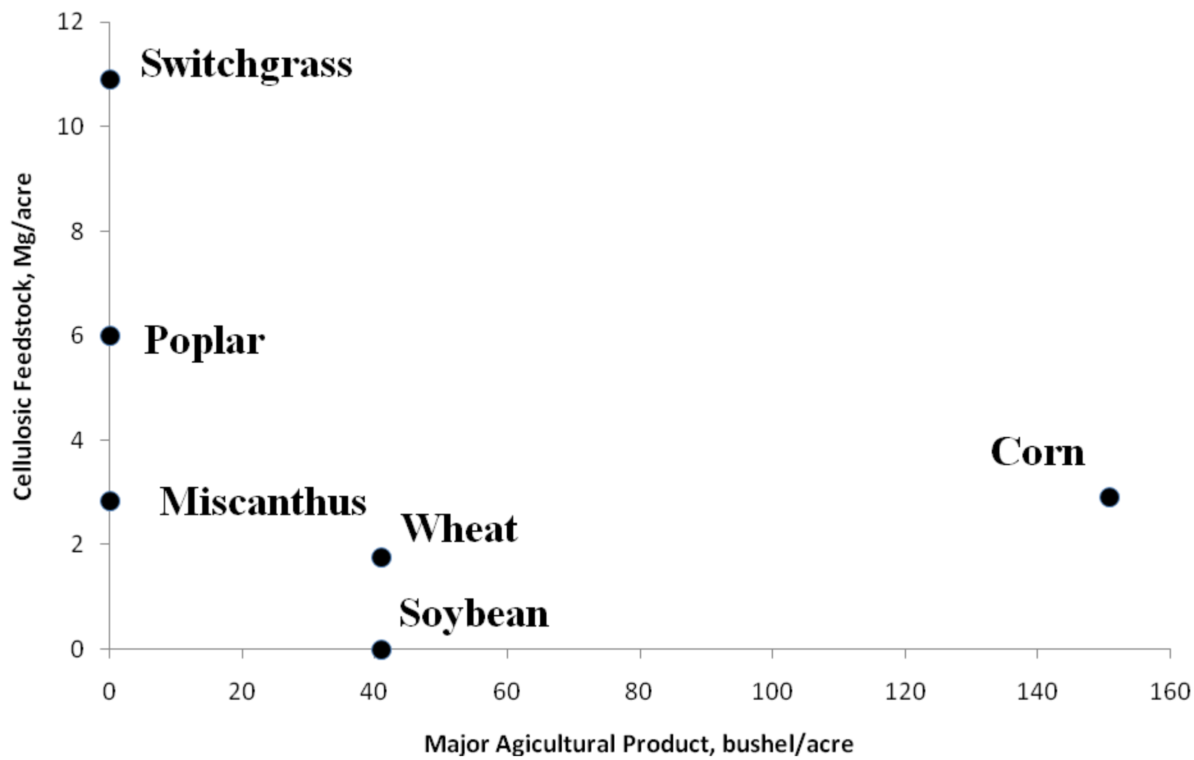

Figure 3. Examples of yields per unit land of main crop product and crop residues usable as cellulosic feedstock for crops. Corn, soybean, and wheat yields are average US yields in 2007 from USDA (2008). Cellulosic feedstock from crops is estimated at a rate of 0.0215 U.S. ton dry matter/acre for corn (Wilcke and Wyatt 2002) and 69.76 × yield (bushel/acre) + 1067.7 pound/acre for wheat (Kerstetter and Lyons 2001). The yields of dedicated energy crops are 3 U.S. ton/acre (2.85 Mg/acre) dry matter for Miscanthus, 8-22 Mg/ha with an average of 6 Mg/acre for Poplar, and 11.5 U.S. ton/acre (10.9 Mg/acre) for Switchgrass (BFIN 2008).

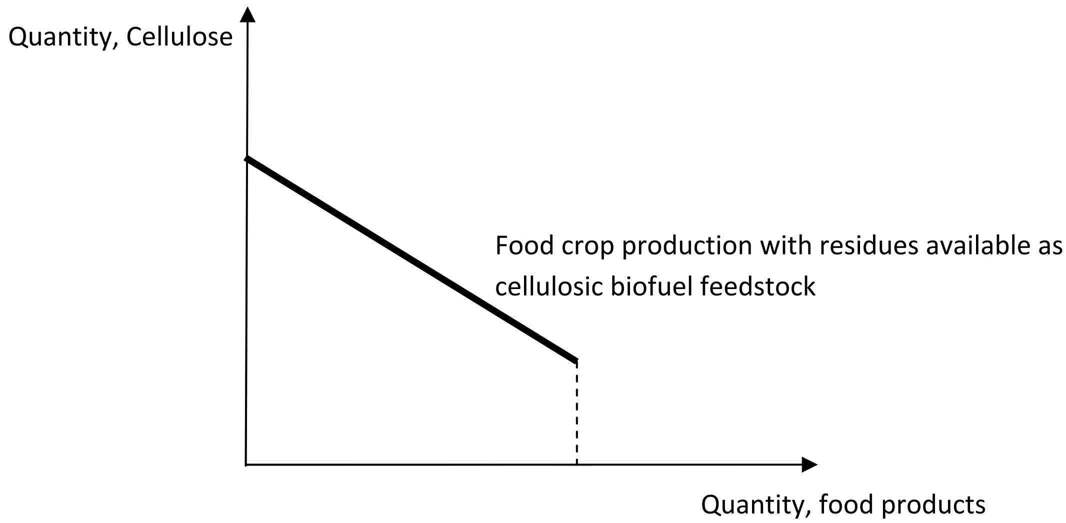

Figure 4. Possible combination of cellulose and food production from different allocation of available land between the two crops. The solid line represents the possible combinations of cellulose and grain production where residues from food crops (such as corn) are available for use as cellulosic feedstocks for advanced biofuels. In this case, even if all land is allocated to producing grain, cellulosic feedstocks are still available from residues.

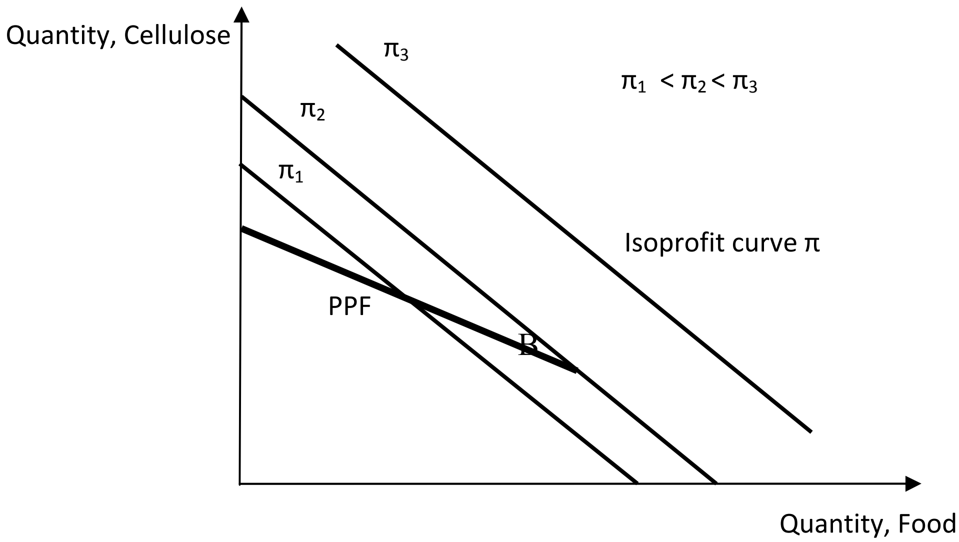

Figure 5. Optimal allocation of land between food and cellulosic biomass crops. Production possibilities frontier PPF represents all combinations of cellulose and food possible from land available for crop production. π_1 , π_2, and π_3 represent alternative profit levels. At the relative prices illustrated, the most profitable point to produce is point B, where isoprofit line π_2 is tangent to the PPF and all land is devoted to the food crop (which produces both food and a cellulosic byproduct).

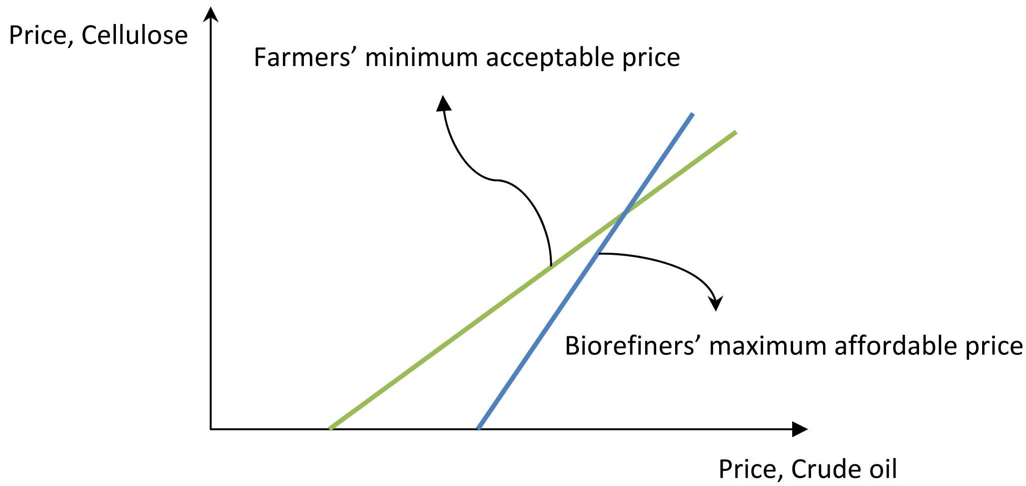

Figure 6. Demonstration of changes of estimated farmers’ minimum acceptable price and biorefiners’ maximum affordable price for cellulosic feedstocks with the market price of crude oil. Farmers can consider converting land to grow cellulosic biomass crops only in the region to the upper right of intersection of the two curves, where the biorefiners’ maximum affordable price exceeds the farmers’ minimum acceptable price.

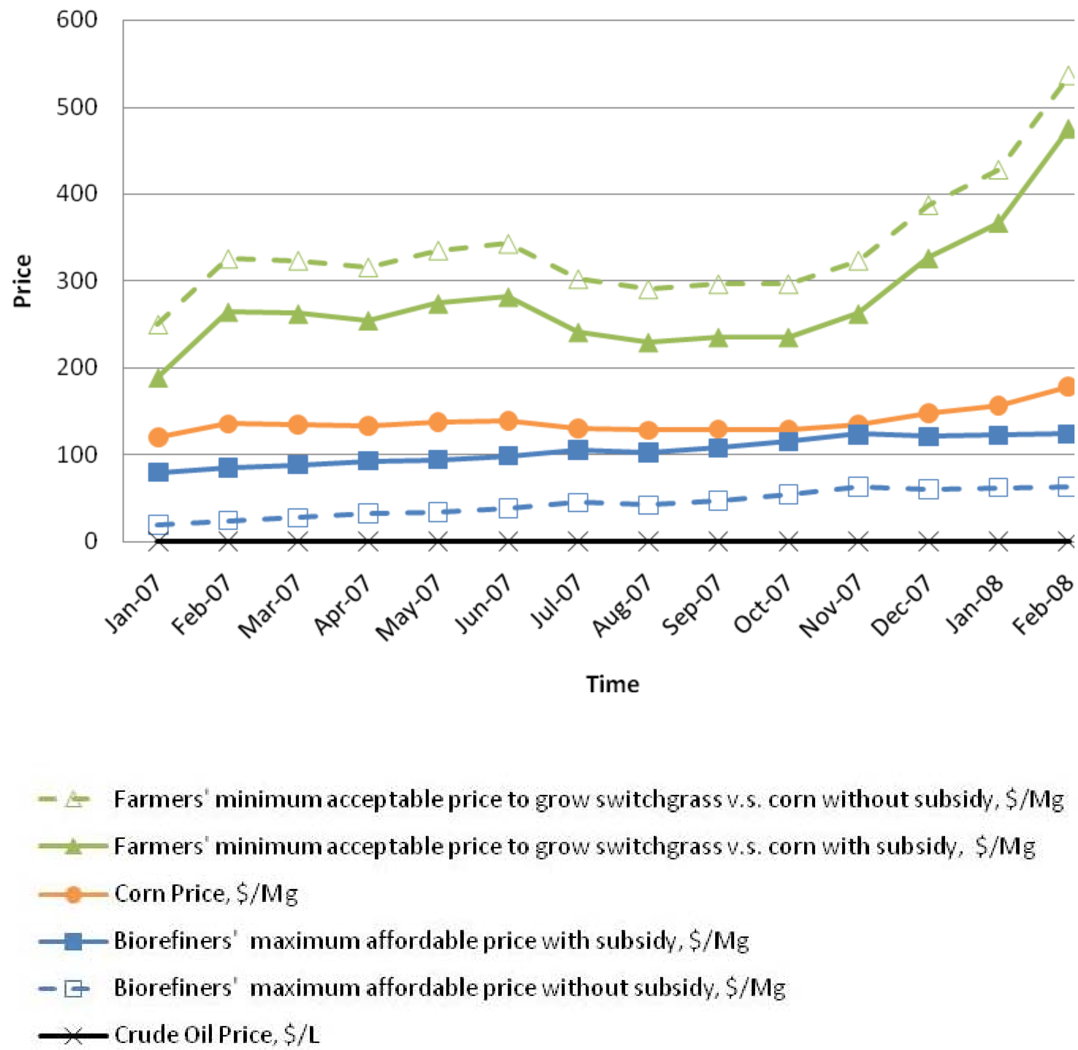

Figure 7. Trends in crude oil price, corn price, and empirical estimates of farmers' minimum acceptable price and biorefiners' maximum affordable price for switchgrass. With rising crude oil prices, farmers' minimum acceptable price increases more quickly compared to biorefiners' maximum affordable price.

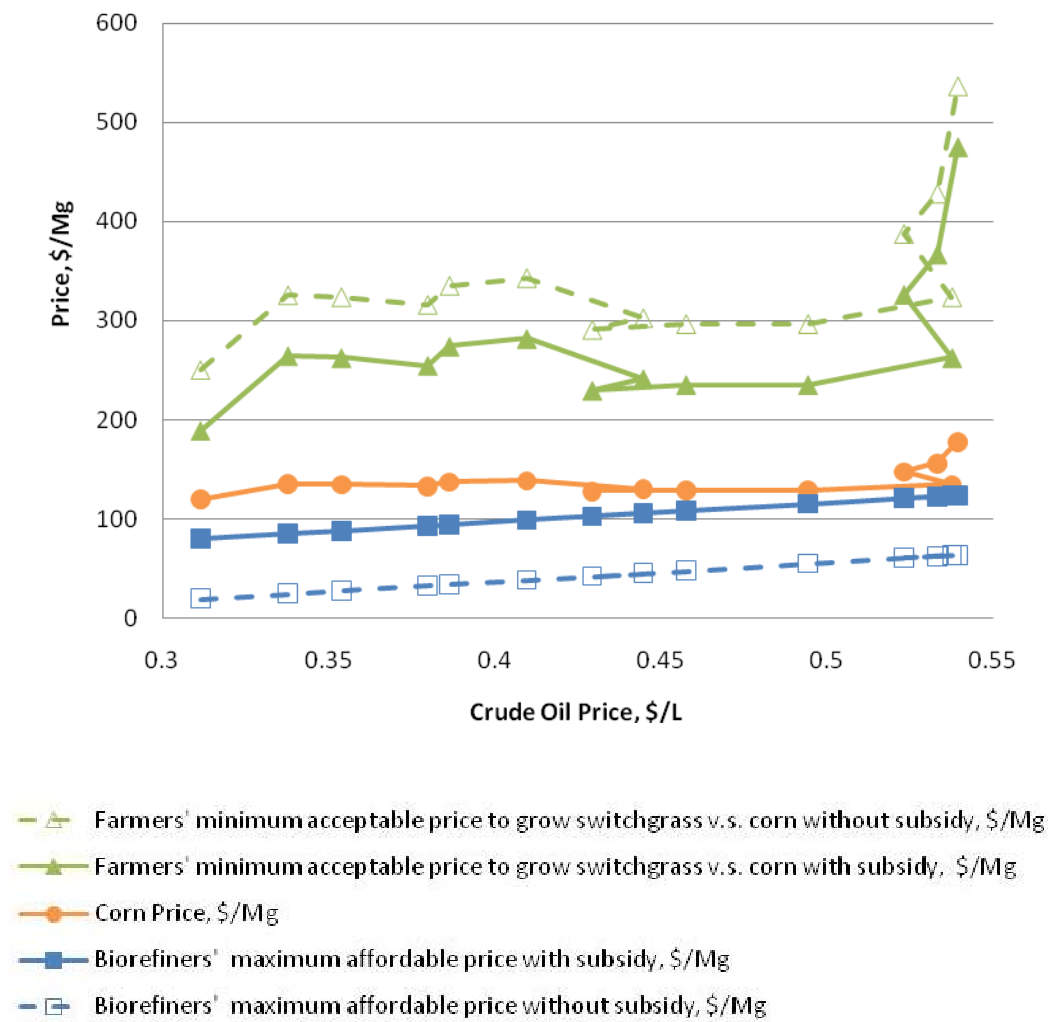

Figure 8. Empirical estimates of farmers' minimum acceptable price and biorefiners' maximum affordable price for switchgrasss at different crude oil prices. Farmers can profitably convert land from growing corn to switchgrass only in the domain where the biorefiners' maximum affordable price exceeds farmers' minimum acceptable price. However, that condition is not met in this simulation of conditions in 2007-08.