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Market interactions, farmers' choices, and the sustainability of growing advanced biofuels: a missing perspective?

Yong Jiang* and Scott M. Swinton

Department of Agricultural, Food and Resource Economics, US Department of Enery Great Lakes Bioenergy Research Center, Michigan State University, East Lansing, USA

Advanced biofuels such as cellulosic ethanol are of great interest in the USA. With agriculture being the major source of feedstock for advanced biofuels, how farmers would respond to markets and policy incentives in providing such feedstock can directly affect sufficient and sustainable supply of advanced biofuels and their environmental sustainability. In this study, we developed an economic model to examine farmers' production choices in a context where agricultural markets are linked to energy markets. We identified the economic conditions under which farmers could maximize their profits by converting current grain cropland to grow cellulosic biomass crops. An empirical illustration showed that with current technology, farmers are unlikely to grow switchgrass as a dedicated energy crop instead of corn on cropland. The biofuel incentives in the 2008 Farm Bill can improve the competitiveness of switchgrass, but may stimulate corn production as well, with corn residues as an alternative feedstock for advanced biofuels. The continuous, possibly expanding, corn production in future raises the same issues for advanced biofuels as for corn grain-based ethanol. To assure the environmental sustainability of advanced biofuel production, further research is needed to help design environmental policies alongside existing biofuel initiatives.

Keywords: biomass; energy; advanced biofuels; corn; land use; switchgrass; ethanol

Introduction

While high petroleum prices combined with government support have stimulated the production of corn grain-based ethanol biofuel in the USA, policy interest has been extending to advanced biofuels that can be made from a broad range of biomass such as herbaceous or woody crops or municipal wastes (Somerville 2006; Kennedy 2007). Compared to corn grain-based ethanol biofuel, advanced biofuels made from cellulosic biomass have many advantages. For example, advanced biofuels such as cellulosic ethanol have lower greenhouse gas emissions and higher energy efficiency than ethanol made from corn grain (Lynd 1996; Farrell et al. 2006; Hill et al. 2006). Moreover, being made from a broad range of inedible biomass, advanced biofuels do not influence food prices as directly as ethanol made from corn grain. This feature makes advanced biofuels socially attractive, especially when there is concern over the impact of corn for fuel on food supply (Runge and Senauer 2007) and when US policy of promoting corn grain-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 grain-based ethanol alone to reach this goal (Copulos 2003, 2007; Greene et al. 2004; Perlack et al. 2005; Osborne 2007).

Advanced biofuels have not been produced at commercial scale, despite their potential economic, social, and environmental appeal. To stimulate their development, the US Government has promulgated a series of policy initiatives. For example, the US 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 by 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 US$1.01/gallon for cellulosic biofuel refiners (Section 15321), and a cost-sharing program matching up to US$45/ton for collection, harvest, storage, and transportation of biomass crops (Section 9011). With agriculture being the current focus of biofuel policy, how farmers respond in providing biofuel feedstock becomes an important policy question.

Farmers' production choices on which feedstock to produce or which crops to grow – including dedicated cellulosic energy crops – directly affect the development and sustainable supply of agriculture-based advanced biofuels and their environmental sustainability. To produce cellulosic biofuel feedstock, farmers face many alternatives: they could simply collect crop residues as cellulosic feedstock from food crops in current production. Yet, crop residues alone may not provide sufficient feedstock but could exacerbate environmental issues associated with production of food crops such as corn. Farmers could also provide cellulosic feedstock by allocating land to grow dedicated energy crops, such as switchgrass, miscanthus, or poplar, which have the potential to provide sufficient feedstock but may be subject to the food versus fuel debate if grown on cropland. So, which feedstock will farmers likely choose to provide under the current market situation to meet the RFS of 16 billion gallons of cellulosic ethanol?

*Corresponding author. Email: jyong@anr.msu.edu

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How will the economic incentives in the newly enacted farm bill affect farmers' decisions, and thus the supply of cellulosic biomass feedstock? What policy implications can be derived from the farmers' production behavior? All these questions of policy importance are linked to the fundamental problem: how farmers' production decisions will respond to market prices and policy initiatives.

The farmers' production choice problem, although critically important, has been under-recognized in the science community. For example, the Billion Ton report asserted that US agricultural and forest lands have the potential to produce over 1.3 billion dry tons of biomass per year to displace 30% 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 estimation was derived largely based on technical feasibility rather than farmers' economic behavior needed to supply the target level of biomass. Tilman 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 will respond to markets and policy incentives in the biofuel economy 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 and how this linkage drives farmers' production choices. Within this market setting, we show how the production choices faced by farmers between dedicated cellulosic energy crops and food crops (especially crops with residues available as biofuel feedstock) are linked to the energy and agricultural markets and associated policy incentives. To illustrate the farmer's choice problem, we focus on a typical case where farmers can supply cellulosic feedstock from either switchgrass (a dedicated biomass crop) or from corn (a food crop that produces cellulosic residues). We use US market data and production parameters representative of the 'Corn Belt' states to evaluate farmers' production choices under the current market situation, conversion technology, and policy incentives. We also 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.

Background

The market phenomenon of the biofuel economy

The current emerging biofuel economy is characterized by an increasingly strong connection between energy and agricultural markets. Figure 1 shows the trends of crude oil prices, ethanol biofuel production, and corn prices since 1981, which have exhibited increasing correlations especially after 2001. As demonstrated in Figure 1, US ethanol biofuel production started in 1981, which may be attributed to the high crude oil price of around US$35/barrel at that time and the US biofuel policy. Since then, crude oil price gradually fell to around US$20/barrel, and fluctuated around that level from 1985 to 2000, before increasing rapidly. Within the same period, US ethanol biofuel production had been steadily increased from 83 million gallons in 1981 to 1.77 billion gallons in 2001, with an average growth rate of approximately 80 million gallons per year. After 2001, the correlations between crude oil prices, ethanol biofuel production, and corn prices became strong. Crude oil price rose dramatically from around US$25/barrel in 2001 to close to US$70/barrel in 2007. Associated with the soaring petroleum price, US ethanol biofuel production also largely increased, with average growth rising from 80 million gallons per year before 2001 to about 674 million gallons per year over the period 2001–2007. Meanwhile, corn price started to increase from a little over US$2/bushel before 2005 to US$4/bushel in 2007.

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

A graphic exposition of the linkage between energy and agricultural markets

The global petroleum market is linked to the US ethanol market by the increasing petroleum price plus a US biofuel subsidy that attracts supply of substitute energy at relatively high cost. In the global petroleum market (Figure 2A), the recent expansion in petroleum demand from demand curve D_{t1} to demand curve D_{t2} drives the market equilibrium supply at s_{t1} moving toward a higher level s_{t2} at a higher energy supply cost. The rising petroleum prices make gasoline supplies in the US fuel market (Figure 2B) more costly, shifting the supply curve 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 supply of petroleum-based fuel. Consequently, even if the demand for fuels in the US 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 competition of imported biofuels. The US ethanol market (Figure 2C) shows the supply of ethanol

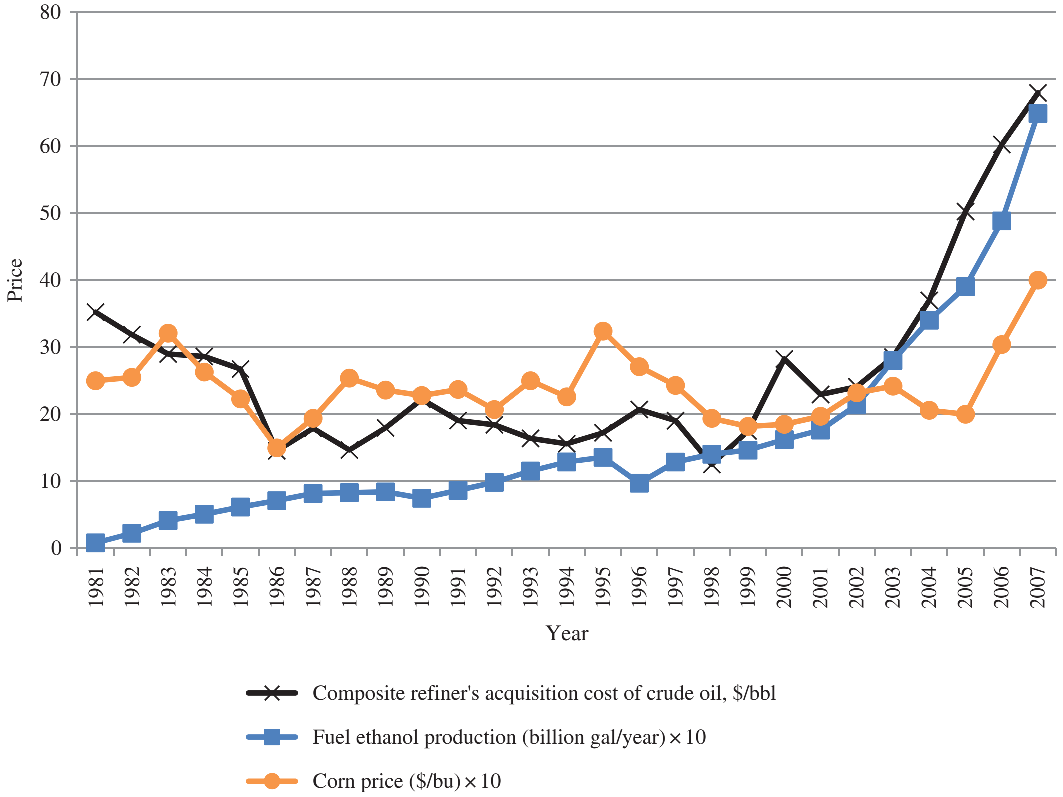

Figure 1. Trends of composite refiner's acquisition costs of crude oil, fuel ethanol production, and corn prices over the period of 1981–2007.

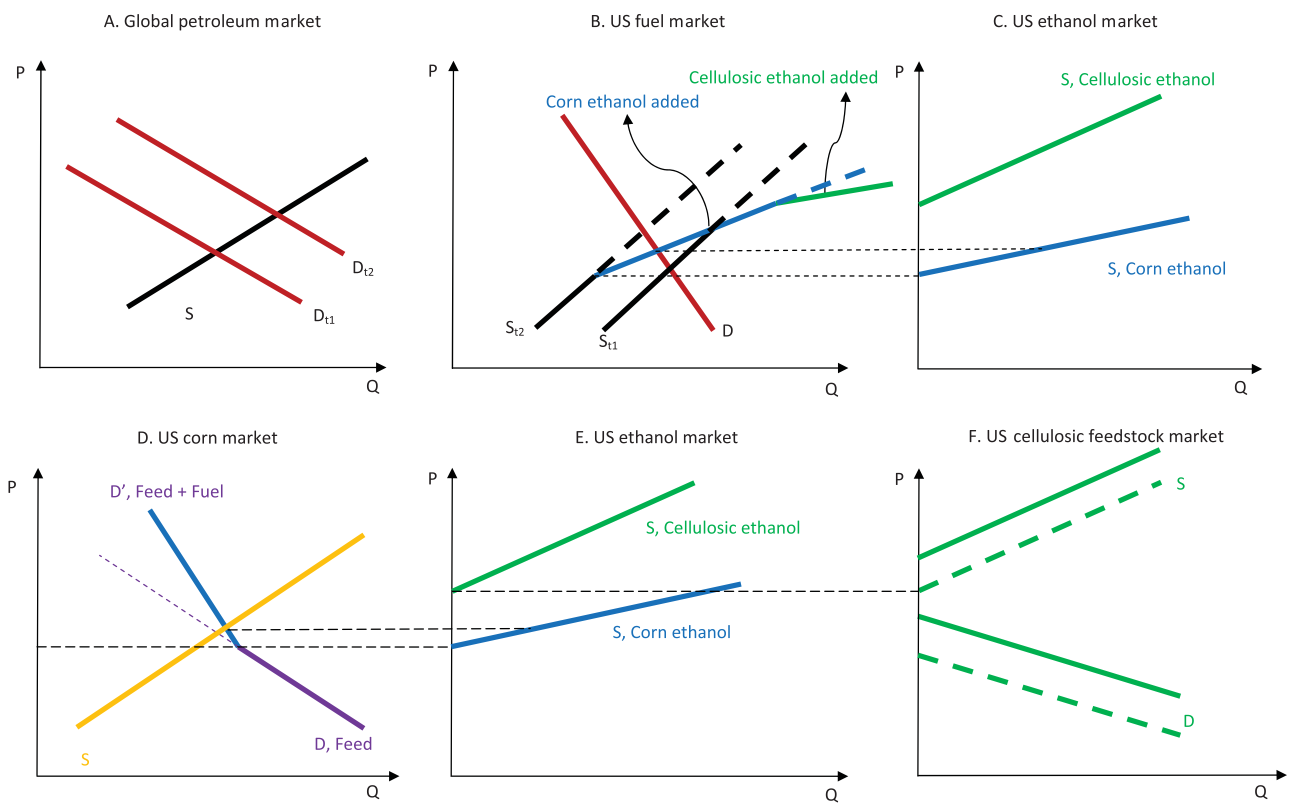

Figure 2. Interaction of commodity markets: petroleum, fuels, ethanol, corn, and cellulosic biomass crops. A. global petroleum market. B. US fuel market. C. US ethanol market. D. US corn market. E. US ethanol market. F. US cellulosic feedstock market.

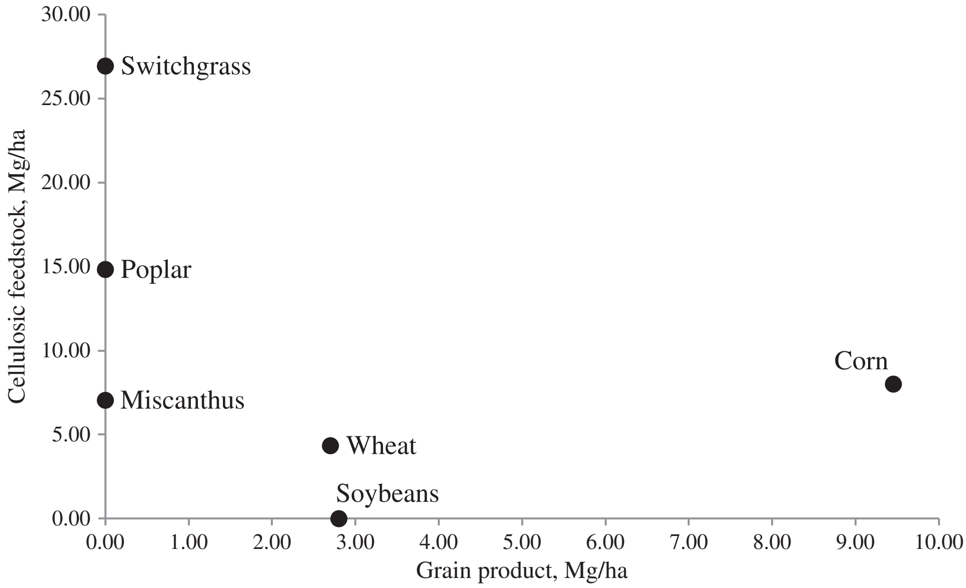

Figure 3. Examples of crop yields per unit land of grain products and crop residues usable as cellulosic feedstock. Corn, soybeans, and wheat yields are average US yields in 2007 from USDA (2008). The amounts of cellulosic feedstock from crops are estimated at a rate of 0.0215 Mg dry matter/bushel for corn (Wilcke and Wyatt 2002) and 69.76 × wheat yield(bushel/acre) + 1067.7 pound/acre for wheat (Kerstetter and Lyons 2001). The yields of dedicated energy crops in dry matter are 7.0 Mg/ha for miscanthus, 14.8 Mg/ha for popular, and 26.9 Mg/ha for switchgrass (BFIN 2008).

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 biofuel in turn increases the demand for corn to make biofuels in addition to livestock feed. In the corn grain market (Figure 2D), the biofuel need creates an epochal kink in demand for corn grain, which drives prices higher than would be otherwise with corn being mainly used as livestock feed. Meanwhile, no market currently exists for cellulosic biomass crops to make advanced ethanol (Figure 2F) because the highest price that biorefiners can afford to pay for biofuel feedstock at the current fuel price remains below what even the most efficient farmer can accept in supplying cellulosic feedstock. The market potential of cellulosic biofuel feedstock, however, could improve if new technology were developed that could either reduce the cost of converting cellulosic feedstock to advanced biofuels or increase the yield of biofuel feedstock. An advance in conversion technology would raise the price that biorefiners can afford to pay for feedstock, while a yield increase would reduce the price that farmers can accept for supplying biofuel feedstock.

Methods

What to grow is the most basic question faced by farmers. In this study, we assume that farmers' decisions on which crops to grow are driven by maximizing profit, given market prices of agricultural products and their production costs. A simple yet policy-relevant way to examine farmers' responses 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 the two. A special and interesting case is that the farmer can grow food crops with crop residues available as cellulosic feedstock for advanced biofuels. Figure 3 illustrates examples of yields per unit land of six crops that produce grain and/or cellulosic feedstock products. Switchgrass, miscanthus, and poplar yield only cellulosic feedstock. Soybean produces only food grain product. By contrast, corn and wheat are food crops that can provide both grain and cellulosic feedstock. 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.

Model setup

Consider a farmer with a total amount of A units of cropland available for agricultural production. Suppose the farmer allocates A_{food} units of cropland to a food crop and the remaining $A–A_{\text{food}}$ units of land to grow a dedicated cellulosic biomass crop. With a fixed output production function, per unit land produces a units of food grain for the food crop and b units of cellulosic feedstock for the dedicated energy crop. Assume the food crop also generates crop residues that can provide c units of cellulosic feedstock as a byproduct indistinguishable from that produced by the dedicated energy crop. Consequently, the total output of food grain, Q_{food}, is equal to aA_{food}; and the total output of cellulosic feedstock, $Q_{\text{cellulose}}$, is equal to $b(A–A_{\text{food}}) + cQ_{\text{food}}$. Given that not all crop residues from food grain production can be sustainably harvested due to conservation concerns, we

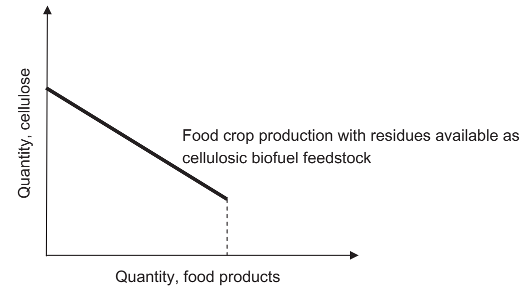

Figure 4. Possible combinations of cellulose and food production from different allocation of available land between the two crops. The solid line represents the possible combination of cellulose and food production, where residues from food crops are available and can be used as cellulosic feedstock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

introduce a harvesting ratio ε to capture the portion that is collectable. So, the total output of cellulosic feedstock that farmers can produce based on their land allocation decision can be expressed as $Q_{\text{cellulose}} = b(A - A_{\text{food}}) + c\varepsilon Q_{\text{food}}$.

Based on the model above, we can derive the production possibility frontier (PPF) of food grain versus cellulosic feedstock for the A units of available cropland as follows:

$$\frac{1}{b}Q_{\text{cellulose}} + \frac{1}{b}\left(\frac{b}{a} - c\varepsilon\right)Q_{\text{food}} = A. \tag{1}$$

As demonstrated in Figure 4, more cellulosic feedstock can be produced for given levels of food grain than otherwise would be possible if no crop residue were available as cellulosic feedstock from food grain production. As we will see, the potential joint production of both food grain and cellulosic feedstock from food crops has important implication for farmers' allocation of land between food and cellulosic biomass crops. Note that the straight-line PPF is the outcome of the assumption of a fixed output production function of land, which implies separable crop outputs. The negatively-slope 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. Otherwise, with a positive-slope PPF (i.e., $b < ac\varepsilon$), all cropland will be allocated to food crops for higher maximum yields of cellulosic feedstock, given maximum outputs of food grain.

Linking farmers' production decisions to the markets

With the above setting for agricultural production, the optimal allocation of cropland between food and cellulosic biomass crops depends on the relative profits per unit land devoted to each crop. The profit per unit land devoted to each crop is determined by the market price of crop product and its production cost. Denote P_{food} as the market price of food grain and $P_{\text{cellulose}}$ as the market price of cellulosic feedstock. Suppose the production cost per unit crop output is α for the food crop and β for the cellulosic biomass crop, both of which include harvesting costs. Also we assume that the production cost of cellulosic biomass crops include transportation cost. Further, we assume the harvesting cost per unit output of crop residues is γ, which is less than the production cost per unit output of cellulosic feedstock from the dedicated energy crop, β. Denote h as the transportation cost per unit output of crop residues. Mathematically, the farmer allocates land between both crops so as to maximize profit:

$$\begin{aligned}\pi = {} & P_{\text{food}}Q_{\text{food}} + P_{\text{cellulose}}c\varepsilon Q_{\text{food}} - \alpha Q_{\text{food}} \\ & - (\gamma + h)c\varepsilon Q_{\text{food}} + P_{\text{cellulose}}Q_{\text{cellulose}} - \beta Q_{\text{cellulose}}.\end{aligned} \tag{2}$$

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

$$\begin{aligned}\pi = {} & [P_{\text{food}} + P_{\text{cellulose}}c\varepsilon - \alpha - (\gamma + h)c\varepsilon]Q_{\text{food}} \\ & + (P_{\text{cellulose}} - \beta)Q_{\text{cellulose}}.\end{aligned} \tag{3}$$

Without losing generality, assume $P_{\text{food}} > \alpha$ and $P_{\text{cellulose}} > \beta$. Based on economic optimization, the optimal allocation of cropland between growing the food versus dedicated energy crops would be: 1) all land allocated to the food crop with crop residues available as cellulosic feedstock, if $[P_{\text{food}} + P_{\text{cellulose}}c\varepsilon - \alpha - (\gamma + h)c\varepsilon]/(P_{\text{cellulose}} - \beta) > b/a - c\varepsilon$; 2) all land allocated to the dedicated energy crop, if $[P_{\text{food}} + P_{\text{cellulose}}c\varepsilon - \alpha - (\gamma + h)c\varepsilon]/(P_{\text{cellulose}} - \beta) \quad b/a - c\varepsilon$; or 3) any point along the PPF as the farmer is indifferent on which crop to grow, if $[P_{\text{food}} + P_{\text{cellulose}}c\varepsilon - \alpha - (\gamma + h)c\varepsilon]/(P_{\text{cellulose}} - \beta) = b/a - c\varepsilon$.

The following condition must be satisfied for farmers to grow dedicated energy crops when they could also grow food crops with crop residues available as cellulosic feedstock:

$$\begin{aligned}& [P_{\text{food}} + P_{\text{cellulose}}c\varepsilon - \alpha - (\gamma + h)c\varepsilon]/(P_{\text{cellulose}} - \beta) \\ & \le b/a - c\varepsilon.\end{aligned} \tag{4}$$

This economic condition can further be reduced to:

$$\begin{aligned}P_{\text{cellulose}} \ge {} & \{a/[b - 2ac\varepsilon]\}[P_{\text{food}} - \alpha - (\gamma + h)c\varepsilon \\ & + (b/a - c\varepsilon)\beta],\ \textit{if}\ b/a > 2c\varepsilon.\end{aligned} \tag{5}$$

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

$$\begin{aligned}P^{\text{farmer}}_{\text{cellulose}} = {} & \{a/[b - 2ac\varepsilon]\}[P_{\text{food}} - \alpha - (\gamma + h)c\varepsilon \\ & + (b/a - c\varepsilon)\beta].\end{aligned} \tag{6}$$

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

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

This equation shows that the market price of cellulosic feedstock needs to cover at least the production cost of the dedicated energy crop, the forgone profit associated with the competing food crop, and the saving in production cost associated with the food crop that can be attributable to the cellulosic feedstock byproduct from crop residues compared to growing the dedicated energy crop. If there are no residues available from the food crop that can provide cellulosic feedstock, the corresponding farmers' MinAP would be:

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

which is smaller than otherwise possible.

The cellulosic feedstock market

The above section establishes the minimum feedstock price acceptable for farmers to grow dedicated energy crops when they could also grow food crops with a cellulosic crop residue byproduct. Farmers can increase their profits by allocating their cropland to dedicated energy crops rather than food crops only if the market price for cellulosic feedstock is greater than the minimum price required. The market price for cellulosic feedstock, however, depends on how much biorefiners can afford to pay for the feedstock compared to what farmers would accept. To biorefiners, the maximum price affordable for feedstock is determined by the market price of biofuels and their refinery costs.

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

Denote the market price of cellulosic feedstock $P_{\text{cellulose}}$, the biofuel yield of cellulosic feedstock r, the capital cost per unit biofuel yield k, and the cash operating cost per unit biofuel yield m. Biorefiners are willing to produce cellulosic biofuels only if:

$$P_{\text{biofuel}} - k - m - P_{\text{cellulose}}/r \geq 0, \quad (9)$$

i.e.,

$$P_{\text{cellulose}} \leq r(P_{\text{biofuel}} - k - m). \quad (10)$$

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

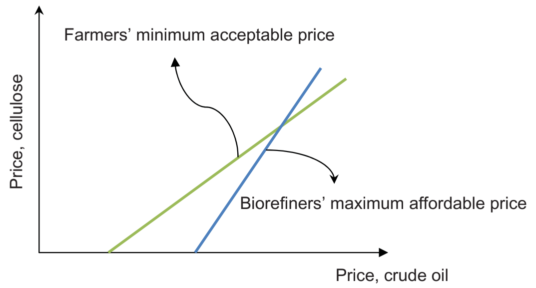

Figure 5. Demonstration of changes in estimated farmers' minimum acceptable price and biorefiners' maximum affordable price for cellulosic feedstock with the market price of crude oil. Farmers can consider converting land to grow cellulosic biomass crops only in the region between the two curves to the upper right of their intersection, where the biorefiners' maximum affordable price exceeds the farmers' minimum acceptable price.

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

As we can see, an increase in biofuel price or a decrease in biofuel production cost can raise biorefiners' MaxAP for cellulosic feedstock. Crude oil price and technology advance can affect the price of biofuels and their production costs, respectively, and thus influence biorefiners' MaxAP in the feedstock market.

Figure 5 depicts the relationship between crude oil 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. To the lower left of the intersection of the two curves, there are no cellulosic feedstock prices that are acceptable to both farmers and biorefiners, because there is no overlap between the areas defined by the farmers' MinAP curve and the biorefiners' MaxAP curve for different combinations of cellulosic feedstock and crude oil prices. To the upper right of the intersection of the two curves, the area between the farmers' MinAP curve and the biorefiners' MaxAP curve represents the region in which cellulosic feedstock prices are acceptable to both parties, given crude oil prices.

Empirical illustration

We employ the model above to empirically illustrate the production choices faced by farmers with market data and representative production parameters. 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 energy crops when they could also grow food crops with cellulosic feedstock available from crop residues. We also use this empirical model to examine the effect on farmers' production choices of the biomass assistance program and the new tax credit in the 2008 Farm Bill.

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 US 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 suggested 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 that is most widely grown in the US and will likely remain one of the major cash crops thatt 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 production.

In addition, advanced biofuels are proposed based on their multiple advantages, environmental benefits in particular, over corn grain-based ethanol biofuel. Given that corn residues (stover and cob) could be harvested as cellulosic feedstock, not all advanced biofuels have the same environmental benefits over those from corn grain. The comparison between switchgrass and corn can provide implication for evaluating the environmental sustainability of advanced biofuels and for biofuel policy.

Empirical equations and parameters

To highlight the linkages between the global petroleum market, US domestic ethanol market, and the cellulosic feedstock market, we estimate biorefiners' MaxAP for cellulosic feedstock as a function of crude oil prices via the relationship between ethanol biofuel price and crude oil price. Based on monthly US market data over the period of 2000–2006, Hurt et al. (2006) empirically identified the wholesale gasoline price as a function of crude oil price:

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

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 US$0.25/gal, we can derive:

$$P_{\text{ethanol}}(\$/\text{gal}) = \frac{2}{3} P_{\text{gasoline}}(\$/\text{gal}) + 0.51 + 0.25. \quad (13)$$

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

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

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

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

From Equation (6), farmers' MinAP for switchgrass as the dedicated energy crop when the competing crop is corn can be expressed as:

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

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

Results

Using 2007–2008 US 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 January 2007 to February 2008, farmers' MinAP for growing switchgrass rose from US$275/Mg to US$590/Mg (column 4) as the US average corn price rose from US$119.97/Mg to US$178.18/Mg. If we ignore the potential profit from corn residues as feedstock, farmers' MinAP for growing switchgrass would drop to US$100–161/Mg (column 5). In both cases, farmers' MinAP were greater than biorefiners' MaxAP for feedstock, although the rising crude oil price from US$0.31/L to US$0.54/L raised biorefiners' MaxAP from US$21/Mg to US$69/Mg (column 6). This price gap illustrates that at the current conversion technology and market conditions, switchgrass as a dedicated energy 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 46% 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 3–8 times the production cost of switchgrass. Even if we assumed away the profit of corn grain production at low corn prices, the cost-saving from corn residue as a byproduct for feedstock still remained an important cost component comparable to the production cost of switchgrass. In contrast, what biorefiners could afford to pay for cellulosic feedstock 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 favors producing corn rather than switchgrass on cropland for typical production conditions.

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

Parameter	Unit[a]	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 US average annual corn yield has reached around 150 bushel/acre (USDA National Agricultural Statistics Service 2008).
Production cost, α	US$/Mg (US$/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. (2007) used stover mass to grain mass ratio of 1:1, or dry weight harvest index (HI) of 0.5 reported by (Gupta et al. 1979), and a dry mass of 21.5 kg/bushel of corn assumed by Wilcke and Wyatt (2002). Sheehan et al. (2004) used dry mass of 25.4 kg/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 stover could be collected due to equipment constraints.
Residue harvesting cost, γ	US$/Mg (US$/US ton)	31.61 (28.74)	2002	Graham et al. (2007) estimated corn stover collection cost as a function of stover collected in the field, including US$7.17/ Mg nutrient replacement cost: y(US$/Mg) = 50.65 × (Mg/ha)$^{-0.41}$ for collected stover $x > 3.3$ Mg/ha.
Transportation cost, h	US$/Mg (US$/US ton)	9.51 (8.65)	2007	Duffy (2008) estimated transportation to plant cost at US$8.65/ ton in Iowa, which translates into US$0.14/gal assuming an ethanol yield of 60 gal/ton.
Switchgrass yield, b	Mg/ha (Mg/acre)	9.9 (4)	2001	Duffy (2008) assumed switchgrass yield of 4 ton/acre in Iowa; Perrin et al. (2008) summarized alternative estimates of switchgrass yield, including 6.4 Mg DM/ha (2.59 dry ton/ acre) based on commercial-scale field data from North Dakota to Nebraska, 7.6 Mg DM/ha (3.08 dry ton/acre) (Duffy and Nanhou 2002), 9.0 Mg DM/ha (3.65 dry ton/acre) (Epplin 1996), 11.1 Mg DM/ha (4.50 dry ton/acre) (Hallam et al. 2001).
Production cost, β	US$/Mg (US$/ US ton)	75 (68)	2007	Collins (2007). Perrin et al. (2008) summarized alternative estimates of the production cost of switchgrass in 2003 dollars, including US$63.83/Mg DM, US$95.90/Mg DM (Duffy and Nanhou 2002), US$29.35 (Epplin 1996), and US$72.52/Mg DM (Hallam et al. 2001).
Capital cost, k	US$/l (US$/gal)	0.15 (0.55)	2007	Collins (2007).
Cash operating cost, m	US$/l (US$/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 L/Mg, or 66.3 gallon/Mg (Sheehan et al. 2004).

Note: [a]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 L for liquid in the USA.

The effect of the 2008 Farm Bill

The farm bill introduces policy incentives to both biorefiners and farmers that can change the calculations given above. This analysis only considered a tax credit of US$1.01/gallon for cellulosic ethanol refiners (Section 15321) and a cost-sharing program matching US$1 for each US$1 per US ton provided by biorefiners up to US$45/US ton for collection, harvest, storage, and transportation of biomass crops (Section 9011). With the incentive from the cost-sharing program, we substracted the maximum limit of US$45/US ton from the total of transportation and production costs. We assumed that corn residue is not eligible for the cost-sharing subsidy.

Results show that the cost-sharing program could reduce farmers' MinAP to US$122–437/Mg for growing switchgrass instead of corn (column 7). The tax credit of US$1.01/gallon for biorefiners could raise biorefiners' MaxAP from US$21–69/Mg to US$88–136/Mg for the same range of crude oil prices (column 9). Together, the tax credit coupled with cost-sharing could reduce the gap between biorefiners' MaxAP and farmers' MinAP for cellulosic feedstock. It is worth noting that the cost-sharing subsidy is only for the first two years when a farmer participates. After that, farmers' MiniAP would bounce back up to the level without the cost-sharing subsidy.

Figures 6 and 7 graphically show changes of farmers' MinAP and biorefiners' MaxAP with the prices of corn and crude oil. In Figure 6, when crude oil price went up and raised 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

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], US$/L (US$/bbl)	2. Corn price[b], US$/Mg (US$/bushel)	3. Forgone profit of corn grain, US$/Mg	4. Farmers' MinAP[c], US$/Mg	5. Farmers' MinAP with corn residues unavailable, US$/Mg	6. Biorefiners' MaxAP, US$/Mg	7. Farmers' MinAP with farm bill subsidies[d], US$/Mg	8. Farmers' MinAP with corn residues unavailable and farm bill subsidies, US$/Mg	9. Biorefiners' MaxAP with farm bill subsidies, US$/Mg
01/07	0.31 (49.51)	119.97 (3.05)	127.74	274.80	100.27	20.92	122.31	50.77	87.58
03/07	0.35 (56.26)	134.91 (3.43)	208.65	355.71	115.94	29.95	203.21	66.44	96.61
05/07	0.39 (61.44)	137.27 (3.49)	221.42	368.48	118.42	36.87	215.99	68.92	103.53
07/07	0.44 (70.72)	130.59 (3.32)	185.23	332.29	111.40	49.28	179.79	61.90	115.93
09/07	0.46 (72.77)	129.41 (3.29)	178.84	325.90	110.17	52.02	173.41	60.67	118.68
11/07	0.54 (85.52)	134.91 (3.43)	208.65	355.71	115.94	69.06	203.21	66.44	135.72
02/08	0.54 (85.80)	178.18 (4.53)	442.84	589.90	161.32	69.43	437.41	111.82	136.09

Notes: [a] Crude oil prices are measured by the US refiners' acquisition costs of imported crude oil in unit of $/barrel, which are from the US Energy Information Administration (2008); crude oil prices are converted to SI unit with 1 barrel = 158.99 L in the US for petroleum.
[b] Corn prices are from USDA National Agricultural Statistics Service (2008), which are 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 $75/Mg dry matter without Farm Bill subsidy and $25.5/Mg dry matter with Farm Bill subsidy assuming $49.5/Mg (or $45/US ton) in maximum paid by the US government to share the cost; forgone profit of corn grain depends on the market price of corn grain, and is calculated in column 4; and forgone profit of corn residue is estimated at around $72/Mg dry matter. Corn residue is assumed ineligible for the farm bill biomass cost-sharing subsidy of up to $49.5/Mg (or $45/US ton) provided by the US government.
[d] This analysis only considers a tax credit of $1.01/gallon for cellulosic ethanol refiners (Section 15321) and a biomass cost-sharing program matching $1 for each $1 per US ton provided by biorefiners up to $45/US ton for costs of collection, harvest, storage, and transportation (Section 9011) in the 2008 Farm Bill (HR 2419).

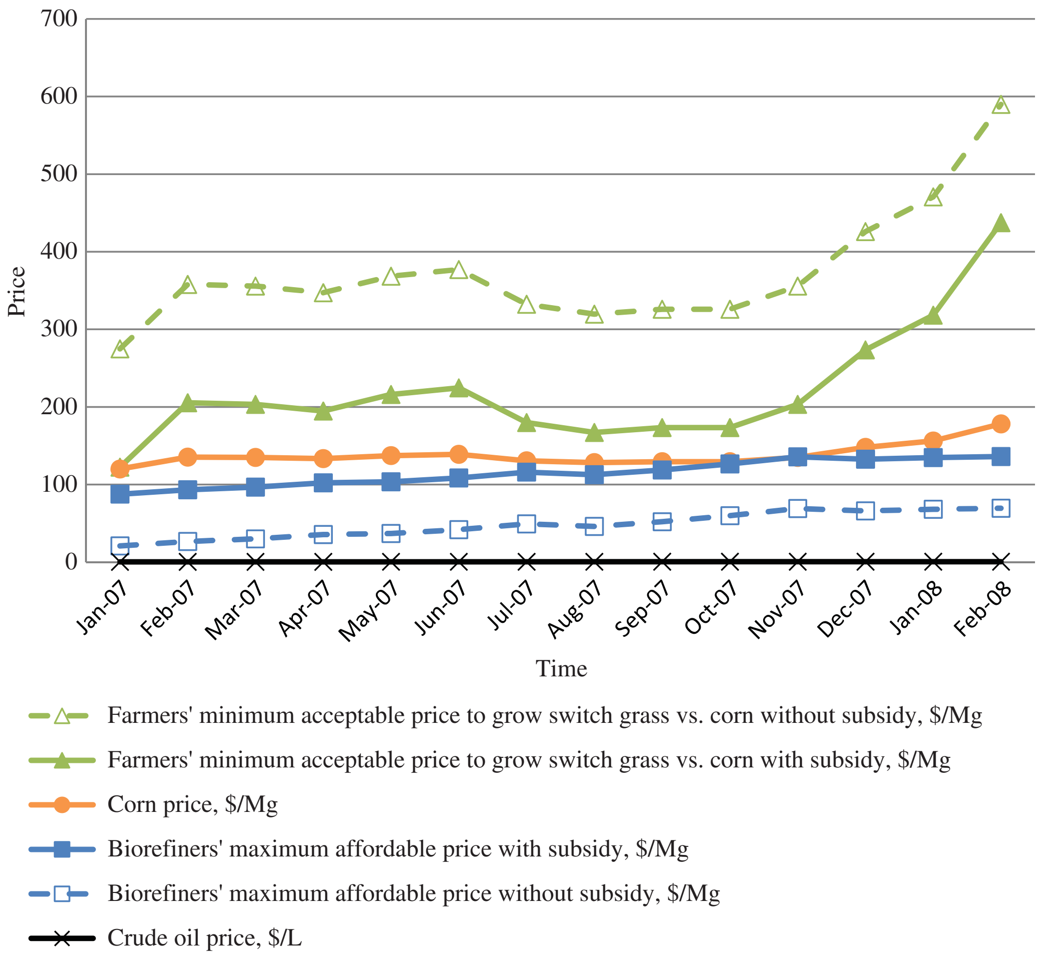

Figure 6. Trends in crude oil prices, corn prices, and empirical estimates of farmers' minimum acceptable prices and biorefiners' maximum affordable prices for switchgrass. With rising crude oil prices, farmers' minimum acceptable prices increase more quickly compared to biorefiners' maximum affordable prices.

increased as well. These results can be attributed to the increased profits of growing corn and producing ethanol due to rising prices for corn and crude oil. While a higher price could be offered by biorefiners for feedstock, farmers' MinAP increased more quickly (Figure 7). Consequently, the gap widened between the prices that farmers would accept and what biorefiners could afford to pay for cellulosic feedstock in the market. This larger gap in cellulosic feedstock prices implies that for farmers to voluntarily grow switchgrass instead of corn would require dramatic technological advances to reduce the cost of cellulosic ethanol refining and/or the cost of switchgrass production.

Conclusion

This analysis has important policy implications. While agriculture holds the promise to supply sufficient feedstock for producing advanced biofuels, how farmers would respond in providing the feedstock becomes critical. The importance of this issue is justified by its relevance to two inversely related policy questions. If dedicated energy crops compete with food crops for cropland, how could policy-makers design better biofuel policy to promote energy independence and sustainable biofuels without raising food prices? On the other hand, if dedicated energy crops cannot compete at all with food crops for cropland, where will dedicated energy crops be grown other than on cropland to supply a significant portion of US fuel needs? 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 cropland. Yet, how farmers' decisions driven by the markets would affect biofuel supply and its environmental implication have received little attention from the science community.

In this study, we showed how the biofuel economy links the global petroleum market to US ethanol biofuel markets and the US ethanol biofuel market to US agricultural markets for corn and dedicated energy crops in particular. We further developed an economic model

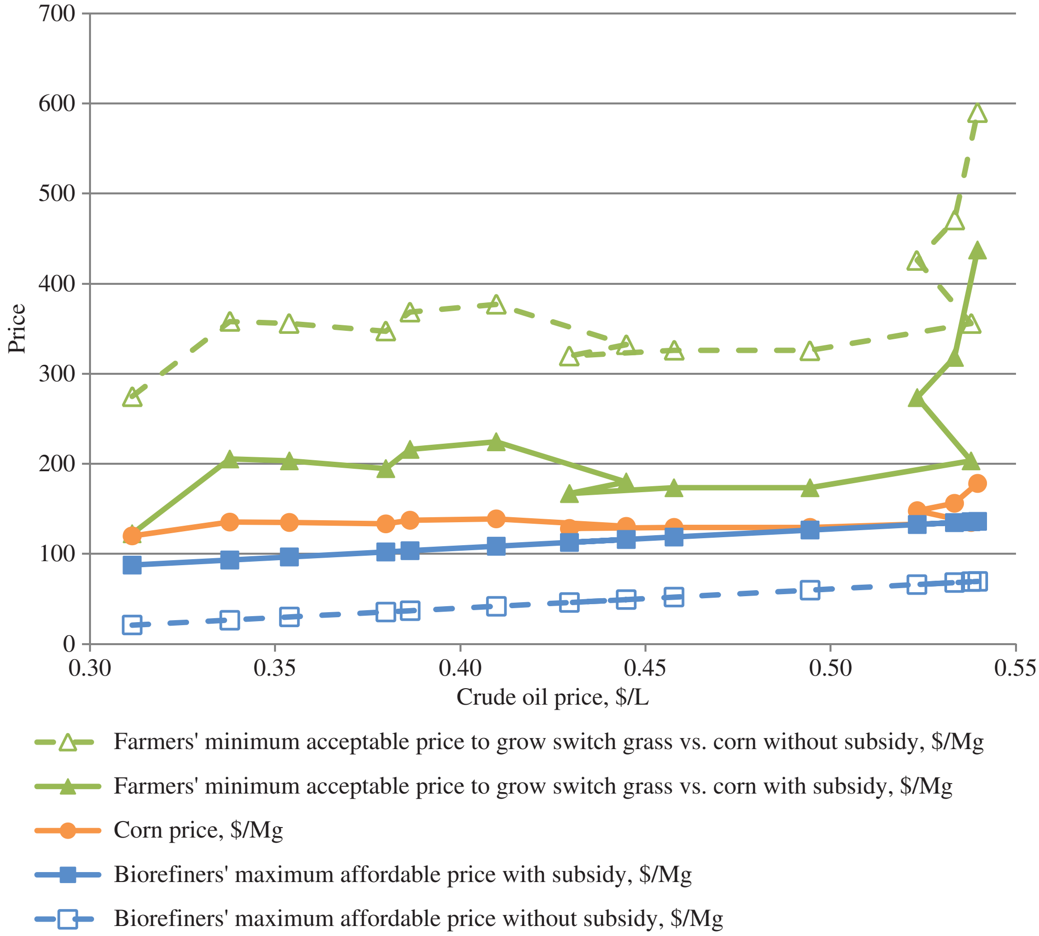

Figure 7. Empirical estimates of farmers' minimum acceptable price and biorefiners' maximum affordable price for switchgrasss different crude oil prices. Farmers can consider converting land from growing corn to switchgrass only in the area where the biorefiners' maximum affordable price exceeds the farmers' minimum acceptable price.

characterizing the production choices faced by farmers that are linked to markets and market integration from petroleum to agricultural products. The economic model shows that for cropland currently in food production, the minimum price required to compensate farmers for growing dedicated energy crops rather than food crops with crop residues available as cellulosic feedstock should cover at least three cost components: the production costs of the dedicated energy crops, the forgone profit otherwise available by growing the food crops, and the cost-savings in providing cellulosic feedstock when crop residues from food crops production are available as a cellulosic feedstock byproduct. The model establishes that dedicated energy crops could compete with food crops for cropland 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 at the current conversion technology is mainly determined by petroleum price, while the farmers' minimum acceptable price is largely affected by the prices of competing food crops.

Based on the economic model, we empirically illustrated the production choice of switchgrass versus corn, using parameters from 'Corn Belt' states and price data from 2007–2008. The results show that at the current technologies for producing switchgrass and converting cellulosic biomass to ethanol, the biofuel prices supported by crude oil prices are still insufficient to compensate for growing switchgrass instead of corn on cropland. Indeed, the empirical example demonstrated that the maximum price that biorefiners could afford to pay for cellulosic feedstock only covered a portion of the production cost of switchgrass, while the major cost component for growing switchgrass instead of corn, the opportunity cost of giving up corn production was 3–8 times the production cost of switchgrass. The price gap between farmers and biorefiners for cellulosic feedstock would still exist, although it could be reduced under the new subsidies in the 2008 Farm Bill. This empirical example suggests that a large increase in the yield of dedicated energy crops relative to corn would lower both the opportunity cost and the production cost of growing dedicated energy crops such that the minimum price required to compensate farmers would be reduced. This analysis is particularly relevant to 'Corn Belt' states, the major corn-growing areas in the US, that are at the forefront of much debate and biofuel policy.

Given its use for both feed and grain-based ethanol, corn likely remains an economically attractive crop for cropland. Even if advanced biofuels become economically competitive within the next 10 to 15 years (Stephanopoulos 2007), corn would still stay in fields since corn residue is a readily available feedstock for advanced ethanol biofuel. Indeed, the empirical example showed that farmers' MinAP for growing switchgrass would be 2.7–3.7 times higher without Farm Bill subsidy or 2.4–3.9 times with Farm Bill subsidy when corn residue is economically usable as feedstock to make cellulosic biofuel. This high economic threshold, on one hand, would further discourage growing switchgrass instead of corn on cropland, on the other hand, the added profit from using corn residues to make advanced biofuels would stimulate corn production for not only grain-based ethanol and feed but also advanced biofuels. The continuous, possibly expanding, corn production would raise the same issues for advanced biofuels as those for corn grain-based ethanol: 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, as suggested here, switchgrass cannot generally compete with corn for cropland, especially in traditional corn-growing states (such as Iowa, Illinois, and Indiana), where switchgrass will likely be grown becomes critical to supplying a significant portion of US fuel needs. Producing cellulosic biomass crops may be economically attractive on marginal lands that have lower opportunity costs than prime cropland. As marginal or idle lands are often also vulnerable to soil erosion or best used to provide ecosystem services, such as wildlife habitat and carbon sequestration, 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 initiatives.

Recently, research efforts have begun to analyze the potential supply of cellulosic feedstock (Duff and Nanhou 2002; Hipple and Duffy 2002; Perlack et al. 2005; Jensen et al. 2007; Khanna et al. 2008). For example, Jensen et al. (2007) conducted a survey in Tennessee to analyze farmers' willingness to supply switchgrass for energy production. They found that higher net farm income per unit land had a negative effect on the share of farmland that farmers would be willing to convert. This result is largely consistent with our findings. Our study further contributes to the literature by identifying the cost components that risk-neutral farmers would consider for converting land, and how the absence of cellulosic ethanol as well as feedstock market is economically and quantitatively related to the behaviors of farmers and biorefiners.

Several caveats need to be noted for our analysis. First, we assume farmers are profit-maximizing and risk-neutral. While profit-maximizing may be a reasonable assumption, farmers may be risk-averse or risk-seeking. Our assumption of being risk-neutral, however, sets up a benchmark from which one can examine the effect of risk preference on the compensated prices, such as the option value of maintaining corn production for risk-averse farmers or the option value of growing energy crops instead of traditional food crops for risk-seeking farmers. To incorporate these risk issues is beyond the scope of the present paper. Second, the reliability of the empirical estimates of biorefiners' MaxAP and farmers' MinAP depends on the accuracy of the parameters used for calculation. As justified in Table 2, we believe that these technical and economic parameters represent the best estimates for the 2007–2008 period model. Those estimates can be improved as more accurate parameters reflecting technology improvement and policy updates become available.

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