Crop-Based Biofuel Production under Acreage Constraints and Uncertainty

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CROP-BASED BIOFUEL PRODUCTION UNDER ACREAGE CONSTRAINTS AND UNCERTAINTY

The Energy Independence and Security Act of 2007 (EISA) was signed into law in December 2007. This act mandates the use of 36 billion gallons of biofuels by 2022, of which 15 billion gallons must come from corn-based ethanol and 21 billion from advanced biofuels, including 1 billion gallons of biomass-based diesel and 16 billion gallons of cellulosic biofuels. This new mandate means a significant increase in current biofuel production levels. Corn-based ethanol production was 1.63 billion gallons in 2000, and by the end of 2007 production reached 7.23 billion gallons (see http://www.ethanolrfa.org/industry/statistics/). This increase in corn ethanol production has led to record high nominal corn prices in 2008. Competition for acreage has transferred some of the demand pressure experienced in corn markets to soybean and hay markets; the prices of these commodities have increased substantially as well.

EISA does not specify how the mandates are to be met but states that “the Administrator shall promulgate rules establishing the applicable volumes…no later than fourteen months before the first year for which the applicable volumes will apply.” These mandates, and the methods used to ensure that they are met, will have a profound impact on agricultural markets and agricultural land use patterns in the United States. The purpose of this study is to examine the incentives needed to ensure these mandates are met, and to project the impact of these incentives on U.S. agriculture.

The model we present is based on the assumption that decisions influencing biofuel production can be predicted if one understands the optimal decisions of rational agents in the economy. Farmers will make rational planting decisions based on expected market prices and rotational constraints. Further, they will recognize that land used to produce the raw material for biofuels has an opportunity cost. Investors who build biofuel plants will do so only if they can expect a risk-adjusted return at a par with or superior to investments made elsewhere in the economy.

We take each key decision just described and use parameters and data from the literature to model the decision and the market forces guiding the decision. The resulting sub-models are then combined within a rational, dynamic, stochastic general equilibrium model of U.S. crop and biofuel markets calibrated to reflect actual market conditions as of December 2007. We evaluate the likely response of market participants to changes in incentives such as shocks to crude oil prices and biofuel credits or subsidies.

Previous Literature

Rozakis and Sourie (2005) develop a partial equilibrium linear programming model of the French biofuels sector. Their goal is to make policy suggestions regarding the efficient allocation of land to bioenergy crops and efficient tax exemptions. Zhang, Vedenov, and Wetzstein (2007) develop a structural vector autoregressive model to examine if producers of methyl tertiary butyl ether (MTBE) engaged in limit pricing to prohibit growth of ethanol as a gasoline additive. They find support for this hypothesis, concluding that the U.S. ethanol industry is vulnerable to the import of less expensive sugarcane-based ethanol. Elobeid et al. (2007) provide the first comprehensive model of the bioeconomy, and later Tokgoz et al. (2007) fill some gaps associated with the first article, including work on the equilibrium prices of co-products of the biofuel industries, most importantly distillers grains.

The latter two studies use a world agricultural model from the Food and Agricultural Policy Research Institute (FAPRI) to determine the potential size of the corn-based ethanol sector and describe how it will affect crop and livestock markets. The authors assume that investment in each biofuel sector will occur until expected profit is zero. They do so by calculating the break-even corn prices that drive margins on new corn-based ethanol plants to zero and then simply assume that this corn price will be the market-clearing price. They then calculate the size of the biofuel sector that drives the market to this price and evaluate the impact of this break-even corn price on U.S. and world agriculture. They ignore risks associated with investments in biofuel plants.

Our model enhances the literature by incorporating awareness of risk into the investor's decision problem. Returns to biofuel production are uncertain because of variability in crop yields and in the crude oil price, which determines the price of gasoline, ethanol, and other transportation fuels. By incorporating the stochastic nature of these variables into the model, we can compare the endogenous risk-adjusted return to different types of biofuel production and determine which will be attractive to investors. Accounting for risk-adjusted returns is more realistic, and a stochastic model delivers probability distributions over future commodity prices and returns of the biofuel industry. In addition, we model the bioeconomy in a general equilibrium framework, allowing us to consider an array of issues such as the link between the market prices for biofuel feedstocks and risk-adjusted investment decisions that are not appropriate in a partial equilibrium setting such as that used in the Elobeid et al. and Tokgoz et al. studies. To the best of our knowledge, this is the first attempt to model the interaction between the U.S. energy and agricultural sectors in a theoretically consistent way.

The Economy

The economy we model consists of farmers; agricultural commodity demanders, who will use the commodity as an input either in producing food or energy; and investors, who can choose among four different investment alternatives. An investor can choose to invest in a corn ethanol plant, a biodiesel plant, a cellulosic ethanol plant, or simply choose to invest in the "market portfolio." The collective actions of these investors will affect future commodity demand, as the plants take time to build and come online. We recognize that as technology advances, cellulosic biomass may be converted into another form of biofuel, such as butanol. However, for the purpose of this study, we consider cellulosic material being converted into ethanol since this is the best information we have at this time. Fundamental uncertainty in the economy comes through uncertainty in agricultural commodity yields and crude oil prices. We assume these two random variables are independent with joint probability distribution $f\left(\zeta^t, \varepsilon^t\right) = g\left(\zeta^t\right) h\left(\varepsilon^t\right)$, where ζ^t is a vector of yield realizations, and ε^t is the realization of crude oil prices. Assuming independence of commodity yields and crude oil prices is equivalent to assuming that domestic biofuel production will not influence world crude oil prices. These variables produce uncertainty in agricultural commodity prices, returns to biofuel production, and in other energy prices such as that of gasoline, diesel, ethanol, and biodiesel. The timeline of decisions in the economy, as shown in figure 1, unfolds as follows. At time zero, governmental policy on taxes and subsidies are set, the biofuel capacity currently existing is known, and agents within the economy have beliefs about the distributions of crude oil prices and crop yields into the future. At time period one, investors plan biofuel expansion or contraction. Many years elapse between time periods one and two, with farmers making crop allocation decisions each year. These allocation decisions are driven by maximization of expected profits, rotational constraints, and land scarcity. The decisions show some interesting cyclical patterns, as farmers tend to favor soybeans in years following years in which a large number of corn acres are grown. We need these annual decisions because we calibrate the model to actual market data for late 2007. However, the short run results are not otherwise useful because the economically relevant interactions occur after plants are built, and this can take several years. Therefore, we do not present results for these intermediate years, and we allow time period two to represent the long-run equilibrium in our model.

Commodity Supply

The crops available are heterogeneous in their intertemporal effects on soil productivity; some enhance soil fertility while some degrade it. Producers weigh the benefit of continuously planting high-value crops, such as corn, against the cost of decreased soil fertility in the next planting season. In addition, expected harvest-time price plays a crucial role in agricultural supply.

Under the rational expectations hypothesis, producers form expectations about the current season's aggregate production level, and harvest-time price for each crop. The actions of producers, therefore, cause the production and harvest-time prices to be noisy realizations of their ex-ante expected values (Muth 1961). Eckstein (1984) develops a dynamic model in which producers make land allocation decisions in each period and the equilibrium is defined by rational expectations. Eckstein's model incorporates past land allocation decisions into the production functions, and uses dynamic programming to determine the path of equilibrium land allocations and price vectors. Several empirical models have borrowed from the basic structure of Eckstein's work (Aradhyula and Holt 1989; Orazem and Miranowski 1994; Tegene et al. 1988). Many other articles consider problems that focus on allocating acreage heterogeneous in productivity (Wu and Adams 2001). We model commodity supply in the spirit of both Eckstein and Muth, because scarcity of land is key in determining the potential of biofuel industries.

In the model, a single representative producer has an endowment of one unit of land. This unit of land is representative of the productivity of U.S. cropland in terms of its yield potential and its rotational constraints. The producer takes both output prices and a cost function as given. Output prices and yields are uncertain, but all agents in the economy know the joint distribution among prices and yields. Faced with these, the producer allocates land in the beginning of the period to three different crops, corn, soybeans, and switchgrass, in each period *t*. We could give the farmer the ability to plant miscanthus and qualitatively the results would remain the same; only the magnitude of the impact of land-intensive cellulosic crop production would change. We chose switchgrass, in part, because we have scenarios in which cellulosic biofuel production is not viable, and it is easy to imagine a market for switchgrass in the absence of biofuel production. It simply would be marketed as hay for cattle consumption. Miscanthus currently has no such alternative use. We index the crops as follows: corn, i = 1; soybeans, i = 2; and switchgrass, i = 3. In period *t*, the producer's profit is given by

$$\tilde{w}_t = \sum_{i=1}^{3}\sum_{j=1}^{3} \tilde{p}_i^t \tilde{Q}_i(\pi_{ij}^t, s^{t-1}, \tilde{\zeta}_{it}) - c_i(\pi_{ij}^t)$$

where $\tilde{p}_i^t$ is crop i's output price in time *t*. The quantity produced of crop i is $\tilde{Q}_i(\cdot)$. The state variable, $\mathbf{s}^{t-1}$, imposes a yield penalty associated with continuous cropping practices. The nominal cost function for crop *i* is $c_i\left(\pi_i;\Theta_i\right)$, where Θ_i is a vector of parameters defining each crop's nominal cost function. Thus, it does not account for the opportunity cost of the land. The proportion of land allocated to crop *i* at time *t* that was in crop *j* last year is π_{ij}^t. Crop yields are a function of the crop planted last year, the proportion of land endowment in crop *i*, and time, in addition to a random error term. Production technology is characterized by $\frac{\partial c_i}{\partial \pi_{ij}^t} > 0$. The producer is risk neutral in profit, and thus wishes to maximize the present value of current and future expected profit subject to land constraints. To this end, she chooses a sequence of land allocation vectors, $\left\{\pi^t\right\}_{i=1}^{\infty}$, to solve her problem:

$$\max_{\left\{\pi^t\right\}} \sum_{t=0}^{\infty} \beta^t E\left[\tilde{w}_t\right] \quad s.t. \ \sum_{i=1}^{n}\sum_{j=1}^{n} \pi_{ij}^t = 1 \quad \forall \ t = 1, \ 2, \ldots$$

$$\pi_{1i}^t + \pi_{2i}^t + \pi_{3i}^t = \pi_i^{t-1} \quad \forall \ \left(i, \ t\right)$$

$$\pi_{i1}^t + \pi_{i2}^t + \pi_{i3}^t = \pi_i^t \quad \forall \ \left(i, \ t\right)$$

$$\pi_{ij}^t \geq 0 \qquad \forall \ \left(i, \ j, \ t\right)$$

$$\pi_{ij}^0 \quad \text{given}$$

and where

$$\pi^t = \begin{bmatrix} \pi_{11}^t & \pi_{21}^t & \pi_{31}^t \\ \pi_{12}^t & \pi_{22}^t & \pi_{32}^t \\ \pi_{13}^t & \pi_{23}^t & \pi_{33}^t \end{bmatrix}.$$

The total proportion of crop *i* planted in time *t* is π_i^t. We can best think of the constraints as a mechanism accounting for the law of motion of the land allocations. The necessary conditions for optimality follow.

Euler Equations:

$$\pi_{ij}^{t} : E_t\left[\left(-\tilde{p}_1^{t}\frac{\partial\tilde{Q}_1}{\partial\pi_{1j}^{t}}+\frac{\partial c_1}{\partial\pi_{1j}^{t}}+\tilde{p}_i^{t}\frac{\partial\tilde{Q}_i}{\partial\pi_{ij}^{t}}-\frac{\partial c_i}{\partial\pi_{ij}^{t}}\right)\right]+\beta E_t\left[\left(-\tilde{p}_1^{t+1}\frac{\partial\tilde{Q}_1}{\partial\pi_{1j}^{t+1}}+\frac{\partial c_1}{\partial\pi_{1j}^{t+1}}+\tilde{p}_i^{t+1}\frac{\partial\tilde{Q}_i}{\partial\pi_{ij}^{t+1}}-\frac{\partial c_i}{\partial\pi_{ij}^{t+1}}\right)\right]=0$$

$i \neq 1$

$$E_t\left[\left(\tilde{p}_i^{t}\frac{\partial\tilde{Q}_i}{\partial\pi_{ij}^{t}}-\frac{\partial c_i}{\partial\pi_{ij}^{t}}\right)+\beta\left(\tilde{p}_i^{t+1}\frac{\partial\tilde{Q}_i}{\partial\pi_{ij}^{t+1}}-\frac{\partial c_i}{\partial\pi_{ij}^{t+1}}\right)\right]=E_t\left[\left(\tilde{p}_1^{t}\frac{\partial\tilde{Q}_1}{\partial\pi_{1j}^{t}}-\frac{\partial c_1}{\partial\pi_{1j}^{t}}\right)+\beta\left(\tilde{p}_1^{t+1}\frac{\partial\tilde{Q}_1}{\partial\pi_{1j}^{t+1}}-\frac{\partial c_1}{\partial\pi_{1j}^{t+1}}\right)\right] \quad i\neq 1$$

These necessary conditions require the producer to equate the marginal net benefit of growing soybeans (switchgrass) to the marginal benefit of growing corn. The marginal benefit is realized through the crop's marginal contribution to utility this period and the next time period. The contribution to next period's utility is through the benefits of crop rotation on next period's yield. There are nine Euler equations in nine unknowns. Given our assumptions about production technology and preferences, we are guaranteed a solution to the farmer's acreage allocation problem, and we can solve for a farmer's expected utility maximizing acreage allocation decisions. After substituting these acreage allocation decisions into the production functions, we recover the period *t* commodity supplies for each crop given the random yield shock, ζ^t. Notice from the Euler equations that both price and the nominal cost of producing other crops are important in determining a crop's supply function:

$$\tilde{Q}_i^{t,s}\left(\tilde{\mathbf{p}}^t;\Theta,\tilde{\zeta}^t,s^{t-1}\right)=\sum_{j=1}^{3}s_{ij}^{t-1}\tilde{\zeta}_i^t\pi_{ij}^{t*}(\cdot).$$

Commodity Demand

Demand for agricultural commodities comes from two primary sources, food and energy. The commodities are used as food through utilization as animal feed and for direct human consumption in the form of vegetable oils or cereal grains. Additionally, they are used to create biofuels (ethanol or biodiesel). We do not specify the optimization problem in these sectors; we only consider a reduced-form aggregate demand function for each commodity, which captures demand derived from both food uses and energy uses. We assume, though, that aggregate demands for the commodities are the result of many competitive firms in these sectors maximizing profits using the commodities as inputs in their production processes. Demand for commodity *i* in period *t* is given by $\tilde{Q}_i^{t,d}\left(\tilde{\mathbf{p}}^t, n_i^t\right)$, and is a function of the stochastic vector of current commodity prices, $\tilde{\mathbf{p}}^t$, and the number of biofuel plants n_i^t in operation at time *t*. We assume the aggregate demand for each commodity, *i*, has the expected properties, $\frac{\partial Q_i^{t,d}\left(\tilde{\mathbf{p}}^t, n_i^t\right)}{\partial p_i} < 0$ and $\frac{\partial Q_i^{t,d}\left(\tilde{\mathbf{p}}^t, n_i^t\right)}{\partial n_i} > 0$. We do not make a priori assumptions about the sign of the cross-price derivatives in the conceptual model. It is conceivable for the commodities to be either substitutes or complements, especially with respect to livestock feed, and we leave this to be established in an empirical specification later. Since biofuel plants take time to build and come online, the number of plants in existence for a given crop year is fixed. Hence, the current year's demand curve for these commodities is fixed and known to all agents in the economy for given yield shock realizations and past crude oil price realizations. Later, when we implement the model, we will specify functional forms for the demand equations.

The Investors

The final agents of note in our economy are the potential investors in biofuel plants. In each period, investors can choose among four different investments: a corn ethanol plant, a biodiesel plant, a switchgrass ethanol plant, or in a market portfolio.[1] The market portfolio is a portfolio of S&P 500 stocks, which gives the investor an option if no biofuel investment seems attractive. If an investor chooses to build a biofuel plant, it will not come online until the end of the period.

We assume investors seek the largest risk-adjusted return on investment possible, and there exists a riskless asset in the economy returning RFR, the risk-free rate. The investors use the Capital Asset Pricing Model (CAPM) to evaluate investment alternatives (Sharpe 1964). The investors calculate the security market line to give a measure of the expected (required) rate of return for an asset, *a*:

$$Required\ Return_a = RFR + \beta_a \left(R_M - RFR \right)$$

where *M* is the market portfolio, R_M is the expected return of the market portfolio, σ_M^2 is the variance of market portfolio returns, R_a is the return of asset *a*, and

$\beta_a = \dfrac{Cov\left(R_a, R_M\right)}{\sigma_M^2}$. Armed with estimates of these parameters, an investor can calculate the difference in expected return and required return of asset *a* as calculated with the CAPM. The rational investor chooses the project with the highest excess returns over the required return. However, if the difference is negative for each of the biofuel plants, an investor will choose to invest in the market portfolio.

Returns to Biofuel Production

Input costs in each sector are determined by feedstock costs and other production and capital costs. We do not consider technological advancement in the production of biofuels. We take technology as given and consider how the bioeconomy will develop over time. Therefore, non-feedstock production costs and capital costs are exogenous.

Feedstock costs are the most important input cost to biofuel production, and determined by market equilibrium. The per gallon annual rate of return to producing biofuel of type *a* is $R_a = \frac{q_a{}^t\left(\varepsilon^t\right)}{k_a\left(\zeta^t\right)}$, where $q_a{}^t\left(\varepsilon^t\right)$ is the effective price received by the plant for its product, which is the market price plus any subsidy, such as the blenders tax credit. The market price is a function of the crude oil price realization, ε^t. The per gallon cost of producing biofuel of type *a* is $k_a\left(\zeta^t\right)$, which includes both feedstock and non-feedstock production costs. Hence, the rate of return depends on the yield realization in that year as well as the acreage allocation decisions of farmers.

Long Run Competitive Equilibrium

In our economy, a long-run competitive equilibrium at time *t* is defined by

(*i*) a sequence of pricing functions $\left\{\tilde{p}_i^t\left(\tilde{\zeta}^t,\ \tilde{\varepsilon}^t,\ \tilde{n}^t\right)\right\}_{t=0}^{\infty}$ for $i = 1,\ 2,\ 3$;

(*ii*) a sequence of agricultural commodity demand functions $\left\{\tilde{Q}_i^{t,d}\left(\tilde{\mathbf{p}}^t, \tilde{n}^t\right)\right\}_{t=0}^{\infty}$ for $i = 1,\ 2,\ 3$;

(*iii*) a sequence of agricultural commodity supply functions $\left\{\tilde{Q}_i^{t,s}\left(\tilde{\mathbf{p}}^t, s^{t-1},\ t\right)\right\}_{t=0}^{\infty}$ for $i = 1,\ 2,\ 3$;

(*iv*) a sequence of investment functions $\left\{\tilde{n}_i^{t+1}\left(\tilde{\mathbf{p}}^{t+1}\right)\right\}_{t=0}^{\infty}$ for $i = 1,\ 2,\ 3$;

(*v*) the law of motion of land allocation

$$\pi^t * \mathbf{1} = \left[\pi_1^{t-1},\ \pi_2^{t-1},\ \pi_3^{t-1}\right]',\ \left(\pi^t\right)' * \mathbf{1} = \left[\pi_1^t,\ \pi_2^t,\ \pi_3^t\right]'.$$

Given the sequence of pricing functions, the sequence of biofuel plants in operation, crop yield realizations, and crude oil price realizations, commodity markets clear in each period. That is, $\tilde{Q}_i^{t,s}\left(\tilde{\mathbf{p}}^{t*}, s^{t-1},\ t\right) = \tilde{Q}_i^{t,d}\left(\tilde{\mathbf{p}}^{t*}, \tilde{n}_i^{t*}\right)\quad \forall i = 1,\ 2,\ 3$ and $\forall$ t.

We not only require that markets clear, but also impose the condition that, at the margin, the returns of each project equal the required risk-adjusted returns as determined by the CAPM:

$$\begin{aligned} R_{corn\ ethanol}\left(\tilde{\mathbf{p}}^{t*}, \tilde{n}^{t*}_{corn\ ethanol}\right) &= RR_{corn\ ethanol} \\ R_{biodiesel}\left(\tilde{\mathbf{p}}^{t*}, \tilde{n}^{t*}_{biodiesel}\right) &= RR_{biodiesel} \\ R_{switch\ ethanol}\left(\tilde{\mathbf{p}}^{t*}, \tilde{n}^{t*}_{switch\ ethanol}\right) &= RR_{switch\ ethanol} \end{aligned}$$

where *RR* is the required return to the biofuel plant as determined by the CAPM.

The zero excess return conditions ensure we have investment in each of the biofuel plants until the prices of feedstock (corn, soybeans, and switchgrass) are bid up to the point at which an investor is indifferent between investing in any of the biofuel plants and investing in the market portfolio. When investment in one or more plants cannot meet this condition, then investment equals zero.

Implementing the Model

Our question is empirical in nature. The incentives present for the biofuel industry to expand or contract depend upon many factors, including the price of crude oil, demand for corn and soybeans for food uses, and weather variability. Exploring more than the most basic results of this model requires us to specify functional forms and evaluate the results numerically via Monte Carlo simulation.[2] The model starts with the month of December 2007 when producers of corn, soybeans, and switchgrass (hay) were planning how they would allocate acres in the 2008 cropping season.

Our strategy for simulating the economy is to specify functional forms for both agricultural commodity supply and demand and to calibrate the distribution of crude oil prices and commodity yields at specified dates in the future. A joint draw from these distributions implies an equilibrium price for corn, soybeans, and switchgrass and thus implies return levels in each biofuel industry.

Commodity Supply

We parameterize the production function for the agricultural commodities as

$$\tilde{Q}_i\left(\tilde{p}^t,\ \tilde{\zeta}^t,\ s^{t-1},\ t\right)=\sum_{j=1}^{3} s_{ij}^{t-1}\tilde{\zeta}_i^t\pi_{ij}^{t*}\quad \forall\ i,\quad j=1,2,3$$

where s^{t-1} is the yield penalty associated with continuous cropping practices. We impose a yield penalty only for continuous corn rotations.[3] We draw from the joint beta distribution of yields,

$$\tilde{\zeta}^t \sim \beta\left(\begin{bmatrix}\mu_{corn}^t \\ \mu_{soybean}^t \\ \mu_{switchgrass}^t\end{bmatrix}, \Sigma^{-1}, \mathbf{q}^t{}_{max}, \mathbf{q}^t{}_{min}\right)$$

$$\mu_{corn}^t=-3843.83+1.99t,\quad \mu_{soybean}^t=-99.52+.52t,\quad \mu_{switchgrass}^t=-13.94+.0086t$$

$$\Sigma^{-1}=\begin{bmatrix}228.08 & 39.71 & 1.58 \\ 39.71 & 10.83 & 0.312 \\ 1.58 & 0.312 & 0.031\end{bmatrix},\quad \mathbf{q}_{\max}^t=\begin{bmatrix}\mu_{corn}^t+3\sigma_{corn} \\ \mu_{soybean}^t+3\sigma_{soybean} \\ \mu_{switchgrass}^t+3\sigma_{switchgrass}\end{bmatrix},$$

$$\mathbf{q}_{\min}^t=\begin{bmatrix}\mu_{corn}^t-2\sigma_{corn} \\ \mu_{soybean}^t-2\sigma_{soybean} \\ \mu_{switchgrass}^t-2\sigma_{switchgrass}\end{bmatrix},$$

using the algorithm developed by Magnussen (2004). The mean of this joint distribution follows a linear trend through time, which was estimated from historical yield data for years 1980 through 2006 maintained by the National Agricultural Statistics Service.[4] The matrix Σ^{-1} is the variance-covariance matrix for the yields of the three crops. We assume the nominal total cost functions of the agricultural commodities are quadratic, given by $c_i\left(\pi_{ij}^t\right) = a_i\,\pi_i^t + \kappa_i\left(\pi_i^t\right)^2 \quad \forall\ i = 1, 2, 3$. We use estimates of U.S. annual supply elasticities for each crop from FAPRI's agricultural outlook model. Using these elasticity estimates, we can solve for the κ_i parameters. We calibrate the intercepts, a_i, so that the model matches current market conditions. Motivation for upward-sloping marginal cost curves is that as land becomes more concentrated in a certain crop, costs will rise because of the need to invest in additional pest control and nutrient inputs.

Commodity Demand

We specify a simple, constant elasticity, reduced-form demand function for each commodity. We use the intermediate-term own- and cross-price demand elasticities for beef from the Economic Research Service/Penn State World Trade Organization model as our estimates of the $\alpha_1^i, \alpha_2^i, \alpha_3^i$. The price distribution of crude oil influences commodity demands indirectly through the number of biofuel plants of each type in the economy; in our simulation, crude oil prices are lognormal and calibrated to match current conditions in the futures market:[5,6]

$$Q_i^d\left(\tilde{\mathbf{p}}^t,\ \tilde{\varepsilon}^t,\ n_i^t\right) = \alpha_0^i\left(\tilde{p}_1^t\right)^{\alpha_1^i}\left(\tilde{p}_2^t\right)^{\alpha_2^i}\left(\tilde{p}_3^t\right)^{\alpha_3^i}\left(n_i^t\right)^{\alpha_4^i}\ \ \forall\ i = 1,\ 2,\ 3.$$

One of the equilibrium conditions requires the number of biofuel plants in each industry to be such that there are no excess returns over the required return. The parameter α_4^i is simply an elasticity measuring the percentage change in quantity demanded over the percentage change in the number of plants when an additional plant is built. To calculate α_4^i, we assume that all plants of a given type are homogeneous in capacity[7] and that while online they run at full capacity. Using these parameterizations of commodity supply and demand, as shown in table 1, and making draws from the joint yield and crude price distribution, we can solve for equilibrium commodity prices and determine the distribution of returns to each kind of biofuel plant.

Accounting for Cellulosic Ethanol from Corn Stover and Wood Chips

If switchgrass ethanol is commercially viable, then presumably cellulosic ethanol produced from corn stover and wood chips will be commercially viable. This is because these biomass sources do not compete directly for acres from high-value crops such as corn and soybeans and thus would not have as large an implicit land cost. Because production of these feedstocks occurs outside the framework of our model, we need to make some assumptions about how much ethanol will be produced from these sources. For example, if stover is utilized at a 25% removal rate, and corn stover mass is produced in a ratio of 1:1 with corn grain mass, then 5.45 billion gallons of ethanol will be produced from corn stover (Blanco-Canqui and Lal 2007; Graham et al. 2007). Further, six billion gallons of biofuel produced from wood chips or other woody residue sources may be a reasonable expectation given the "billion ton" study by Perlack et al. (2005). Note that in this example 4.54 billion gallons per year must come from switchgrass ethanol or other land-intensive biomass sources to meet the cellulosic mandate in the EISA Renewable Fuel Standard (RFS). Since it remains unclear exactly how cellulosic biofuel will come into existence, we also present after the section containing the main results a sensitivity analysis varying the amount that must come from land intensive biomass production.

Calculating Returns to Biofuel Production

The forces most affecting returns to biofuel production are feedstock costs and governmental policy. Feedstock costs are determined endogenously within the model; corn and switchgrass are fed directly into the ethanol and cellulosic ethanol plants. For biodiesel, soy oil (not soybeans directly) is the feedstock. Our model produces equilibrium soybean prices but not soy oil prices. We estimate a simple linear relationship between the price of soybeans and the price of soy oil using recent data:[8]

$$\textit{Soy Oil Price} = 0.044 * \textit{Soybean Price} - .009 \quad R^2 = 0.878$$

Each type of biofuel produces a co-product that generates value that can offset some of the feedstock cost. Corn ethanol produces dried distillers grains, dried distillers grains with solubles (DDGS), or wet distillers grains, which are used in beef, pork, and poultry rations in limited quantities. These co-products substitute for corn and soybean meal in livestock rations. Therefore, the price of DDGS moves with the prices of corn and soybean meal. Distillers grains have approximately the same digestible energy content as corn, so here we give a credit to corn ethanol plants for DDGS consistent with its ability to substitute for corn in livestock rations (Shurson et al. 2003). The biodiesel production process yields glycerin, fatty acids, and filter cakes. We credit 8¢ per gallon to the biodiesel producer based on the current market value for these co-products (Paulson and Ginder 2007).

Production of ethanol from switchgrass produces lignin, which is combustible and will be used to generate electricity within the facility or will be sold back to the electrical grid (Aden et al. 2002). We credit switchgrass ethanol with 10¢ per gallon as suggested in Aden et al. (2002). The per gallon non-feedstock costs of producing corn-based ethanol and cellulosic ethanol are 76¢ per gallon and 97¢ per gallon, respectively, while the non-feedstock cost of producing biodiesel is 55¢ per gallon (Paulson and Ginder

2007; Tokgoz et al. 2007).

Revenue realized by biofuel plants relates directly to crude oil prices. For simplicity, we assume that the price of ethanol and diesel are deterministic linear functions of the price of crude oil. We used monthly spot prices from January 1994 through August 2007 of the Cushing Oklahoma crude oil, New York Harbor conventional gasoline, and U.S. No. 2 wholesale/resale markets to estimate the linear relationship: [9]

$$\textit{Wholesale Gasoline Price} = 0.21 + 2.84 * \textit{Crude Oil Price} \qquad R^2 = 0.97$$

$$\textit{Wholesale Diesel Price} = -4.00 + 3.13 * \textit{Crude Oil Price} \qquad R^2 = 0.98$$

E10 is the term given to a 10% ethanol, 90% gasoline blend. E85 refers to an 85% ethanol, 15% gasoline blend. E10 is utilized for its ability to oxygenate gasoline, which enhances combustion and reduces emissions (NSTC, 1997). E85 is only used in flex-fuel vehicles specially designed to withstand the corrosive properties of alcohol-based fuel. Ethanol has about two-thirds the energy value of gasoline (Shapouri et al. 1995).

Following Tokgoz et al. (2007), we assume based on the demand-side model that when annual production is greater than 14 billion gallons per year, the E10 market becomes saturated, causing ethanol to be priced at the margin according to its energy value. When production is below this threshold, we assume that ethanol is priced at a premium to gasoline, valued for its properties as an additive (Hurt et al. 2006). To account for this transition in ethanol pricing, we interpolate between the additive and energy value pricing rules, as follows:

$$P_{ethanol} = \begin{cases} 1.05 * P_{gasoline} & \text{if } ethanol\ production < 14\ bil\ gal \\ \left(1.05\lambda + .667\left(1-\lambda\right)\right) * P_{gasoline} & \text{if } 14\ bil\ gal < ethanol\ production < 16\ bil\ gal \\ .667 * P_{gasoline} & \text{if } ethanol\ production > 16\ bil\ gal \end{cases}$$

where $\lambda = \frac{ethanol\ production - 14}{16-14}$.

We are ignoring short-term distribution-related bottlenecks because market forces will reward those who solve these localized problems. There is a much more serious bottleneck that occurs once all gasoline contains a 10% blend. To expand beyond this point, ethanol needs to sell below its energy value to incentivize the sale of 85% blends. The need for this price change cannot be eliminated by the construction of new infrastructure. Returns to biofuel production are calculated and compared to the required return as defined by the CAPM. There will be entry (exit) into a biofuel sector until the excess returns over the required return zero. Since we are interested in long-run equilibrium, we solve for the number of biofuel plants in the crop year consistent with this condition.

Limitations of the Model

Before we present the results, we should discuss some limitations of the model.The assumptions that allow the model to be run both in terms of relationships in the data and the behavior of participants represent a simplification of true market conditions that currently exist and that are likely to exist in the future. The results we present should be interpreted with this limitation in mind.

International trade is not present in our model. Currently there is a $0.54-per-gallon specific tariff and a 2.5% ad valorem tariff on imported ethanol, which effectively limits the importation of Brazilian sugarcane-based ethanol. These tariffs could be removed, or adoption of cost-reducing advances in sugarcane-based ethanol might make Brazilian ethanol attractive even with the import tariffs in place. If either of these situations were to happen, an international sector would need to be added.

The model adjusts to long-run equilibrium whereby the number of biofuel plants in each sector is such that none earns excess returns over the required return. This is clearly not the way the industry would evolve in reality; the transitions would be gradual and carried out over a number of years, and the industry might possibly overshoot the equilibrium outcome. While consideration of these factors would add some realism to the model, it would also add a level of complexity not required to address our questions of interest.

Results

We simulate long-run equilibrium in the bioeconomy under different scenarios regarding biofuel tax credits, biofuel production mandates, and crude oil prices. To establish a baseline against which we compare different scenarios, we simulate the model using pre-EISA governmental policies. That is, we include the Volumetric Ethanol Excise Tax Credit from the American Jobs Creation Act of 2004, which includes a $0.51-per-gallon credit for ethanol, and a $1.00-per-gallon credit to biodiesel. We also use current expectations of future crude oil prices. As a proxy for this, we use the mean of the daily NYMEX December 2008 contract price for crude oil during October 2007, which is $78.63. The baseline case includes an existing corn ethanol industry with a capacity of 6.8 billion gallons per year, a biodiesel industry with a capacity of 1.2 billion gallons per year, and no cellulosic ethanol industry in 2007.[10,11]

The baseline results (table 2) show sustained high commodity prices and persistence in corn-intensive cropping patterns. The corn ethanol sector expands until total production exceeds 18 billion gallons per year. Biodiesel and cellulosic ethanol from switchgrass are not viable in this scenario. Cellulosic ethanol never expands, and the biodiesel sector contracts so that there are no biodiesel plants operating in the long run. These results suggest that under pre-EISA policy, once the opportunity cost of land is taken into account, rational investors will not build biodiesel or cellulosic ethanol plants. This raises an interesting question, why does the current biodiesel industry exist? Biodiesel production continues to expand every year (Westcott 2007) despite the fact that the biodiesel industry is not producing at capacity (Radich 2004), and potential for profit looks grim as the industry faces high soybean prices. Perhaps biodiesel producers were counting on a successful lobbying effort to secure higher subsidies for biodiesel relative to corn ethanol; this strategy proved quite rational after the passage of the EISA.

Renewable Fuel Standard Scenarios

In the remaining scenarios, we impose the biofuel production levels indicated by the new RFS in the EISA of 2007 and consider the bioeconomy's equilibrium outcomes for three different long-run crude oil price scenarios. We assume that the greenhouse gas reduction requirements in the legislation are met for all biofuels. After imposing the biofuel production levels, our model allows us to solve for the level of subsidy (tax credit) required to maintain the zero-excess-return condition in addition to delivering equilibrium agricultural commodity prices and acreage allocations. Corn has a mean long-run equilibrium price of \$4.76 per bushel, soybeans, \$13.01 per bushel, and switchgrass, \$164.62 per ton. Long-run equilibrium acreage allocations are 61% of acres in corn, 19% in soybeans, and 20% in switchgrass or hay.

We are interested in comparing the level of tax credit required to maintain the no-excess-return conditions across different crude oil price scenarios (see table 3). We cannot say, a priori, whether high crude oil prices will imply higher or lower zero-excess-return tax credit levels. Crude oil prices act on biofuel returns in two ways. Most obviously, high crude oil prices imply high biofuel prices, positively affecting returns to biofuel production. In addition, biodiesel benefits from high crude oil prices by the resulting strong output prices it enjoys, but so does corn ethanol, and switchgrass ethanol. This creates more intense competition for acreage among the energy crops, and results in higher feedstock costs. This reduces the return to each kind of biofuel production. Without simulating the model, we cannot determine which effect is stronger.

Land allocations under the EISA RFS shift toward crops that produce fuels mandated at a high level. Incentives provided to “greener” fuels diffuse through the economy and cause a shift in land allocation patterns. The mandate results in much higher commodity prices than in the baseline. If the cellulosic mandates are designed to avoid the feed-versus-fuel trade-off, our results suggest it may actually exacerbate the situation by inducing even higher feedstuff costs than under the regime with only corn ethanol in production. With a fixed amount of land, it is impossible to increase the amount of *each* crop devoted to energy *and* maintain the same level of consumption of each commodity for food uses such as feeding livestock.

Sensitivity of Results to Required Levels of Switchgrass Production

The amount of cellulosic biofuel production that is feasible from corn stover and woody biomass is uncertain. This will be a significant factor in determining long-run commodity prices and acreage allocation patterns because the amount not covered by corn stover and woody biomass will be met with land-intensive biomass crops.

Table 4 presents the results of several scenarios increasing the amount of switchgrass ethanol needed to meet the new RFS. In the first scenario, we consider the case in which the new RFS for cellulosic ethanol can be met exclusively with corn stover and woody residue, and no land-intensive biomass is needed. Note that we calculate that the subsidy given to cellulosic ethanol (including corn stover and wood chip ethanol) must reach $0.90 per gallon before the switchgrass ethanol sector would begin to expand. The final scenario requiring 10.55 billion gallons of switchgrass ethanol per year is arithmetically equivalent to assuming 25% of corn stover will be collected for ethanol and there is no production of ethanol from wood chips. With increasing requirements on land-intensive biofuel, we see higher commodity prices and higher subsidy levels needed to maintain the required biofuel industry sizes. The sensitivity analysis is also useful in that it hints at how the results might have been quantitatively different had we simulated the model with miscanthus instead of switchgrass.

Conclusions

Our results lead to some general conclusions about the future of biofuels in the United States. Competition for land ensures that providing an incentive to just one crop will increase equilibrium prices of all. Also, at pre-EISA subsidy levels, neither biodiesel nor switchgrass ethanol is commercially viable in the long run. In order for switchgrass ethanol to be commercially viable, it must receive a differential subsidy over that awarded to corn-based ethanol. Since switchgrass competes for the same acres as corn, and corn-based ethanol is less expensive to produce, corn-based ethanol will always have a comparative advantage over switchgrass ethanol with a homogeneous subsidy.

Corn and soybeans compete for the same acreage, so when energy prices are such that corn-based ethanol is stimulated, then the price of soybeans must also increase if the farmer is to continue to allocate land to soybeans. This increase in soybean prices reduces the profitability of biodiesel even in scenarios in which energy prices are high. This means that under pre-EISA subsidy levels, the soy oil biodiesel sector is not viable under any energy price considered. If the EISA mandates are to be met in a voluntary fashion, then the biodiesel sector will require a higher relative subsidy than it enjoys today.

We calculate the subsidies required to stimulate biofuel production to the levels required by the EISA RFS. We find that subsidy levels are needed in the range of $0.22 to $0.78 per gallon for corn ethanol, $1.97 to $2.90 per gallon for biodiesel, and $1.55 to $2.11 for cellulosic ethanol. Crude oil price realizations in the future will determine the subsidy levels required to maintain industry sizes required by the new RFS. The new RFS results in much higher commodity prices than in the baseline. This suggests that the cellulosic mandates in the EISA that appear designed to avoid the feed-versus-fuel trade-off may actually exacerbate the situation relative to a situation in which corn-based ethanol is allowed to expand. Cellulosic ethanol is more expensive to produce, and switchgrass-based ethanol is more land intensive than corn-based ethanol. Therefore, the severity of upward pressure on commodity prices caused by the new RFS will be determined largely by the ability to produce cellulosic ethanol from biomass that is not land intensive. Policies that expand cellulosic ethanol beyond levels that can be supplied by corn stover and woody biomass are therefore more expensive in terms of the subsidy that is required and the resulting increase in food and feed prices that result.

Endnotes

[1] We consider only corn, soybeans, and switchgrass because we focus on the decision of a farmer who must allocate crop ground. Other cellulosic feedstocks such as woodchips are not well suited to crop ground (Lewandowski et al. 2003).

[2] All simulations were conducted in Matlab.

[3] We assume a 10% yield drag on continuous corn rotations.

[4] This is given in per harvested acre. We use alfalfa as a proxy for switchgrass yields, since the tonnage per acre is approximately equivalent to the switchgrass yields projected in the literature. See http://www.nass.usda.gov/.

[5] The prices of other fuels (e.g., gasoline and biodiesel) are based on their relationship to crude oil prices.

[6] Implied volatility in crude oil prices is estimated from 2007 option data. In the first scenario we take as the mean of the crude oil price distributions in each period to be the NYMEX price of the December futures contract in the relevant year on October 2, 2007. In a subsequent scenario, we increase the crude oil futures price to reflect the dramatic increase in oil prices that occurred between October 2007 and December 2007.

[7] We assume corn ethanol plant capacity is 53.05 mgy, biodiesel plant capacity is 20 mgy, and cellulosic ethanol plant capacity is 51.1 mgy. Corn ethanol and biodiesel capacity is based on capacity of current plants as published by the Renewable Fuels Association and the National Biodiesel Board. Cellulosic ethanol capacity is based on Aden et al. 2002. See http://www.ethanolrfa.org/industry/locations/ and http://www.biodiesel.org/buyingbiodiesel/producers_marketers/ProducersMap-Construction.pdf.

[8] The relationship is estimated from the daily nearest cash prices on the CBOT from October 17, 2005 to September 14, 2007.

[9] Historical data are maintained at http://tonto.eia.doe.gov/dnav/pet/pet_pri_spt_s1_d.htm.

[10] For existing ethanol industry capacity and locations, see http://www.ethanolrfa.org/industry/locations/ (September 2007).

[11] For existing biodiesel industry capacity and locations, see http://www.biodiesel.org/buyingbiodiesel/producers_marketers/ProducersMap-Existing.pdf (September 2007).

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Table 1. Parameters Used in Monte Carlo Simulation

	κ_i	a_i	α_0^i	α_1^i	α_2^i	α_3^i	α_4^i
Corn	0.112		9	−0.258	0.002	0	0.19
Soybeans	1.54	−56.99	6	0.081	−0.379	0	0.26
Switchgrass	221.64	−0.785	1.2	0	0	−0.16	0.06

Table 2. Assumptions in the Baseline Scenario

	Corn	Biodiesel	Switchgrass		
2007 Biofuel industry sizes (billion gallons)	6.8	1.2	0		
2007 Acreage proportions[a]	0.50	0.30	0.20		
Tax credits ($/gal)	$0.51	$1.00	$0.51		
	2008	2009	2010	2011	2012
Current expectation of future crude prices ($/barrel)	$78.63	$78.63	$78.63	$78.63	$78.63

[a] From NASS (http://www.nass.usda.gov/index.asp).

Table 3. Long-Run Results under Different Tax Credits, RFS Mandate, and Crude Oil Price Scenarios

	Baseline	New RFS Mid Crude	New RFS High Crude	New RFS Low Crude
$E\left[p_{crude}\right]$ ($/barrel)	$78.63	$78.63	$95	$65
$E\left[p_{corn}\right]$ ($/bu)	$4.29	$4.76	$4.76	$4.76
$E\left[p_{sb}\right]$ ($/bu)	$11.37	$13.01	$13.01	$13.01
$E\left[p_{sg}\right]$ ($/ton)	$141.47	$164.62	164.62	$164.62
Land allocations $\left(\pi_1\ \pi_2\ \pi_3\right)$	(.65 .19 .16)	(.61 .19 .20)	(.61 .19 .20)	(.61 .19 .20)
Corn ethanol production (billion gallons)	18.5	15	15	15
Biodiesel production[a] (billion gallons)	0bgy	1	1	1
Switchgrass ethanol production (billion gallons)	0	4.55	4.55	4.55
Tax credit Corn ethanol ($/gal)	$0.51	$0.53	$0.22	$0.78
Tax credit– biodiesel ($/gal)	$1.00	$2.49	$1.97	$2.90
Tax credit– cellulosic ethanol ($/gal)	$0.51	$1.86	$1.55	$2.11

Note: Shaded portions are exogenous in the scenario.
[a]Production from soy oil feedstock.

Table 4. Sensitivity of Crop Prices and Required Subsidy Levels to Increasing Switchgrass Ethanol Levels

	New RFS Mid Crude	New RFS Mid Crude	New RFS Mid Crude	New RFS Mid Crude
$E\left[p_{crude}\right]$ ($/barrel)	$78.63	$78.63	$78.63	$78.63
$E\left[p_{corn}\right]$ ($/bu)	$3.98	$4.66	$4.83	$4.96
$E\left[p_{sb}\right]$ ($/bu)	$10.29	$12.65	$13.25	$13.67
$E\left[p_{sg}\right]$ ($/ton)	$127.52	$159.75	$168.05	$173.67
Land allocations $(\pi_1\ \pi_2\ \pi_3)$	(.64 .20 .16)	(.61 .19 .20)	(.61 .19 .21)	(.60 .18 .21)
Corn ethanol production (billion gallons)	15	15	15	15
Biodiesel production[a] (billion gallons)	1	1	1	1
Switchgrass ethanol production (billion gallons)	**0**	**2.55**	**6.55**	**10.55**
Tax credit–corn ethanol ($/gal)	0	0.49	0.55	0.58
Tax credit–biodiesel ($/gal)	1.54	2.34	2.59	2.72
Tax credit–cellulosic ethanol ($/gal)	0.90	1.77	1.92	1.99

Note: Shaded portions are exogenous in the scenario.
[a]Production from soy oil feedstock.

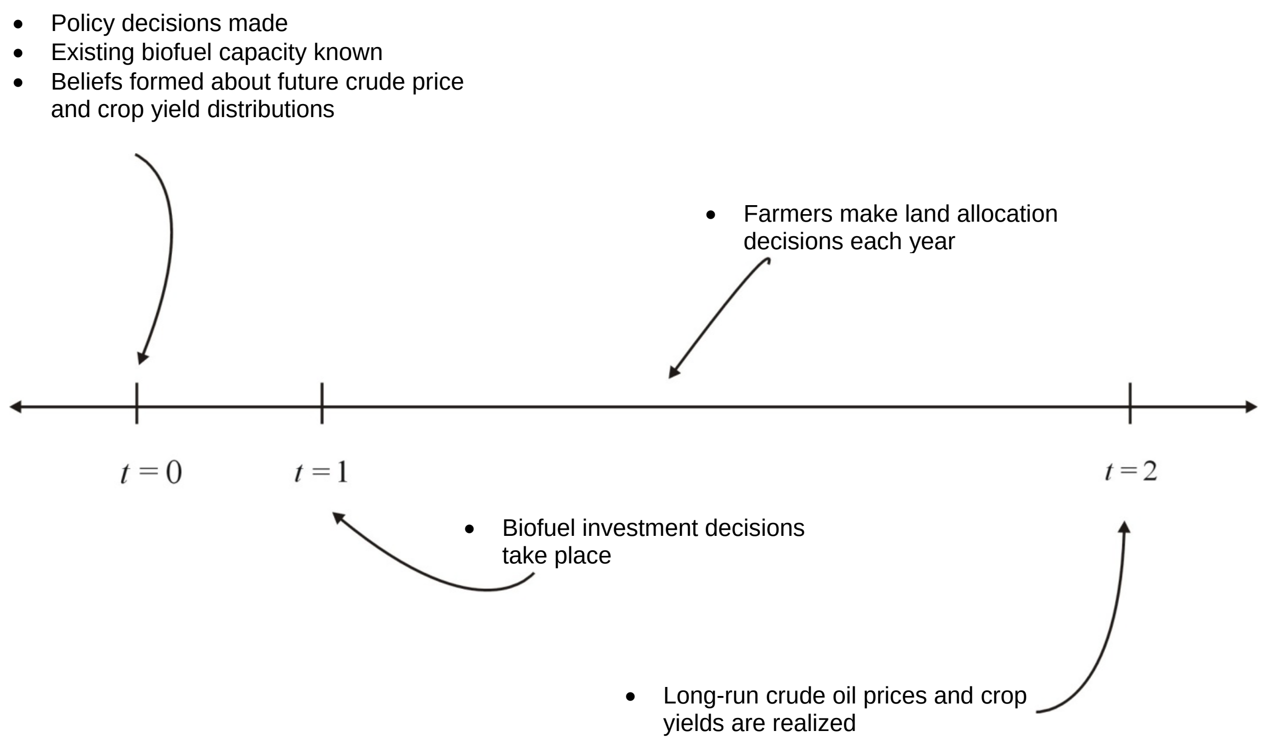

Figure 1. Decision timeline for commodity production