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Meeting Biofuels Targets: Implications for Land Use, Greenhouse Gas Emissions and Nitrogen Use in Illinois

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Abstract: This article develops a dynamic micro-economic land use model to identify the cost-effective allocation of cropland for traditional row crops and perennial grasses and the mix of cellulosic feedstocks needed to meet pre-determined biofuel targets over the 2007-2022 period. Yields of perennial grasses are obtained from a biophysical model and together with county level data on costs of production for Illinois are used to examine the implications of these targets for crop and biofuel costs, greenhouse gas emissions, and nitrogen use. The economic viability of cellulosic feedstocks is found to depend on their yields per acre and the opportunity cost of land. The mix of viable cellulosic feedstocks varies spatially and temporally with corn stover and miscanthus co-existing in the state; corn stover is viable mainly in central and northern Illinois while miscanthus acres are primarily located in southern Illinois. Biofuel targets lead to a significant shift in acreage from soybeans and pasture to corn and a change in crop rotation and tillage practices. The biofuel targets assumed here lead to a reduction in greenhouse gas emissions but an increase in nitrogen use.

Biofuels are increasingly being viewed as the center piece in any strategy for energy independence, stable energy prices, and greenhouse gas (GHG) mitigation in the U.S. A key challenge to the expansion of biofuel production is the allocation of limited agricultural land between crops and biomass to meet the needs for food, feed and fuel and its potential to raise the prices of food/feed crops. The share of corn being used for ethanol production has increased from 10% to 28% between 2004/2005 and 2007/2008, and despite an unprecedented increase by 15% in the acreage under corn in 2007 relative to 2005, corn prices reached record high levels in 2007 that were twice as high as those in 2005.

Energy policy in the U.S. initially sought to promote production and use of first-generation biofuels, corn ethanol, through mandates and tax credits; this has changed due to concerns about the implications of expanding demands for corn ethanol for food prices as well as the greater potential of cellulosic biofuels to mitigate climate change. The recently enacted Energy Independence and Security Act of 2007 places greater emphasis on the next generation of biofuels and mandates that 21 of the 36 billion gallons of ethanol be advanced biofuels that reduce GHG emissions by at least 50% relative to baseline levels.

Unlike the current generation of biofuels based on a single feedstock, that is corn, cellulosic biofuels can be produced from several different feedstocks including crop residues, woody biomass, and perennial grasses. Crop residues, being by-products of crop production do not create a food-fuel competition for land. However, currently available corn stover would meet only about a third of the advanced biofuels mandate for 2022 in the U.S. necessitating reliance

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on other sources, such as perennial grasses (Perlack et al., 2005). The latter also offer the potential for various environmental benefits compared to row crops they may displace and to corn-based ethanol.

Two perennial grasses, switchgrass (*Panicum virgatum*) and miscanthus (*Miscanthus x giganteus*), have been identified in particular as among the best choices as dedicated energy crops in the U.S. (Heaton et al., 2004; Lewandowski et al., 2003). These grasses have higher yields than others, provide high nutrient use efficiency, and require growing conditions and equipment similar to those for corn, making them compatible with conventional crop cultivation. They can provide a larger volume of biofuels per acre and lower life cycle GHG emissions per gallon of fuel than corn ethanol and thus alleviate the competition for land. Moreover, unlike corn, switchgrass and miscanthus can be grown on marginal lands and have the potential to reduce soil erosion and chemical run-off due to low chemical input needs and root structure².

This article develops a dynamic micro-economic land use allocation model that determines the profit maximizing land use choices to meet a targeted level of corn ethanol and cellulosic ethanol (from corn stover, miscanthus and switchgrass) over the 2007-2022 horizon while taking into account the spatial heterogeneity in yields, costs of production, and land availability within a region. Spatially heterogeneous yields of switchgrass and miscanthus are obtained from a biophysical crop growth model and used to examine the heterogeneity in the viability of biofuels from alternative feedstocks across geographical locations and the mix of feedstocks that is likely to be economically viable. A second purpose of this article is to examine the impact of these biofuel targets for the price of food crops that will be displaced from cropland and for the cost of producing biofuels to meet given mandates. The diversion of corn needed to meet the target for corn ethanol is expected to raise the prices of both corn and other competing commodities, and thus the cost of production of corn ethanol. Rising corn prices would also raise the opportunity costs of land to be converted to energy crops and thus the costs of producing cellulosic biofuels.

This article also investigates the effects of biofuel targets on nitrogen use and lifecycle GHG emissions. Biofuels from different feedstocks differ in their nitrogen requirements, energy-balance, and life-cycle emissions. While corn-ethanol reduces GHG emissions relative to gasoline, the production of corn is nitrogen and carbon intensive compared to perennial grasses. Reliance on current-generation biofuels, therefore, poses a trade-off between reducing GHG emissions and potentially increasing nitrate run-off and causing water quality problems.

The model is operationalized using county-specific data for Illinois to examine the economic and environmental implications of biofuels targets over the period 2007-2022. Illinois produces 17% of corn and 19% of the ethanol in the U.S. and has the climatic and soil conditions conducive to the production of herbaceous perennials that can be used as feedstocks for cellulosic biofuels. Estimates of nitrogen use and life-cycle GHG emissions associated with biofuels from different feedstocks are based on county-specific production practices in Illinois.

² There have been some concerns that miscanthus, as an introduced species, might be an invasive plant. However, most varieties used for biofuel production (like *Miscanthus x Giganteus*) are sterile hybrids and do not produce seed.

The next section describes the related literature. The economic model is described in Section 3 followed by a description of the dedicated energy crops being considered here and the data and assumptions underlying the numerical simulation. Results of the numerical simulation are presented in Section 5 followed by conclusions in Section 6.

2. Related Literature

The dynamics of agricultural land use changes have been examined by several studies. Foremost among these are the studies based on the Forest and Agricultural Sector Optimization Model (FASOM) which is a multi-period, price endogenous, spatial market equilibrium model of land allocation between agricultural crops and forests. The model is run on a decadal time step. Biophysical relationships that quantify the growth of timber and the sequestration of carbon in forests and land are included. Alig et al. (1997) apply this model to investigate the allocation of land among 39 crop and livestock activities and forests across five regions in the U.S. to achieve given carbon sequestration targets, while Alig et al. (2000) examine the land use implications of producing hardwood short rotation woody crops on cropland for the US pulp and paper sector and its impact on the agricultural and forest sectors in the U.S.

McCarl et al. (2000) apply FASOM to examine the competitiveness of electric power generation using bioenergy from milling residues, whole trees, logging residues, switch grass, and short-rotation woody crops instead of coal while disaggregating the U.S. into eleven homogenous regions. McCarl and Schneider (2001) expand this model into the ASMGHG model to investigate competitiveness of various carbon mitigation strategies that include soil sequestration, biofuel crops, and afforestation at alternative carbon prices across 63 regions in the U.S. They find that at low carbon prices, soil carbon sequestration through a change in cropping practices is competitive while at high carbon prices, abatements are achieved mainly through use of biomass for power generation and conversion of land to forests.

Another dynamic agricultural sector model used to analyze allocation of cropland in the U.S. is POLYSYS (Ugarte et al., 2003). The model includes various traditional and energy crops and investigates land use impacts of exogenously set bioenergy prices. It is more regionally disaggregated than FASOM with 305 agricultural statistical districts as defined by the USDA and provides annual estimates of changes in economic outcomes. Walsh et al. (2003) apply POLYSYS to examine the potential for using CRP land to produce bioenergy crops at various bioenergy prices and find that switchgrass is more competitive than woody bioenergy crops and that annual farm income and crop prices would increase due to bioenergy crop production.

A few studies examine the environmental effects of the ethanol mandate. English et al. (2008) apply POLYSYS to show that the corn ethanol mandate will lead to major increases in corn production in the Corn Belt, shifting soybeans and wheat production to the southeast and shifting cotton westward over the period 2007-2016 (assuming that cellulosic biofuels are not feasible over this period). Fertilizer use and soil erosion will increase significantly while soil carbon sequestration will decline. Malcolm (2008) uses Regional Environment and Agriculture Programming Model (REAP), a partial-equilibrium model of the U.S. agricultural sector consisting of 50 regions to quantify the extent to which substitution of crop-residue based cellulosic ethanol for corn ethanol reduces soil erosion and nutrient deposition.

The dynamic land use allocation model developed here differs from the models used in studies mentioned above in that spatial and temporal heterogeneity in returns to land are incorporated at county level rather than much broader regions considered in these studies, and the optimal mix of competing cellulosic feedstocks—corn stover, miscanthus and switchgrass—is examined to meet the ethanol mandates. Due to the perennial nature of miscanthus and switchgrass, we use a multi-period dynamic rolling horizon model. The model generates a time path of the costs of meeting the biofuel mandate and examines its sensitivity to assumptions about the costs of producing cellulosic feedstocks. A biophysical model of energy crop yields and life cycle analysis of carbon emissions is integrated with the land use model to examine the environmental implications of land use changes to meet the specified targets.

3. The Model

A dynamic spatial optimization model is developed to analyze market prices, socially optimal land use strategies, and production and consumption of various row crops and perennial crops while meeting specific targets for ethanol production in Illinois over the 16-year planning horizon of 2007-2022. The annual crops considered here are corn, soybean, wheat, and sorghum, while the perennial crops considered are alfalfa, switchgrass and miscanthus. Since Illinois is a major producer of corn and soybeans, a significant change in the crop pattern in this region is likely to alter the market prices of these two commodities. Therefore, when determining the optimum resource allocation the model incorporates market equilibrium prices for corn and soybeans as endogenous variables. This is done by using a conventional approach where the sum of consumers' and producers' surplus is maximized subject to demand-supply balances, resource availability constraints, and technical constraints underlying production possibilities in Illinois (see, McCarl and Spreen, 1980; Takayama and Judge, 1971) for a rigorous presentation of this methodology and a review of studies that used this approach). Consumers' behavior is represented by constant elasticity demand curves for soybeans and for traditional (non-ethanol) uses of corn, both specified regionally, while the prices of wheat, sorghum and alfalfa are fixed at their base year levels. The parameters of the regional constant elasticity demand curves for corn and soybeans are computed based on national demand elasticity estimates of these commodities and their the base year consumption levels (quantities sold at the farmgate) using the method in Kutcher (1972). When computing the producers' surplus, returns from commodity sales and the costs associated with production of row crops and perennial crops, costs of land conversion between perennial and row crops, and the processing costs of both corn ethanol and cellulosic ethanol are incorporated in the objective function of the model. In addition, returns from the sales of co-products of biofuel production (such as Distiller's Dried Grains with Solubles (DDGS) and electricity, a byproduct of cellulosic biofuel production) are included in the producers' surplus, with the price of DDGS linked to the price of corn. The production costs of row crops vary with alternative management practices (rotations and tillage choices) while the costs and the yields of perennials vary with the age of the perennials.

The model determines optimal allocation of agricultural land simultaneously in all of the 102 counties in Illinois that are heterogeneous in their crop productivity and related costs, including the costs of producing biofuels (due to differences in feedstock costs), across various crops, rotations and management practices while satisfying the county-level land availability

constraints, policy constraints (ethanol targets), and various technical constraints underlying the row crop rotation choices and dynamics of perennial crop production. The annual targets for corn ethanol and cellulosic ethanol for Illinois are assumed to be proportional to those set by the renewable fuels mandate, based on the current share of Illinois in national ethanol production.

The perennial nature of switchgrass and miscanthus requires consideration of year-to-year changes in crop yields and costs, thus multi-year production plans. For this we use a 10-year planning horizon assuming that farmers make long-term production plans based on anticipated prices in each year, the dynamics of crop yields and costs, and the demands for corn and biomass that are consistent with the ethanol targets. Due to the steady increase in ethanol production targets the demand for agricultural land would also increase and some marginal lands currently not being utilized may be converted to crop land, the extent of conversion would depend on the variations in crop prices over time. Therefore, in our analysis we treat the agricultural land supply as ‘semi-endogenous’ using a ‘rolling horizon’ approach. Specifically, we solve a 10-year market equilibrium model for each year of the 2007-2022 period assuming a fixed land supply in each run (differing by county), but the county land availability is varied between successive runs based on estimated land supply elasticities and an expected crop price index. Out of the resulting multi-year solution we take the first-year values of the crop production, consumption, and price variables and assume that they are ‘realized’ while the rest corresponding to a long-term optimal plan may be altered in subsequent runs. We use the endogenous first-year prices for all crops to determine the overall price index and incorporate this information to adjust the land availability in the subsequent runs. In this iterative procedure we first solve the model using the base-year (2007) land availability and ethanol targets for 2007-2022. Then, using the 2007 prices determined endogenously and observed prices prior to 2007 we compute the expected crop price index for 2008, update the land availability accordingly, and solve the model again considering the ethanol targets for the next 16 years (i.e. 2008-2023). This is repeated for each year of the planning horizon with the ethanol targets beyond 2022 being set at their levels in 2022.

Another salient feature of the model used here is the limited flexibility for changes in optimal crop patterns. To prevent unrealistic changes in land use, we incorporate a combination of historical and hypothetical acreage patterns into the land allocation for each row crop. Observed historical acreages can be used under ‘normal’ conditions to guide the potential planting behavior for row crops as in McCarl (1982) and Önal and McCarl (1991). Since we are considering further increases in the production of corn and planting new bioenergy crops in order to meet mandatory cellulosic ethanol targets, unprecedented land use patterns are likely to occur in the near future. To ensure that the model can generate results which are consistent with farmers’ planting history and potential future trends, we incorporate both historical and hypothetical acreage pattern (crop mixes, each mix being a vector of crop acreages) in the model. The hypothetical crop mixes included in the model are generated *a priori* based on estimated acreage supply elasticities (both own price and cross price elasticities) and considering a set of price vectors in which crop prices (for corn, soybeans, and wheat only) are varied systematically. In addition, we impose a constraint that governs the dynamics of land conversion between perennials and row crops. These constraints are partly imposed by the allowable crop rotation possibilities and partly by limits imposed on the extent to which land can be converted from conventional to conservation tillage and from row crops to perennial grasses.

4. Data

We estimate rotation and tillage specific costs of production in 2007 prices for four row crops—corn, soybeans, wheat and sorghum—and three perennial grasses—alfalfa, switchgrass and miscanthus. The three perennial grasses have lifetimes of 5, 10 and 20 years, respectively. Application rates for nitrogen, potassium, phosphorus and seed for the four row crops and for alfalfa vary with yields per acre (University of Illinois Extension, 2002), as do the costs of drying and storage of crops (FBFM, 2003). Costs of producing row crops and alfalfa are obtained from the Farm Business and Farm Management data (FBFM, 2007). County-specific, five year (2002–2006) historical average yield per acre for each row crop is obtained from National Agricultural Statistics Service (USDA/NASS, 2008a) and used to construct these costs for each of the 102 counties in Illinois. Observed yields per acre are assumed to be those under a corn-soybean rotation, which is the dominant rotation practiced in Illinois. Corn yield per acre under a continuous corn rotation is assumed to be 12% lower than under a corn-soybean rotation. Costs of machinery operation, depreciation, and interest vary across the northern, central, and southern regions of Illinois and are obtained from the FBFM data for various years (FBFM, 2003; FBFM, 2007; FBFM, 2008). The per acre costs of labor, building repair and depreciation, and overhead (such as farm insurance and utilities) are excluded from these costs of production since they are likely to be the same for all crops and would not affect the relative profitability of crops. These are, therefore, part of the opportunity costs of using existing farm land, labor, and capital to produce bioenergy crops.

Corn stover yield for each county and each rotation is obtained from corn yields assuming a 1:1 ratio of dry matter of corn grain to dry matter of corn stover and 15% moisture content in the grain (Sheehan et al., 2003). Corn stover yields range from a low of 2.25 t dm per acre (metric tons of dry matter per acre) in southern Illinois to a high of 4 t dm per acre in northern and central Illinois. In the absence of long term observed yields for switchgrass and miscanthus, a crop productivity model MISCANMOD is used to simulate these yields in Illinois using GIS data on climate, soil moisture, solar radiation and growing degree days, as described in Khanna et al. (2008). Harvestable yields of miscanthus and switchgrass are estimated to be lower in northern Illinois (9.8 t dm per acre and 4.4 t dm per acre, respectively) than in southern Illinois (12.1 t dm per acre and 5.8 t dm per acre, respectively). This pattern of yield is in contrast to that observed for corn and corn stover. This is because solar radiation and growing degree days which are more abundant in southern Illinois are critical determinants of biomass yield while soil quality is more important for corn yields.

Agronomic data indicate that miscanthus does not yield harvestable biomass in the first year; it provides 50% of its maximum yield in the second year, and 100% of yields from the third year onwards for its remaining life. For switchgrass, we assume that 50% of the maximum yield can be harvested in the first year and full yield can be obtained in the second year and onwards. We also assume that 33% of the peak yield is lost during harvest of miscanthus, but there are no harvest losses for switchgrass (unlike Khanna, 2008; Khanna et al., 2008). Harvested switchgrass and miscanthus have moisture contents of 15% and 20%, respectively.

In estimating the costs of producing miscanthus and switchgrass, we rely on agronomic assumptions about fertilizer, seed, and pesticide application rates for switchgrass and miscanthus described in Khanna et al. (2008), while updating the costs of inputs using 2007 prices.

Miscanthus is planted using rhizomes and planting costs are estimated at \$1000 per acre. Costs of harvesting switchgrass and miscanthus (i.e., mowing, raking, baling and staging) are obtained from the FBFM data (FBFM, 2007; FBFM, 2008) and from Duffy (2007). Costs of mowing/conditioning and raking in Illinois are \$14.2 and \$4.5 per acre, respectively, while the cost of staging is \$2.75 per bale (with a weight of 950 lbs). Baling costs for switchgrass and miscanthus are based on current estimates of the cost of baling hay. The cost of baling hay with a yield of 1.18 metric tons per acre is estimated to be \$20.5 per acre in Illinois. We consider a high cost scenario in which baling costs of switchgrass and miscanthus increase proportionately with yield. In the low cost scenario the fixed costs of baling (tractor and implement overhead) are estimated to be \$14.3 per acre and to be invariant with yield. The variable costs of baling include costs of fuel, lube, and labor which depend on the biomass yield to be baled. These are estimated to be \$5.25 per metric ton (FBFM, 2008). We also consider a high and a low cost scenario for storage of biomass; the former with storage in an enclosed building and the latter with storage in the open field on crushed rock covered by tarp. Storage costs are estimated to be \$18.37 per metric ton in the former case (Duffy, 2007) and \$3.22 per metric ton in the latter case (Brummer et al., 2000). Loss of biomass is assumed to be 2% and 7% in the high and low cost scenarios, respectively.

The costs of producing corn stover include the cost of fertilizer that needs to be applied to replace the loss of nutrients and soil organic matter due to removal of residue from the soil. The costs of replacement fertilizer are obtained by assuming that removal rates of N, P, and K are 7.72, 1.76 and 16.76 pounds, respectively, per dry metric ton of stover removed as estimated by Sheehan et al. (2003). In addition, corn stover collection will involve a second pass through the field using commercial equipment after harvesting the corn grain. The costs of mowing, raking, baling, and staging are determined for a high cost and low cost case using similar assumptions as described above. Similar to Malcolm (2008), we assume that 50% of the residue can be removed from fields if corn is produced using no-till continuous corn rotation and 30% can be removed if conventional till was practiced. These estimates are more conservative than those in Khanna (2008). In addition, we consider a scenario of high stover yield, in which 70% of residue can be removed from fields if corn is produced using no-till continuous corn rotation and 50% can be removed using conventional till while other cost items remain the same as in the low cost scenario.

The estimates of breakeven cost of production of cellulosic feedstocks under average yield conditions in Illinois are shown in Table 1. The opportunity costs of land are the foregone profits from a corn-soybean rotation on that land. In the case of corn stover, the opportunity cost of land is estimated under the assumption that demand for corn stover leads to a switch from a corn-soybean rotation to continuous corn with 12% lower corn yields and 40 lbs per acre greater fertilizer applications in the absence of nitrogen fixation by soybeans (University of Illinois Extension, 2002). The costs of producing these feedstocks vary considerably due to spatial differences in their yields as well as differences in the costs of land. The costs of corn and corn stover are lower in the northern and central regions of Illinois, while the lowest costs for miscanthus prevail in the southwestern and southern regions of Illinois. The per unit cost of producing switchgrass in Illinois is extremely high compared to miscanthus.

Table 1. Farmgate Costs of Production of Cellulosic Feedstocks in Illinois

Cost Items (\$/Acre)	Switchgrass		Miscanthus		Corn Stover		
Scenario	High Cost	Low Cost	High Cost	Low Cost	High Cost	Low Cost	High Yield
Fertilizer	66.7	66.7	29.8	29.8	11.85	11.85	16.59
Chemicals	7.7	7.7	0.5	0.5	-	-	-
Seed	7.0	7.0	70.8	70.8	-	-	-
Interest on operating inputs	5.7	5.7	7.1	7.1	0.83	0.83	1.16
Preharvest Machinery	14.1	14.1	11.0	11.0	-	-	-
Harvesting	117.4	82.5	277.5	151.6	55.0	52.3	60.15
Storage	77.3	14.6	199.3	37.6	29.8	5.6	7.86
Annualized Total Operating Cost (\$/acre)	296.3	198.3	595.9	308.4	97.5	70.6	85.8
Annualized deliverable yield (t dm/acre) ^a	3.5	3.3	8.5	8.1	1.4	1.3	1.79
Breakeven cost (\$/t dm)	84.5	59.6	70.1	38.2	70.2	55.1	47.91
Opportunity cost of land (\$/ t dm) ^b	125.8	132.6	51.9	54.7	61.5	64.8	46.26
Breakeven cost inc. land (\$/t dm)	210.3	192.2	122.0	92.9	133.6	119.9	94.03

^a Deliverable yield at the farmgate estimated after including losses during harvest and storage. Yield losses during storage are assumed to be 7% in the low cost scenarios and 2% in the high cost scenario.

^b Opportunity cost of land is estimated assuming a price of \$5 per bushel for corn and \$12 per bushel for soybeans and a yield of 145 bushels/acre for corn and 50 bushels/acre for soybeans with a corn-soybean rotation.

Ethanol yield from corn grain is 2.8 gallons of denatured ethanol per bushel of corn. Based on pilot demonstrations cellulosic biofuel yield from a nth-generation stand alone plant is estimated as 87.3 gallons per metric t dm of biomass (Wallace et al., 2005). Because of its high deliverable yield (average annualized value of 8.5 t dm per acre), miscanthus produces 86% more ethanol than corn per unit of land (with a yield of 145 bu/acre under a corn-soybean rotation), more than twice as much as switchgrass and five times as much as corn stover.

The cost of conversion of corn grain to ethanol is obtained from a dry mill ethanol plant simulator developed by Ellinger (2008), which simulates the performance of a 100 million gallon capacity plant over a seven-year period. The cost is estimated to be \$0.69/gallon in 2007 prices with adjustments based on Wu (2008). A co-product credit for DDGS is included assuming that 17.75 lbs of DDGS is produced per bushel of corn used for ethanol. The non feedstock costs of producing cellulosic ethanol are estimated to be \$1.46 per gallon for a 25 million gallon capacity plant operating 330 days a year in 2007 prices (Wallace et al., 2005).

The costs of biofuel production from alternative feedstocks are reported in Table 2. Ignoring the opportunity cost of land, corn ethanol has the highest feedstock cost while ethanol from miscanthus has the lowest. When the opportunity cost of land is included, miscanthus is still the cheapest feedstock at farmgate but switchgrass becomes the most expensive. Under average conditions, the cost of ethanol production from corn is estimated as \$1.99/gal while the cost of cellulosic ethanol varies between \$2.61/gal and \$3.96/gal, with miscanthus ethanol being the cheapest and switchgrass ethanol the most expensive.

Table 2. Cost of production of biofuels from alternative feedstocks (in \$/gallon)^a

Feedstock	Feedstock cost ^b		Opportunity cost of land		Non feedstock cost	Co-product credit	Total cost		Feedstock cost at farmgate ^c	
	High cost	Low cost	High cost	Low cost			High cost	Low cost	High cost	Low cost
Corn	1.78	1.78	-	-	0.69	0.48	1.99	1.99	1.78	1.78
Corn stover	1.03	0.84	0.70	0.74	1.46	0.12	3.08	2.92	1.53	1.37
Switchgrass	1.18	0.89	1.44	1.52	1.46	0.12	3.96	3.71	2.41	2.20
Miscanthus	1.01	0.65	0.59	0.63	1.46	0.12	2.95	2.61	1.40	1.06

^a Due to space limitations, costs of biofuel from corn stover in the high yield scenario are not reported in this table. These costs are: feedstock cost, \$0.55/gal; opportunity cost of land, \$0.53/gal; total cost, \$2.42/gal; and feedstock cost at farmgate, \$0.87/gal.

^b This cost includes transportation cost but excludes opportunity cost of land.

^c This cost excludes transportation cost but includes opportunity cost of land.

To obtain the demand functions for corn and soybeans faced by Illinois producers, we use short-run national demand and supply price elasticities estimated by various sources. For corn, we use the demand elasticity of -0.16 (OECD, 2001) and supply elasticity of 0.2 (Gardner, 1976). The corresponding estimates for soybeans are -0.594 (USDA/ERS, 2007) and 0.45 (Gardner, 1988), respectively. The share of Illinois in the U.S. corn and soybean production in 2007 is 17.1% and 14.9%, respectively (USDA/NASS, 2008a). The commodity prices and production quantity in 2007 (excluding the amount of corn used for ethanol) are used to estimate the parameters of the demand functions for corn and soybeans. For wheat, sorghum and alfalfa, the farmgate prices are assumed to be exogeneous and remain constant throughout the planning horizon at their 2007 values observed in Illinois (USDA/NASS, 2008b).

We use the data on total planted acres by county and state-level prices for corn, soybeans, sorghum, wheat and alfalfa for 1995-2007 to estimate the relationship between cropland acreage and the lagged value of the Laspeyres crop price index for each county (with 1995 as the base year). We determine the elasticity of crop specific acreage responses with respect to own and cross prices for corn and soybeans for each of the nine crop reporting districts (CRD) in Illinois. In the estimation procedure, we incorporate the current and lagged regional acreages, the lagged state level crop prices, a time trend, and the national commodity stock levels in December of the previous year. The crop acreage response elasticities estimated thereby for each CRD are then used for determining the land supply in the counties belonging to that CRD.

We consider six most commonly practiced rotation choices in Illinois and two tillage choices for the row crops. Methods used to determine the costs of production of each crop under conservation tillage are described in Dhungana (2007). County-specific historical acres under each crop (crop mixes) for the period 1995-2007 are obtained from (USDA/NASS, 2008b) and used to set bounds for the allocation of land among crops in each county. We also use simulated (hypothetical) crop mixes for each county, which are generated by assuming different combinations of crop prices increased by 50% and 100% over their 2007 levels and by using the estimated crop specific elasticities mentioned above.

We conduct a life cycle analysis of the above ground CO₂ equivalent emissions (CO₂e) generated from biofuels production using different feedstocks; emissions of the major GHGs are

converted to equivalent levels based on their 100-year global warming potential (IPCC, 2001). We include the CO₂e generated not only from various inputs and machinery used on the farm in the production of each feedstock and the energy used to produce and transport those inputs to the farm, but also from the energy used to transport the feedstock to a biorefinery and the energy used to convert the feedstock to biofuel. Specifically, inputs for feedstock production include fertilizers (e.g., nitrogen, phosphorous and potassium), herbicides, and insecticides. Energy used in the production of biofuel feedstock includes the direct consumption of gasoline, diesel, liquefied petroleum gas, and electricity, and the indirect consumption of energy embodied in farm equipment such as tractors and plows. Similarly, CO₂e generated during the biorefinery phase accounts for the energy used to convert the feedstock to fuel and the energy embodied in buildings and equipment in the biorefinery. CO₂e is obtained by aggregating the CO₂ emissions from the energy used and the GHG emissions induced from the use of the inputs such as nitrogen and lime. For more details regarding the assumptions and parameters used in our life cycle analysis for biofuel feedstock production, see Dhungana (2007); for biofuel conversion, see Farrell et al. (2006). CO₂e from corn stover ethanol is estimated using an incremental emissions approach as described in Wu et al.(2006). Specifically, life cycle emissions arising from stover harvesting and additional chemical application as a result of stover removal are evaluated. If demand for corn stover, miscanthus, or switchgrass leads to a switch away from the baseline corn-soybean rotation to alternative land uses, the change in emissions due to this change is also incorporated.

Finally, the annual corn and cellulosic biofuel production targets for Illinois are assumed to be 20% of their respective annual national ethanol mandates. These targets are specified for each year of the planning horizon (e.g., for 2022 the respective mandates are 3 billion and 4.2 billion gallons).

5. Results

We simulate land use decisions in Illinois between 2007 and 2022 under four scenarios: no biofuel targets (baseline), biofuel targets with high costs of feedstock production (high cost), biofuel targets with low costs of feedstock production (low cost) and biofuel mandates with high corn stover removal rates and low costs of feedstock production (high stover yield) (see Table 3). Imposing biofuel targets has three types of effects on land use. First and foremost, it increases the demand for land, which in turn increases the cropland brought into production relative to the baseline. Second, the mandate leads to a conversion of land from food crops to biofuel crops. Third, the biofuel targets and the resulting demand for corn stover lead to a significant change in the tillage and rotation choices for crop production. More specific results are given below.

Under all three scenarios with biofuel targets, we find that the total land use increases by about 5% by 2022. The results also show an increase in the percentage of land under corn (from 47% to 53%-55%), a decrease in the percentage of land under soybeans (from 45% to 29%), wheat (15% reduction) and pasture (44% reduction). Of the total corn produced, 56% would be used to produce ethanol and 14% of the cropland would be diverted to produce miscanthus by 2022 under the high cost and low cost scenarios. The land under miscanthus would be lower but still significant (10% of the total cropland) under the high stover yield scenario. Switchgrass would not be produced under any of the scenarios we analyzed because of its yield and cost

disadvantage compared with miscanthus. The biofuels target results in the use of 100% of the available corn stover for cellulosic biofuel production in 2022 under all scenarios.

The trends in acreage under corn, stover, and miscanthus under the low cost scenario are shown in Figure 1. We find that miscanthus and corn stover would be used conjunctively to produce biofuels. Specifically, 36% of the cellulosic target in 2022 would be produced from corn stover. Assumptions about corn stover removal rates have a significant impact on the trends in allocation of acreage among cellulosic feedstocks. In this case, stover production begins in 2010 and is used to meet 83% the cellulosic target in 2015 and 53% of the cellulosic ethanol in 2022.

Figure 1. Trends in acreage in low cost scenario

The diversion of land to biofuel production affects the prices of both corn and soybeans because of the reduced acreage and production of these commodities for food and feed uses, as shown in Figure 2. As compared to the baseline, biofuel targets lead to an increase in total production of corn from 1.7 billion bushels in the baseline to about 1.9 billion bushels, a decrease in food and feed uses by about 50% for corn and 36% for soybeans, an increase in corn prices from \$4.22 to \$6.09 per bushel (by 44%) and an increase in the price of soybeans by 7% from \$10.60 to \$11.40 per bushel. Corn and soybean price in the high stover yield scenario are very similar to those in the other scenarios. The cost of producing cellulosic biofuels differs in the three scenarios due to differences in the share of biofuels from corn stover vs. miscanthus.

For instance, the cost of corn ethanol in 2022 is \$2.17 per gallon and that of cellulosic ethanol is \$2.99 per gallon in the low cost scenario and \$4.08 per gallon in the high cost scenario. With the high stover yield, the costs of producing corn ethanol and cellulosic ethanol are lower, \$2.09 and \$2.54 per gallon, respectively.

Figure 2. Trends in prices in baseline and low cost scenario

The cropland under corn-soybean rotation decreases from 80% to 29% in the low cost scenario, and 27% in the high cost or the high stover yield scenarios, while the land under continuous corn increases from 7% to 36%, 37% and 37% in the low cost, high cost and the high stover yield scenarios, respectively. We also see an increase in the land under conservation tillage which allows a larger percentage of corn stover to be collected, from 28% in the baseline to about 59% in both the low and high cost scenarios with the mandate in 2022. The land under conservation tillage increases from 27% to 61% in the high stover yield scenario, leading to a reduction in the land allocated to miscanthus compared to the other two scenarios.

We find considerable spatial variability in the acres devoted to cellulosic feedstocks across counties and over time. Under the low cost scenario, in 2015, 90% of the corn acreage would be in the central and northern counties while corn stover would be collected in 73 of 102 counties (6.3 million acres). In contrast, by 2022, the land under corn is reduced in 33 southern

counties (by 884 thousand acres) due to the increase in the cellulosic biofuel target which in turn increases the acreage of miscanthus in that region, as shown in Figure 3. Under the high stover yield scenario, in 2015, corn stover would be collected from 4.6 million corn acres in 52 central and northern Illinois counties. Under all three scenarios, corn stover is collected from the entire corn acreage in 2022. Under the low cost scenario, towards the end of the planning horizon 67 of the 102 Illinois counties would allocate about 14% of their total cropland to miscanthus production, which expands primarily in the southern counties, from 1.3 million acres in 2015 to 2.5 million acres in 2022.

Finally, we estimate that the cumulative GHG emissions (2007-2022) from production of corn and soybeans and the use of energy equivalent gasoline in the absence of biofuel targets is about 0.84 million metric tons. The total emissions over the same period with biofuel targets are estimated as 0.39 million metric tons, 54% lower than the baseline. This reduction is generated primarily by the displacement of gasoline by ethanol which more than offsets the increase in emissions due to greater corn production. The flip side of this environmental benefit is the increased use of nitrogen in agricultural production, which may have adverse implications for water quality. While the total GHG emissions are halved, nitrogen use would be increased by 25% relative to the baseline level because of several reasons, including: i) the expansion of corn acres, ii) conversion of land from corn-soybean rotation with conventional tillage to the more carbon intensive continuous corn, and iii) removal of corn stover that has to be compensated by increased use of nitrogen fertilizers. Expansion of perennial crop acreage to meet the biomass demand of the cellulosic ethanol industry adds very little to nitrogen use due to its low requirements for nitrogen.

6. Conclusions

This article examines the implications of biofuel production targets up to 2022, mandated by the Energy Independence and Security Act, for the allocation of land among food and fuel crops and the resulting impacts on crop prices. Although the study has a somewhat narrow regional focus, the main conclusions are likely to be valid for U.S. agriculture as a whole, commodity markets, and environmental costs/benefits. We find that biofuel targets lead to a significant shift in the acreage from soybean, wheat and pasture to corn, and a change in crop rotation and tillage practices. Despite an increase in corn production by 12%, the biofuel targets considered here result in significantly higher corn and soybean prices due to the diversion of about 56% of the corn produced to ethanol production. Among cellulosic feedstocks, we find that corn stover is likely to play an important role in meeting the cellulosic biofuel targets in Illinois mainly due to its relatively low cost of production and high yields in this region. All of the available corn stover that can be sustainably harvested is, however, insufficient to meet the biofuel target; this creates demand for miscanthus as an inevitable alternative source of bioenergy. There is considerable spatial variability in the allocation of land to food and fuel crops across Illinois, with much of the corn stover production occurring in central and northern Illinois while miscanthus production occurs mostly in southwestern Illinois. Finally, our analysis highlights the trade-offs involved in relying on biofuels, particularly the current generation of biofuels, in terms of climate change mitigation and water quality improvements. Increased biofuel production reduces GHGs by 54%, but it increases nitrogen use by 25% relative to the baseline. In contrast, cellulosic biofuels from grasses, such as miscanthus, offer the potential for carbon emissions reduction with minimal increases in nitrogen applications.

Table 3. Effect of biofuel targets on land use, crop production and the environment

	Variables (Values calculated for 2022)	Non- ethanol baseline	High Cost	Low Cost	High Stover Yield
Land use	Total land (M Acres)	22.04	23.10	23.09	23.13
	Land under corn (%)	47.83	53.46	53.32	55.27
	Land under soybeans (%)	45.42	28.32	28.50	29.37
	Land under wheat(%)	3.34	2.89	2.83	3.24
	Land under pasture(%)	3.09	1.74	1.74	1.84
	Land under stover (%)		53.46	53.32	55.27
	Land under miscanthus (%)		13.50	13.53	10.18
	Land under conservation tillage(%)	27.55	58.96	58.61	61.49
	Land under corn-soybean rotation (%)	80.05	27.02	29.48	30.58
	Land under corn-corn rotation (%)	7.21	37.25	35.95	36.96
Crop Production, Consumption (M Bushels)	Corn Production	1709.24	1927.1	1923.61	1983.11
	Corn Consumption (non ethanol use)	1709.24	855.67	852.18	911.68
	Soybeans	449.83	283.71	285.69	292.44
Prices in 2022 (in 2007 dollars)	Corn (\$/Bu)	4.22	6.04	6.09	5.85
	Soybean (\$/Bu)	10.59	11.35	11.35	11.31
	Corn ethanol(\$/gallon)		2.16	2.17	2.09
	Cellulosic ethanol (\$/gallon)		4.08	2.99	2.54
Volume of ethanol	Corn (B gallons)		3.00	3.00	3.00
	Stover (B gallons)		1.53	1.53	2.21
	Miscanthus (B gallons)		2.67	2.67	1.99
Environmental Effects	Greenhouse Gas Emissions (M tons)	0.84	0.39	0.39	0.38
	Energy Equivalent Fuel Emissions	0.76	0.26	0.26	0.26
	Corn Production	0.08	0.10	0.11	0.11
	Stover Production		0.007	0.007	0.015
	Miscanthus Production		0.008	0.008	0.005
	Nitrogen Use (1000 tons)	13.39	16.76	16.75	16.91
	Corn Production	12.99	15.79	15.78	15.88
	Stover Production		0.39	0.39	0.49
	Miscanthus Production		0.20	0.20	0.15

Figure 3. Spatial heterogeneity in land use with biofuel targets in low cost scenario

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