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Economics of herbaceous bioenergy crops for electricity generation: Implications for greenhouse gas mitigation☆

Madhu Khanna [a,*], Hayri Önal [a], Basanta Dhungana [a], Michelle Wander [b]

[a] Dept. of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, 1301, W. Gregory Drive, Urbana, IL, 61801, USA
[b] Dept. of Natural Resources and Environmental Sciences, University of Illinois at Urbana-Champaign, IL, USA

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ABSTRACT

This paper examines the optimal land allocation for two perennial crops, switchgrass and miscanthus that can be co-fired with coal for electricity generation. Detailed spatial data at county level is used to determine the costs of producing and transporting biomass to power plants in Illinois over a 15-year period. A supply curve for bioenergy is generated at various levels of bioenergy subsidies and the implications of production for farm income and greenhouse gas (GHG) emissions are analyzed. GHG emissions are estimated using lifecycle analysis and include the soil carbon sequestered by perennial grasses and the carbon emissions displaced by these grasses due to both conversion of land from row crops and co-firing the grasses with coal. We find that the conversion of less than 2% of the cropland to bioenergy crops could produce 5.5% of the electricity generated by coal-fired power plants in Illinois and reduce carbon emissions by 11% over the 15-year period. However, the cost of energy from biomass in Illinois is more than twice as high as that of coal. Costly government subsidies for bioenergy or mandates in the form of Renewable Portfolio Standards would be needed to induce the production and use of bioenergy for electricity generation. Alternatively, a modest price for GHG emissions under a cap-and-trade policy could make bioenergy competitive with coal without imposing a fiscal burden on the government.

1. Introduction

U.S. greenhouse gas (GHG) emissions have increased by approximately 1% each year in the last decade. More than a quarter of the emissions are generated by coal-based electricity production [1]. Concerns about climate change have led to growing interest in renewable fuels for electricity generation and many states in the U.S. have established Renewable Portfolio Standards to encourage utilities to generate a minimum percentage of their electricity from renewable sources. One such renewable fuel source is biomass from bioenergy crops such as willow, short rotation woody crops and herbaceous perennials. As compared to coal, these fuel sources reduce GHG emissions, produce virtually no sulfur dioxide emissions and contain low amounts of ash and mercury [2]. Moreover, compared to the traditional row crops they displace, production of perennial crops requires considerably less fossil fuel energy and can result in much higher soil carbon sequestration [3].

The purpose of this paper is to examine the conditions under which cropland would be allocated to bioenergy crops,

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* *Corresponding author.*
E-mail address: khanna1@illinois.edu (M. Khanna).

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and the spatial variability in that allocation, for co-firing in coal-based power plants in Illinois at various bioenergy prices. The bioenergy crops considered here, switchgrass and miscanthus, are perennial grasses that can be grown on cropland and are being promoted by the USDOE [4]. Switchgrass (*Panicum virgatum*) was identified by the USDOE as a "model" crop due to its relatively high yields, adaptability to a wide range of growing conditions, and environmental benefits [5]. Miscanthus (*Miscanthus x giganteus*) has been studied and grown in Europe for bioenergy and grown experimentally in the US since 2002 following establishment of field trials at the University of Illinois Agricultural Research and Education Centers [6].

Our analysis recognizes that the costs of growing these bioenergy crops and their yields vary both spatially (depending on soil and weather conditions, opportunity costs of land and costs of transportation to power plants) and temporally (depending on the age of the perennial crop). We develop a spatially disaggregated dynamic optimization model using detailed geospatial data on crop yields, input applications and transportation costs to existing coal-based power plants in Illinois to analyze the extent to which cropland can be allocated to bioenergy crops. These costs are determined using a biophysical crop productivity model which simulates bioenergy crop yields depending on soil conditions and climate. This framework is used to examine potential changes in land allocation between bioenergy crops and row crops over a 15-year horizon from 2003 to 2017. The model includes a transportation module that links power plants to bioenergy crop growing areas based on costs of production and transportation. We obtain a supply curve for biomass for Illinois and analyze implications of bioenergy crop production for farm income, subsidy payments and GHG emissions under various assumptions about the technical potential to co-fire biomass with coal.

We also use lifecycle analysis to examine the potential for bioenergy crops to reduce GHG emissions. We incorporate not only the energy consumed during production and transportation of bioenergy crops but also the energy saved by replacing row crops on cropland and the additional soil carbon sequestration achieved. Each of these components is location specific and the GHG mitigation benefits depend on where the bioenergy crops are grown. Our estimation of the soil carbon sequestration potential of crops recognizes that it varies spatially (depending on the land use history and soil and climatic conditions) and temporally (depending on the amount of carbon already present in the soil) [7]. Moreover, there is an upper limit on the amount of carbon that can be stored in soil and the annual sequestration rate diminishes over time as the soil carbon level approaches the equilibrium level established by the land use practice applied [8].

Several studies have estimated the costs of producing switchgrass in the U.S [9–12] and for miscanthus in Europe [13] and in the US [14]. With the exception of the last study which examines the spatial variability in these costs, other studies estimate these costs under representative conditions only. Other studies compare the production cost of switchgrass with herbaceous crops [15–17] and woody crops such as willow and poplar [18]. They find that while the production cost of switchgrass is lower than that of other herbaceous and woody crops they are much higher than that of miscanthus [14]. Cropland allocation at regional level in the U.S. for large-scale production of switchgrass, willow and poplar at various farmgate prices for these crops is examined by [17]. That study, however, does not consider specific end-uses of these crops, the cost of transportation to processing facilities, and environmental implications. A GIS-based model is developed by [19] to examine the cost of delivering feedstock to ethanol facilities while a few studies evaluate the economic viability of co-firing bioenergy with coal in a power plant, under representative conditions. These studies show that substantial policy support is needed to make bioenergy crops, such as willow [20], wood and waste fuels [21], corn stover [22], woody biomass [23] and switchgrass [24], competitive with coal.

This paper makes several contributions to this emerging literature on the economics of bioenergy production. We develop a spatially disaggregated micro-economic framework using detailed geospatial data on crop yields and costs of production and delivery to analyze the extent to which cropland in Illinois can be allocated to bioenergy crops and its spatial pattern. Using site-specific estimates of the lifecycle GHG emissions from alternative crops we find that even modest allocation of land to bioenergy crops for co-firing with coal has the potential to reduce emissions considerably. We provide estimates of the bioenergy prices needed to provide incentives to switch land from row crops to bioenergy crops and show that considerably large subsidies will be needed to make bioenergy competitive with coal given current coal prices, even with a high-yielding grass such as miscanthus. Given the large GHG mitigation potential of bioenergy crops, our analysis suggests that even a moderate carbon price under an international cap-and-trade program can be effective in creating incentives to produce and co-fire bioenergy for electricity generation in Illinois.

In Section 2 we present an overview of the theoretical model followed by a description of the data set in Section 3. A detailed technical description of the model can be found in [25] and [26], which are available from the authors upon request. Simulation results are presented in section 4 followed by the conclusions and policy implications of this study in Section 5.

2. An overview of the model

The model developed here examines the optimal allocation of land among various annual row crops with alternative management practices (rotations and tillage choices) and perennial grasses that can be used for either forage or co-fired with coal in power plants such that the discounted present value of aggregate profits over a specified time horizon is maximized. The study area is divided into sub-regions where each sub-region is assumed to be represented by a single decision maker (an aggregate producer) who is endowed with the productive resources available in that region. The sub-regions differ in terms of crop productivity and the profitability of alternative land uses. They also differ in their proximity and therefore the costs of transporting biomass to existing power plants.

The price of bioenergy paid by all power plants is assumed to be the same. The farmgate price received by bioenergy crop producers in each sub-region differs depending on the proximity to the power plant to which the crop is delivered. We also include constraints on bioenergy demand and supply. We assume that the demand for biomass is constrained by the technical capacity of coal-based power plants to co-fire bioenergy. Experience from co-firing in Europe and the U.S. shows that 5–15% biomass (on energy basis) can be co-fired in coal plants without loss of thermal efficiency and problems of corrosion, fuel handling and fuel feeding [27]. We consider alternative specifications for the co-firing capacity of power plants in sensitivity runs. Incorporation of the biomass transportation costs in the objective function implies that each power plant will acquire its biomass input in the least expensive way subject to the regional biomass supplies. Transportation costs limit the distance from which power plants will obtain biomass. Finally, we include a constraint on the total amount of land available and on the ease with which it can be converted from one type of crop or land use to another, to prevent large-scale and abrupt changes in land use. 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. We limit the change in land under row crops to lie within ±10% of land observed under that crop historically. All input and crop output prices are assumed to be constant over time, but differ across sub-regions depending on their distances to major markets.

We then examine the implications of this land allocation for soil carbon sequestration and lifecycle carbon emissions from power plants. The soil carbon sequestration of alternative land uses depends on the existing stock of soil carbon in each sub-region, the capacity for additional carbon sequestration with each land use alternative in each sub-region, and the length of time a particular land use/practice is maintained continuously. Moreover, the costs and yields of perennials in any sub-region also vary with the age of the perennial. The simulation is run in annual time steps for the 15-year period, 2003–2017. By solving the model repeatedly at different prices of biomass, a supply function of biomass and area allocated to bioenergy crops is obtained for a given assumption about the limit to co-firing by power plants.

3. Data

In the model we use county level data for the state of Illinois. The crop choices include four row crops (corn, soybeans, wheat, and sorghum), grown using either conventional or conservation tillage practices, and three perennial crops including pasture for forage and switchgrass and miscanthus for biomass that can be co-fired with coal. The biomass can be delivered to any of the locations where coal-based electricity-generating plants exist in Illinois. Switchgrass and miscanthus have low input requirements, particularly energy and fertilizers, and a tolerance for the cool temperatures in the Midwest. Thus, they can be grown on a broad range of land types using conventional farming practices. Switchgrass is assumed to have a productive life of 10 years while miscanthus has a life of 20 years, both of which are assumed to be replanted or converted to row crops beyond those times. Crop productivity models as well as field trials in Illinois indicate that miscanthus has relatively high yields, more than twice the yield of switchgrass and higher than those observed in Europe [6,28].

Four types of data are compiled for these crop choices for each of the 102 counties that comprise approximately 940,000 km^2 of cropland in Illinois [29]. These include data on crop yields, rotation- and tillage-specific costs of production for row crops, age-specific costs of production for perennials, and data on location and capacity of coal-fired power plants. Each county is assumed as a decision unit where a representative farmer allocates the available cropland between the crops listed above under the existing average production characteristics pertaining to that county. This implies that the same average costs and crop yields apply to the entire county.

3.1. *Crop yields*

The yields of switchgrass and miscanthus are projected using a process-based crop productivity simulation model, MISCANMOD [30], which is applied to Illinois conditions using long term historical data on climate, weather and soil moisture as described in [14]. Simulated miscanthus yields are lowest in northern Illinois and increase as one moves south as consistent with observed data from field experiments [6]. For switchgrass, we use the results of field experiments in Iowa and Illinois assuming that the average yield of switchgrass is 25% of the yield for miscanthus predicted by MISCANMOD in each county. Yields for corn, soybean, wheat, sorghum, and pasture for each county are set at their five year (1998–2002) historical averages [29]. Land available for all crops (including bioenergy crops) in each county is kept constant at the level planted under these crops in 2002. Due to lack of available data on non-cropland available for conversion to bioenergy crops we do not include it in our analysis.

3.2. *Crop production costs and revenues*

Crop budgets that itemize costs of production for each of the perennial crops and row crops for each county vary by tillage and rotation choice. Production costs include: costs of chemicals, fertilizers and seeds; costs of equipment for land preparation and harvest operations; costs of drying and crop insurance for row crops; costs of storage and transportation of biomass; and interest payments on all variable input costs. A detailed description of the assumptions underlying the determination of these costs can be found in [14]. We also include the cost of switching land from perennials to row crops due to the use of herbicides to control weeds [31]. The costs of land, overhead (such as farm insurance and utilities), building repair and depreciation, and the farmer's own labor are not included in the costs of perennials or row crops since they are assumed to be the same for all crops and do not affect the crop choice. Transportation costs from each county to each coal-fired power plants in Illinois are calculated using the "great circle" distance method based on geo-referenced data on location of county centers and power plants [32].

For expected crop prices we use the county level loan rates for corn, soybean, wheat and sorghum. The price of alfalfa is the average price reported for Illinois by NASS/USDA [29]. We assume that the price that a power plant would be willing to pay for biomass would depend on the price of coal and the energy content of the biomass. The relevant data were obtained from different sources, particularly [33] and [34]. All costs and revenues are discounted to the beginning of the simulation horizon using a discount rate of 4%.

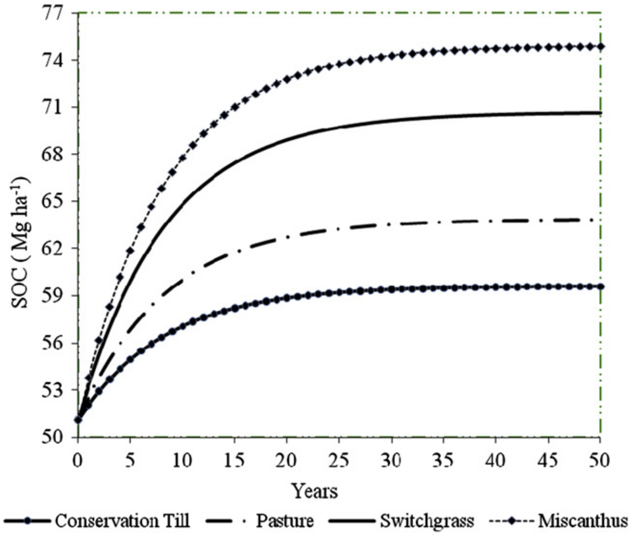

Fig. 2 – Cumulative carbon response function with various land uses in christian county, Illinois.

3.3. *Soil carbon sequestration*

Soil carbon sequestration rates are calculated by assuming a negative exponential time path for sequestration with saturation limits depending on the land use. The land uses considered here are conservation tillage, pasture and perennial grasses. The annual rate of sequestration with a given land use depends on the existing stock of carbon in the soil and on the sequestration potential for that land use. Estimates of the county-specific carbon stocks are obtained from estimates of the percentage of soil organic matter (SOM) for major soil series and the percentage of total county land in that soil series in each county in Illinois from [35] using methods described in [25]. These are shown in Fig. 1. There is a wide variation in the existing carbon stock across counties, ranging from 24.5 to 78.6 Mg ha^{-1} in 2003. Carbon stocks are typically higher in the northeastern and central regions of Illinois. We estimate differing annual sequestration rates across land uses and counties due to the variability in existing levels of accumulated carbon and in sequestration potential with alternative land uses. Carbon accumulation rates are based on each county's site-specific characteristics, specifically the existing level of soil carbon, the long–run equilibrium level of soil carbon and the natural growth rate of carbon accumulation (as in [36]), as shown for Christian county in Illinois in Fig. 2. Methods used to obtain carbon accumulation rates are described in [26] and rates obtained are reported in Table 1. Carbon accumulated on land previously under a given land use (including conservation tillage) is assumed to be released back to the atmosphere if this land switches to a different land use.

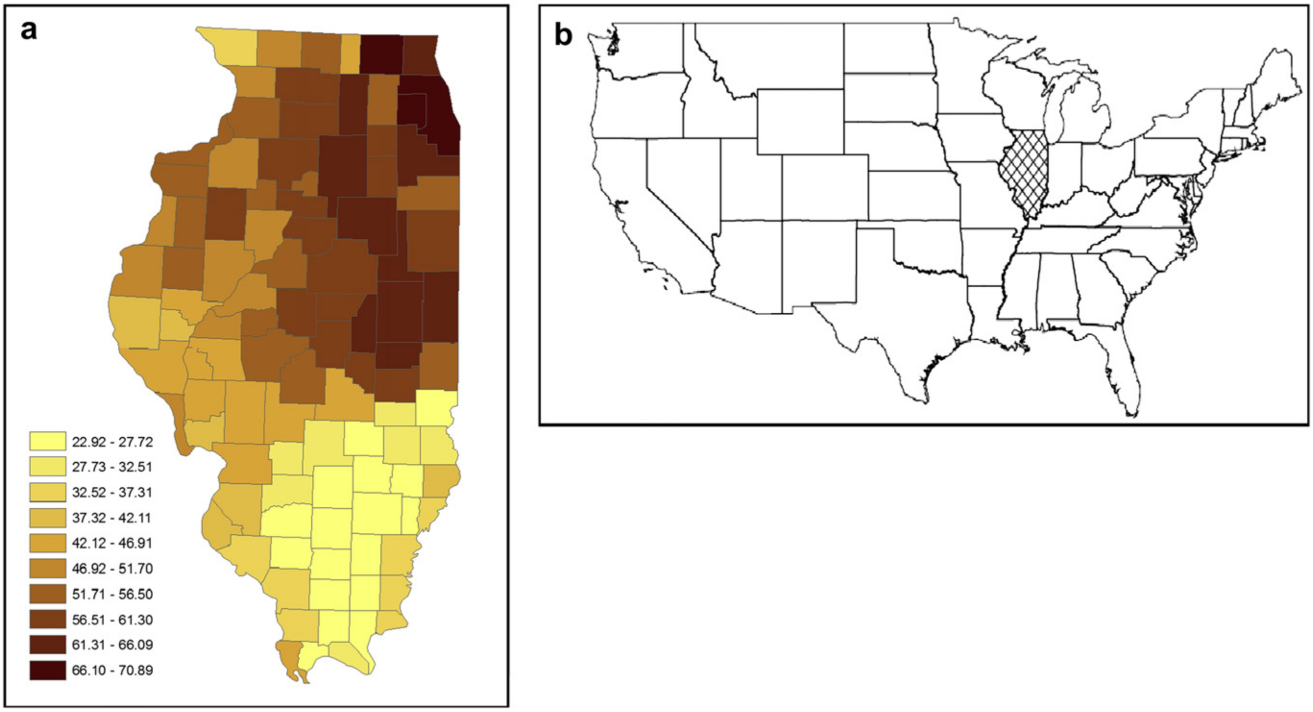

Fig. 1 – a. Soil carbon level in 2003 (t ha^{-1}). b. Map of the United States of America showing location of Illinois. llinois is shown by the cross-hatched area above. Its latitude and longitude are 40°N and 89°W.

Table 1 – Carbon Sequestration Rates.

Land Use	This Study[a] (carbon Mg ha^{-1} in 20 years)	Previous studies (carbon Mg ha^{-1} in 20 years)	References
Conservation till	3.46–10.43	5.93–9.88	[40], [41], [42]
Pasture	5.19–15.64	7.91–24.71	[42], [43], [44]
Switchgrass	7.93–23.99	13.84–22.24	[45], [46]
Miscanthus	9.69–29.21	18.78–27.68	[47], [48], [49]

a This is the range of estimates obtained across the different counties in Illinois. Methods used to obtain these estimates are described in [26].

3.4. *Carbon-dioxide emission mitigation through co-firing*

We estimate the GHG emissions per kilowatt hour (kwh) in CO_2 equivalent (CO_2e) terms of coal and biomass. CO_2e emissions are estimated by aggregating the major GHGs emitted, namely carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), using their 100-year global warming potential factors. These are 1 for CO_2, 23 for CH_4, and 296 for N_2O [37]. To aggregate the above-ground emissions and the soil carbon sequestration we convert CO_2e to carbon (Carbon = 12/44 CO_2e) and report those below. The CO_2e with biomass production is computed using lifecycle analysis and based on energy embodied in the machinery used in the production of each crop, the energy used to produce other inputs such as fertilizers and herbicides, and the energy used directly in the form of fuel for operating machinery and transporting the biomass. The estimates for a representative field in Illinois are presented in Table 2 and the assumptions underlying these are available in [26]. These estimates differ across counties due to differences in input application rates for each crop as described in [14].

We estimate the reduction in emissions for each hectare of land converted from existing uses (which is primarily corn-soybean rotation) to switchgrass or miscanthus (see Table 2). These are estimated using the county-specific input application rates for each crop. Fuel use per hectare for corn production is based on the rate provided for Illinois by [38]. We estimate emissions from switchgrass and miscanthus using input application rates described in [14]. Fossil fuel energy requirements for harvesting and post-harvesting operations are based on an extensive review of European studies [39]. Switchgrass and miscanthus are estimated to generate GHG emissions as CO_2e at rates of 1.66 Mg ha^{-1} and 1.57 Mg ha^{-1}, respectively.

On average switchgrass and miscanthus have the potential to sequester CO_2e at the rate of 3.12 Mg ha^{-1} y^{-1} and 3.78 Mg ha^{-1} y^{-1}, respectively, over the 20 years that it takes to achieve saturation. Electricity generated using switchgrass and miscanthus is estimated to reduce CO_2e emissions (on average) by 1.31 Mg MW h^{-1} and 1.09 Mg MW h^{-1}, respectively (for assumptions underlying this see [25]). This results in negative emissions per megawatt hour generated with bioenergy compared to coal-based electricity which releases CO_2e at the rate of 0.95 Mg MW h^{-1} (Table 2).

4. Results

We first determined the base year (2003) profit maximizing land allocation (including the land under conservation tillage and pasture) without any bioenergy subsidy, which we call the 'business as usual' (BAU) scenario. In this scenario we find that about 45% of the total cropland (940,000 km^2) would be under conservation tillage, about 3% under pasture, and the rest under conventional tillage by the 15th year (2017) (see column 1, Table 3). These optimal allocations are close to (within 10% of) the observed land allocations in 2002 in Illinois.

Next we examined the land that would be allocated to biomass production at various bioenergy prices and with various assumptions about the technical capacity of power plants to co-fire biomass with coal. We first considered an upper limit of 5% for co-firing ratio (the base case) and then increased this limit up to 25% for sensitivity analysis. For space concerns, we report the results obtained under the 15% and 25% rates only (Table 3), and show the planted area under miscanthus in all three cases in 2017 in Fig. 3. If power plants pay a coal energy equivalent price for bioenergy (which would be 20.22 \$ Mg^{-1} of biomass or 1.12 \$ GJ^{-1} at the current coal price of 23.9 \$ Mg^{-1} in Illinois) the minimum subsidy that would be needed to make miscanthus profitable is found to be 1.14 \$ GJ^{-1}. Thus, the lowest price of bioenergy (defined as the coal energy equivalent price for energy plus a subsidy) that farmers would need to receive to make it profitable to grow miscanthus is 2.3 \$ GJ^{-1}. This is equivalent to a coal price of

Table 2 – Carbon Emissions from Electricity Generated by Bioenergy Relative to Coal under Representative Conditions.

Sources of emissions and sinks	Unit	Switchgrass	Miscanthus
Carbon emissions during production of energy crops (a)[a]	CO_2e Mg ha^{-1} y^{-1}	1.66	1.58
Carbon sequestration by energy crops (b)	CO_2e Mg ha^{-1} y^{-1}	3.12	3.78
Carbon emissions displaced by energy crops replacing corn-soybeans (c)	CO_2e Mg ha^{-1} y^{-1}	1.96	1.96
Carbon emissions displaced by energy crops replacing coal (d)	CO_2e Mg ha^{-1} y^{-1}	9.48	30.83
Net mitigation (sink) by energy crop production ($e = b - a + c + d$)	CO_2e Mg ha^{-1} y^{-1}	12.99	35.0
Net reduction of carbon per ton of energy crop ($f = e$/yield)	CO_2e Mg Mg^{-1} DM	2.16	1.81
Net reduction of carbon per megawatt hour	CO_2e Mg MWh^{-1}	1.31	1.09

a For underlying assumptions see [26].

Table 3 – Response of Land Use and Greenhouse Gas Emissions Mitigation to Bioenergy Prices.

Biomass co-firing capacity	Units	BAU	15% co-firing capacity			25% co-firing capacity		
Bioenergy price	$ GJ^{-1}	$2.3	$2.8	$3.2	$ 3.6	$2.8	$3.2	$ 3.6
Land under conservation till	%	45.07	44.09	43.17	42.03	43.99	42.84	41.04
Land under miscanthus	%	0.00	1.65	2.78	4.15	1.75	3.49	5.61
Biomass supply	Tg DM	0.00	4.24	7.02	10.18	4.51	8.81	13.85
Electricity generated with biomass	%	0.00	5.53	9.16	13.27	5.88	11.49	18.06
Average distance to power plants from counties	Km	0.00	24.33	33.50	45.34	24.68	36.48	48.06
Total amount of carbon mitigated in 15 Years	Tg	15.85	38.86	54.12	71.64	40.28	63.79	91.46
-coal displacement by biomass		0.00	21.29	35.27	51.05	22.63	44.20	69.38
-sequestration by miscanthus		0.00	2.05	3.97	6.65	2.16	4.89	8.81
-sequestration by conservation till		14.72	14.37	13.82	12.98	14.34	13.63	12.42
-sequestration by pasture		1.13	1.15	1.06	0.96	1.15	1.07	0.85
% of carbon emission mitigated in 15 years		4.32	10.59	14.75	19.53	10.98	17.39	24.93
Discounted present value of bioenergy subsidy	G$	0.00	1.07	2.17	3.72	1.14	2.72	5.06
Discounted NPV of farm profit	G$	48.1	48.32	490.39	50.17	48.33	49.21	50.72

Note: Baseline annual carbon (not CO_2) emissions from coal-fired power plants are 24.46 Tg.

48 $ Mg^{-1}. At this price 660 ha of miscanthus would be planted (with any co-firing limit). This subsidy rate, however, would result in an insignificant amount of miscanthus production (generating less than 0.01% of electricity in Illinois).

As the subsidy is increased to 1.7 $ GJ^{-1} and the bioenergy price is increased to 2.8 $ GJ^{-1} (=1.12 $ GJ^{-1} + 1.7 $ GJ^{-1}), land allocated to miscanthus production increases from zero to 1.7% of the total cropland. Biomass produced on this land is sufficient to generate 5% of the electricity produced in Illinois. Further increases in subsidy would expand the area under miscanthus (Fig. 3). For instance, an increase in the bioenergy price to 3.6 $ GJ^{-1} would expand miscanthus area to 2.5% of the cropland and more than double the share of coal-based electricity generated from biomass. Our results can also be interpreted as indicating the coal prices needed to induce the use of bioenergy by power plants. Bioenergy prices of 2.8 $ GJ^{-1} and 3.6 $ GJ^{-1} are equivalent to coal prices of 60.2 $ Mg^{-1} and 76.3 $ Mg^{-1}, respectively. As coal prices increase above the current level of 23.9 $ Mg^{-1}, the need for a subsidy for the use of bioenergy would decrease correspondingly.

As the bioenergy price increases, we observe a reduction primarily in the area under row crops (with both types of tillage practices). A small amount of land under hay production is converted to miscanthus, primarily because hay production is very profitable in Illinois. The percentage of cropland under hay production remains at about 2.6% under all scenarios examined here. The reduction in conservation tillage practice is more pronounced than conventional tillage because the former is less profitable in many counties. We do not find it profitable to allocate any land to switchgrass within the range of subsidies considered here. This is because of relatively low switchgrass yields, which results in a high opportunity cost of converting land to it [25]. Increasing the co-firing limit of power plants to 25% increases the area converted to miscanthus production and the electricity generated with bioenergy. As shown in Fig. 3, the area under miscanthus becomes more responsive to bioenergy price as the co-firing capacity increases. We also find that switching from row crops to miscanthus occurs in the first year and area under miscanthus is then constant for the remaining years.

We find that typically power plants would obtain their biomass from multiple counties. A co-firing power plant first exhausts the biomass supply from the lowest cost source. This may not necessarily be the county closest to that power plant because the supply potential in each county is determined by the distribution of cropland under various rotation and tillage practices and constrained by the ease with which land use can be changed across rotations and tillage practices. Another noteworthy finding is that not all power plants would co-fire biomass up to their technically maximum capacity because of the limitation on the availability of biomass at the coal energy equivalent price. For example, with a 15% limit on co-firing, about one-third of the power plants would co-fire miscanthus at a level close to that limit. These power plants are located in the southwest region where the cost of producing miscanthus is relatively low. Allocation of land to miscanthus in those counties is constrained by the power plants' technical potential to co-fire. With a bioenergy price of 2.8 $ GJ^{-1}, five power plants would not co-fire any biomass because of inadequate biomass supply. These power plants are located in the northeastern, central and eastern regions. Five counties in the northeast (Cook, Dupage, Kendal, Lake, McHenry and Will) are primarily metropolitan counties; cropland in these counties accounts for only 2% of the total cropland in Illinois. Moreover, with this subsidy only 0.12% of the cropland in these counties is converted to miscanthus. Excluding these metropolitan

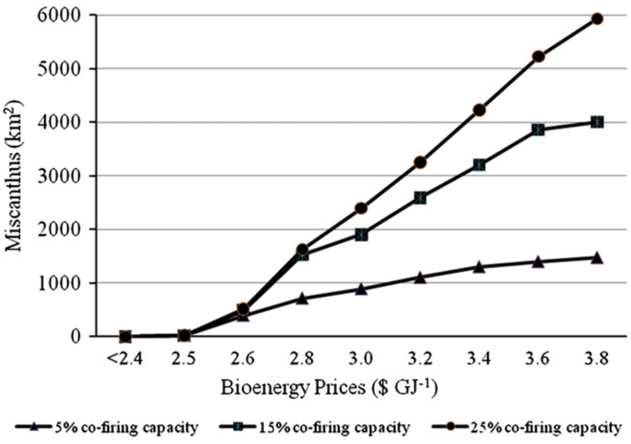

Fig. 3 – Planted area response to bioenergy price.

counties from the analysis has a negligible impact on the results presented here. When the bioenergy price is increased to 3.6 \$ GJ^{-1}, adequate biomass would be supplied and all plants would co-fire (but the co-firing rate in the northeastern power plants would still remain under 1%).

The spatial distribution of miscanthus production favors counties where there is a power plant in close proximity. As shown in Fig. 4a, miscanthus production would be heavily concentrated in the southern counties at the bioenergy price of 2.8 \$ GJ^{-1}. Only 41 of the 102 counties in Illinois would find it profitable to produce miscanthus with the minimum share of county cropland dedicated to miscanthus being 0.2%. About one-third of the miscanthus producing counties would supply more than 70% of the total miscanthus produced in the state. This is mainly due to the low opportunity cost of producing miscanthus, primarily due to the relatively low yields per acre of corn and soybean and the high yield of miscanthus, in those counties. However, the cost advantage gets rapidly eroded as the transportation cost increases. With a bioenergy price of 2.8 \$ GJ^{-1}, the maximum distance that miscanthus could be profitably transported is 56 km while the average distance is 24 km. The proximity of power plants to central and northeastern counties results in lower transportation costs of bioenergy for those counties. This makes it profitable to produce some miscanthus in those counties as well, despite their relatively low miscanthus yield and high opportunity cost of land. The delivered cost of biomass to power plants in those counties is lower for nearby counties than it is for counties in southern Illinois. As Fig. 4b shows, increases in the price of bioenergy expands the area under miscanthus in counties near power plants. Moreover, biomass could now be delivered to power plants located further away. With a bioenergy price of 3.6 \$ GJ^{-1} the maximum distance biomass is delivered goes up to 117 km.

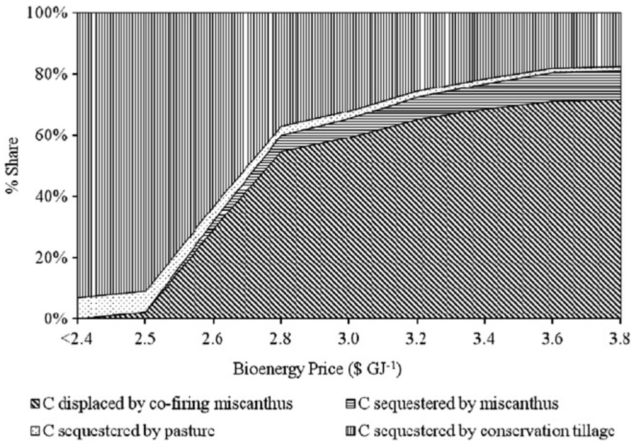

Fig. 5 – Share of alternative approaches to carbon mitigation with 15% co-firing limit.

An increase in the co-firing capacity to 25% would have a modest impact on the maximum distance biomass is transported and the number of counties that produce miscanthus. Only three power plants would co-fire biomass at their 25% capacity if the bioenergy price is 2.8 \$ GJ^{-1}. With a price of 3.6 \$ GJ^{-1}, 6% of the cropland would be allocated to miscanthus and the share of bioenergy based electricity would be 18% of the total electricity generated.

The present value of the subsidy payment needed over 15 years to induce 1.7% of the cropland to switch to miscanthus with a bioenergy subsidy of \$1.7 GJ^{-1} and a 15% co-

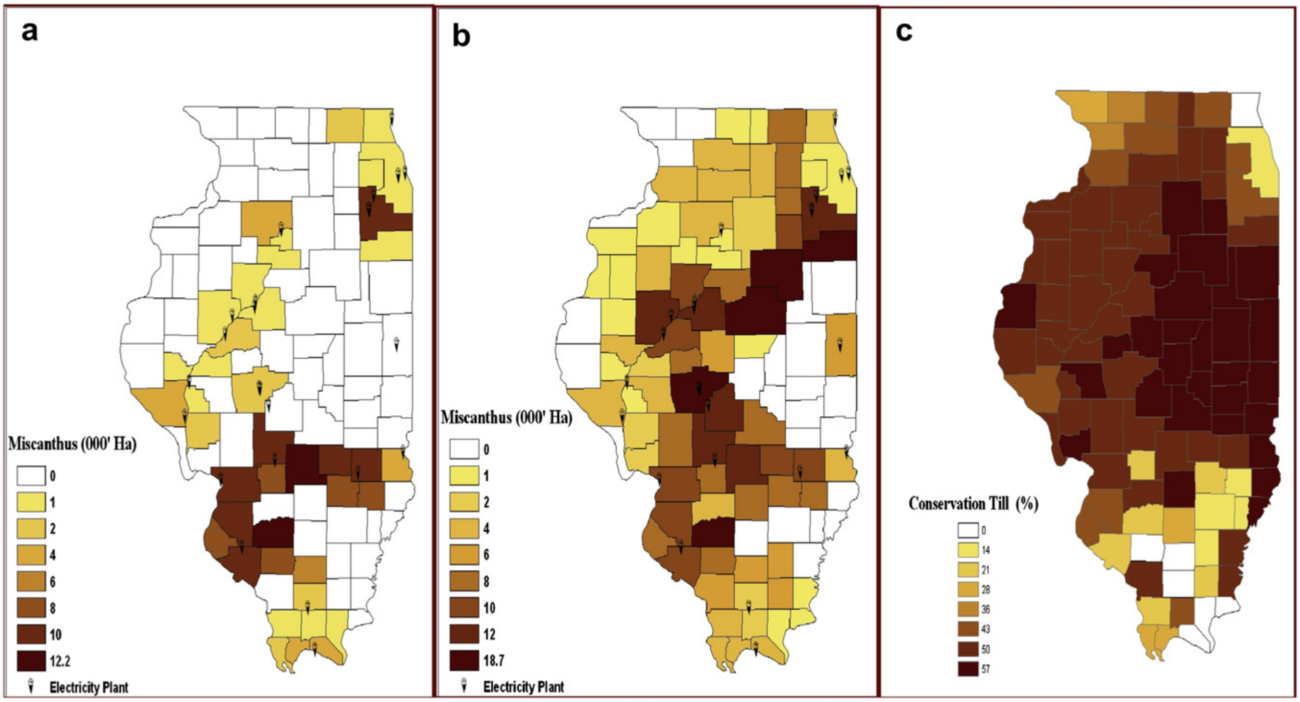

Fig. 4 – a. Area of miscanthus at 2.8 \$ GJ^{-1} and 15% co-firing limit b. Area of miscanthus at 3.6 \$ GJ^{-1} and 15% co-firing limit. c. Share of conservation-tilled area in total cropland with 15% co-firing limit and 2.8 \$ GJ^{-1}.

Table 4 – Sensitivity Analysis with 15% Co-firing Capacity and Bioenergy Price of \$2.8 GJ^{-1}.

Parameters	Increase in row crop yield by 10%	50% Increase in crop price	Doubling discount rate from 4% to 8%	Increase in ease of conversion of land	Increase in miscanthus yield by 10%	Increase in production cost of miscanthus by 25%	25% Increase in biomass harvesting cost	25% Increase in hauling cost
Land under Conservation Till (%)	47.98	44.01	44.45	45.75	44.06	45.07	45.07	44.09
Land under miscanthus (%)	0.99	0.01	0.94	1.84	1.66	0.00	0.01	1.32
Biomass Supply (Mt with 15% moisture)	2.86	0.04	2.47	4.72	5.18	0.00	0.02	3.73
Electricity generated with biomass (%)	3.39	0.05	3.22	6.16	6.12	0.00	0.03	4.42
Average hauling distance (km)	34.99	35.84	33.94	35.97	38.96	0.00	19.57	35.55
Total amount of C mitigated (Tg)	31.29	14.23	31.29	42.81	41.15	15.91	16.01	34.19
-coal displacement by biomass	13.04	0.20	13.04	23.71	23.54	0.00	0.10	17.01
-sequestration by miscanthus	1.22	0.01	1.22	2.37	2.15	0.00	0.01	1.65
-sequestration by conservation till	15.89	13.15	15.89	15.39	14.32	14.77	14.78	14.39
-sequestration by pasture	1.14	0.86	1.14	1.35	1.14	1.13	1.13	1.13
% of carbon mitigated by the 15th year	8.53	3.88	8.53	11.67	11.22	4.34	4.36	9.32
Discounted present value of bioenergy subsidy (M\$)[a]	657.55	10.12	0.00	1194.76	1188.84	0.00	4.96	857.28

[a] The discount factor is 4% and the time horizon considered is 15 years.

firing limit is 1.07 G$. The subsidy payment increases more than three-folds as the bioenergy subsidy is raised to 2.5 $ GJ^{-1} and biomass production grows by 2.4 times. The provision of a bioenergy subsidy, with all the other crop prices fixed, increases profits from miscanthus production relative to competitor crops. A subsidy of 1.7 $ GJ^{-1} raises the discounted value of farm profits by 218 M$; but this occurs at the expense of 1.07 G$ to taxpayers. This expense goes up to 3.72 G$ if the bioenergy subsidy is raised to 2.5 $ GJ^{-1}.

4.1. *Greenhouse gas mitigation*

Some GHG mitigation would occur even under the BAU scenario due to soil carbon sequestration on cropland under conservation tillage and pasture. The aggregate carbon stock is estimated to be 16 Tg in 2003 and to increase by another 16 Tg by 2017. This would mitigate 4.3% of the expected carbon emissions by coal-fired power plants in Illinois over the period 2003–2017 (Table 3).

GHG mitigation increases as the bioenergy price increases and land is converted to miscanthus for co-firing with coal. With 15% co-firing capacity and a bioenergy price of 3.6 $ GJ^{-1}, 20% of carbon emissions from power plants over the period 2003–2017 can be mitigated. With a bioenergy price of 2.8 $ GJ^{-1}, the corresponding reduction in emissions is 11%. Most of the mitigation is due to displacement of coal in power plants. A relatively small percentage of reduction in emissions is due to soil carbon sequestration with most of that being achieved by conservation tillage.

With a bioenergy price of 2.8 $ GJ^{-1}, the total amount of carbon mitigation is 39 Tg. Of this mitigation, 54% is due to the displacement of coal and conversion of land from row crops to miscanthus and 46% is due to soil sequestration (the bulk of which is due to conservation tillage). A large area in central Illinois continues to choose conservation tillage even with a subsidy to miscanthus (Fig. 4c). As the bioenergy price increases to 3.6 $ GJ^{-1}, the share of mitigation due to displacement of coal and conversion of land to miscanthus increases to 72.5%, while the share of soil sequestration reduces to 28%. Moreover, the share of soil sequestration achieved by miscanthus increases from 11% to 33% while that of conservation tillage and pasture declines correspondingly (Fig. 5). This occurs for two reasons. First, the increase in bioenergy price causes more land to switch from conservation tillage and pasture to miscanthus, which results in a net loss of soil carbon relative to the BAU level on this land. Second, the land that is converted from conservation tillage to miscanthus sequesters more soil carbon per hectare. This increased rate of sequestration compensates for the initial loss of soil carbon that occurs due to switching the land from conservation tillage and pasture to miscanthus.

4.2. *Sensitivity analysis*

We examine the sensitivity of our results to various parameters used in the model. In particular, we consider the impact of increasing (i) row crop yields, (ii) row crop prices, (iii) discount rate, (iv) ease of conversion of cropland to biomass production, (v) biomass crop yields, and (vi) production costs of biomass crops. In each case, we change one parameter at a time keeping all other parameters the same as in the scenario of 15% co-firing capacity and 2.8 $ GJ^{-1} bioenergy price. Some of those sensitivity results are presented in Table 4. We find that the area under miscanthus is sensitive to row crop yields, row crop prices, discount rate and production costs of biomass crops. For instance, a 10% increase in row crop yields or a 50% increase in row crop prices, a 25% increase in biomass crop production costs and doubling the discount rate would reduce the cropland share of miscanthus from about 1.7% to less than 1% and in some cases make it close to zero. In recent years, crop prices have indeed increased by more than 50%. Such drastic changes in market conditions would raise the opportunity costs of converting land from traditional crops (corn and soybeans) to miscanthus and reduce the likelihood of converting cropland to perennial grasses. In the sensitivity runs, the reduction in area under miscanthus leads to a corresponding increase in land under conventional tillage while the share of cropland under conservation tillage is fairly stable. The maximum (average) distance that miscanthus is transported remains in the 32 (20) to 56 (35) km range in most cases, although the number of power plants that co-fire biomass changes considerably. To examine sensitivity of our results to increased ease of conversion of land from row crops to perennials, we raise the limit on the extent of change in land under row crops to lie within ±15% of land observed under that crop historically. Increasing the ease of land conversion to biomass crops or increasing biomass crop yields by 10% does not have a large impact on the share of miscanthus in total cropland. It does, however, increase the number of power plants that co-fire biomass and the share of electricity generated from biomass in Illinois. The analysis above assumed a coal price of 23.9 $ Mg^{-1} or (1.12 $ GJ^{-1}). The sensitivity of model results to alternative coal prices is investigated by converting the bioenergy price (including the subsidy) to equivalent coal price. For instance, the bioenergy prices of 2.8 $ GJ^{-1} and 3.6 $ GJ^{-1} are equivalent to coal prices of 60.2 $ Mg^{-1} and 76 $ Mg^{-1}, respectively. Our analysis indicates that as the coal price goes up, the need for bioenergy subsidies will decrease.

5. Conclusions

Our main findings are as follows: Decisions about allocation of land to miscanthus are strongly influenced by the location of production sources relative to power plants (due to transportation costs), by the capacity of power plants to co-fire biomass and the price of bioenergy. At the current coal-equivalent energy price, a relatively large bioenergy subsidy would be needed to make it profitable for farmers to grow miscanthus. At a price of 2.8 $ GJ^{-1} and with 15% co-firing limit, miscanthus would be produced on less than 2% of the 940,000 km^2 cropland in Illinois. Biomass production would occur in 41 Illinois counties mostly concentrated in southern Illinois and within a 56 km radius from the existing power plants. These counties differ in their cropland allocation to miscanthus, which ranges between 0.2% and 10%, and in their share of biomass production, which ranges between 1 and 8% of the total. Most of the power plants in Illinois would utilize biomass in the range between 0.1% and 15% of their production capacity, replacing 5.5% of total electricity supply in Illinois. The present value of subsidy payment needed to replace this 5.5% of the coal-based electricity by bioenergy is 1.07 G$. The carbon mitigation benefits of using bioenergy and associated land use changes considered here are substantial and vary with the bioenergy price and the co-firing capacity of power plants. For the scenarios considered here, these would be within the range of 10–20% of cumulative emissions by the power plants over the period 2003–2017.

Our analysis focused only on Illinois and thus required all biomass produced to be used within the state. Expansion in the geographical coverage of our analysis may result in power plants located near state boundaries obtaining their biomass from adjacent states if it is cheaper to do so. The qualitative results are unlikely to change, however; namely, bioenergy is considerably more expensive than coal-based energy at current prices and even with subsidies bioenergy production would be limited to power plants within a short distance from the producing regions. The sensitivity results show that an increase in the commodity prices and/or crop yields would make it even more difficult for bioenergy crops to compete for land. On the other hand, an increase in coal prices would reduce the need for bioenergy subsidies in order to achieve a given level of cropland allocation to bioenergy production.

Our results have several policy implications. We find that Illinois has a potential for producing 10%–15% of its electricity from biomass by diverting about 5% of its cropland to miscanthus. However, low coal prices are unlikely to create a market incentive to divert land from conventional row crops to biomass crops in Illinois. Thus, government policies will be needed to induce the production of bioenergy crops in Illinois. Policy support could take several forms, including subsidies for the production and use of bioenergy by coal-fired electricity plants, mandates for the use of renewable energy for electricity generation (such as the Renewable Portfolio Standard), or a carbon price under a cap-and-trade program.

These policies differ in the costs incurred by the government, electricity producers, consumers and landowners. Bioenergy subsidies will impose large costs on the government while with mandates those costs will be borne by the power plants since they would have to compensate landowners who switch their lands from corn and soybeans to miscanthus. Alternatively, a carbon price would raise the price of coal and reward the use of bioenergy. It would correct the market prices of coal and biomass so that they will reflect not only the energy content of biomass crops but also their GHG mitigation benefits. Since the CO_2 emissions from coal are approximately 2 kg^{-1} of coal, a tax of about 18 $ Mg^{-1} of CO_2 would raise the price of coal from its current level to about 60 $ Mg^{-1} (equivalent to 2.8 $ GJ^{-1}). Thus, even a moderate carbon tax could make bioenergy competitive with coal and induce about 2% of the cropland in Illinois to produce miscanthus. The costs of a carbon tax would be borne by the producers and consumers of electricity. A carbon price would also be the least-cost approach to mitigating GHG emissions.

The effects of these policies will also differ spatially. Due to the differences in their comparative advantage for producing biomass only some areas in Illinois would be viable areas for biomass-based electricity generation. Thus, land use changes are likely to be significant in some areas and not in others. Moreover, these policies might create incentives to set up new coal-fired power plants that co-fire bioenergy or even power plants dedicated to using bioenergy in areas where there is high potential to produce biomass at relatively low cost. Future research is needed to examine the cost effectiveness and distributional effects of alternative policies to encourage the use of renewable energy for electricity generation and implications of valuing other environmental benefits for soil and water quality associated with the production of perennial grasses, such as reduced nitrogen leaching and sediment run-off.

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