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Costs of producing miscanthus and switchgrass for bioenergy in Illinois

Madhu Khanna, Basanta Dhungana, John Clifton-Brown*

Department of Agricultural and Consumer Economics, University of Illinois, Urbana-Champaign, 440 Mumford Hall, 1301 W. Gregory Drive, Urbana, IL 61801, USA

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ABSTRACT

There is growing interest in using perennial grasses as renewable fuels for generating electricity and for producing bio-ethanol. This paper examines the costs of producing two bioenergy crops, switchgrass and miscanthus, in Illinois for co-firing with coal to generate electricity. A crop-productivity model, MISCANMOD, is used together with a GIS to estimate yields of miscanthus across counties in Illinois. Spatially variable yields, together with county-specific opportunity costs of land, are used to determine the spatial variability in the breakeven farm-gate price of miscanthus. Costs of transporting bioenergy crops to the nearest existing power plant are incorporated to obtain delivered costs of bioenergy. The breakeven delivered cost of miscanthus for an average yield of 35.76 $t\,ha^{-1}$ in Illinois is found to be less than two-thirds of the breakeven price of switchgrass with an average yield of 9.4 $t\,ha^{-1}$. There is considerable spatial variability in the breakeven farm-gate price of miscanthus, which ranges between 41 and 58 $\$\,t^{-1}$ across the various counties in Illinois. This together with differences in the distances miscanthus has to be shipped to the nearest power plant causes variability in the costs of using bioenergy to produce electricity. The breakeven cost of bioenergy for electricity generation ranges from 44 to 80 $\$\,t^{-1}$ DM and is considerably higher than the coal energy-equivalent biomass price of 20.22 $\$\,t^{-1}$ DM that power plants in Illinois might be willing to pay. These findings imply a need for policies that will provide incentives for producing and using bioenergy crops based on their environmental benefits in addition to their energy content.

1. Introduction

Record oil price increases and growing concerns about the national security implications of US dependence on foreign energy sources together with concerns about the threat of global climate change caused by fossil fuel use have created a momentum for developing domestic, renewable energy sources in the US. Perennial grasses are among the renewable sources being considered for generating electricity and for producing biofuels because of their potential to reduce greenhouse gas emissions relative to fossil fuels and to serve as carbon sinks by sequestering carbon in soil [1]. Two perennial grasses, switchgrass (*Panicum viragatum*) and miscanthus (*Miscanthus x giganteus*) [2,3], have been identified as among the best choices for low input bioenergy production in the US and Europe [4,5]. These grasses, hereafter referred to as bioenergy crops, have been studied extensively in Europe (see [5,6]). In the US there has been field research on switchgrass since 1992 [7], while research on miscanthus was initiated recently following establishment of field trials of miscanthus at three University of Illinois Agricultural Research and Education Centers in 2002 [8].

*Corresponding author. Tel.: +1 217 333 5176; fax: +1 217 333 5538.
E-mail address: khanna1@uiuc.edu (M. Khanna).
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The US Department of Energy identified switchgrass as a "model" crop among 18 other herbaceous crops (not including miscanthus). Both crops have a tolerance for the cool temperatures in the Midwest and can be grown on a broad range of land types using conventional farming practices. Crop productivity models as well as field trials indicate that miscanthus can have relatively higher yields in the Midwest, more than twice those of switchgrass and higher than miscanthus yields observed in Europe [4,8].

To engender a viable bio-based energy system, bioenergy crops must compete successfully both as crops and as fuels. Owners of cropland will only produce these crops if they provide an economic return that is at least equivalent to returns from the most profitable conventional crops. The first purpose of this paper is, therefore, to estimate the breakeven prices that would be needed for miscanthus and switchgrass to provide incentives to grow these crops under average conditions in Illinois, and to examine the sensitivity of these prices to a variety of assumptions about costs of harvesting and transportation, row crop prices and discount rates. The second purpose is to examine the spatial variability in the breakeven price of miscanthus across Illinois. This price is likely to differ by location for a variety of reasons. Productivity of miscanthus is expected to vary spatially with climate and soil quality. The profitability of row crops, that determines the opportunity costs of the land that switches to miscanthus, is also expected to vary spatially due to differences in yields, costs of production and prices of row crops across the state.

A key component of this analysis is simulating the spatial pattern of miscanthus yields using a biophysical model, MISCANMOD [9]. Spatial yield maps and crop budgets for bioenergy crops and row crops together with transportation costs are incorporated to obtain site-specific breakeven prices of miscanthus. Finally, we examine the implications of these spatially variable breakeven prices for the cost of bioenergy delivered to power plants after including costs of transportation. The latter will vary not only with the costs of production but also with the location of the production source relative to existing coal-based power plants in the state.

2. Previous research

Switchgrass is a perennial warm season grass that is a dominant species of the remnant tall grass prairies in the US. Field trials indicate that the Cave-in-Rock variety performed best in the northern central plains in the US and the average yield in Iowa in 1998 and 1999 was 9.4 metric tons of dry matter per hectare ($t\,DM\,ha^{-1}$) while the best yield was $12.5\,t\,DM\,ha^{-1}$ [10,11]. Switchgrass yields in field trials in Illinois (using the Cave-in-Rock variety) averaged $9.52\,t\,DM\,ha^{-1}$ and ranged between 3.7 and $18.8\,t\,DM\,ha^{-1}$ across three locations in 2004 and 2005 [8]. These yields are lower than those simulated for switchgrass in southern US by Kiniry et al. [12], which range from 12.2 to $22.1\,t\,ha^{-1}$.

Miscanthus is a perennial rhizomatous grass; a sterile hybrid genotype *M. x giganteus* has been studied extensively through field trials in several European countries but is non-native to the US. A key concern with large-scale introduction of a non-native bioenergy crop, such as miscanthus, in the US is its potential to be an invasive species [13]. *M. x giganteus* is a cross between two species and has three sets of chromosomes instead of the normal two. This prevents the normal pairing of chromosomes needed to form fertile pollen and ovules and makes it sterile. It has been grown in the European Union on a very large scale for over 20 years with no evidence of becoming invasive (for more details see [14]). The yields of *M. x giganteus* have been found to range between 4 and $44\,t\,DM\,ha^{-1}$ per year [5,15]. An extensive review of literature on switchgrass and miscanthus productivity by Heaton et al. [16] indicates that switchgrass yield is on average $12\,t\,ha^{-1}$ lower or half that of miscanthus yields observed in Europe. At a side-by-side field trial of switchgrass and miscanthus at three locations in northern, central and southern Illinois in 2004–2005, average peak yields (2004–2005) ranged between 32.5 and $50.8\,t\,DM\,ha^{-1}$ and were lowest at the northern Illinois site. Miscanthus yields were found to be three to four times higher than switchgrass yields at these three locations [8].

Studies of the costs of growing switchgrass in specific regions in the US [17–19] find that these costs are lower than those of other herbaceous crops [20] and of willow and poplar [21–23] and of short rotation woody crops [24]. Estimates of the costs of production of switchgrass and miscanthus vary considerably across studies. While Epplin [18] estimates the costs of production and transport of $9\,t\,DM\,ha^{-1}$ of switchgrass in Oklahoma to an ethanol producing facility 64 km away to be 37.08 $\$\,t^{-1}$, Duffy and Nanhou [17] estimate the costs of production in Southern Iowa to be as high as $74.3\,\$\,t^{-1}$. McLaughlin et al. [19] estimate that at a national average yield of $9\,t\,DM\,ha^{-1}$ and a farm-gate price of $44\,\$\,t^{-1}$ it would be profitable to grow switchgrass on 16.9 million hectares in the US. Farm-gate costs of producing $18\,t\,DM\,ha^{-1}$ of miscanthus in UK are estimated (after conversion to dollars using the relevant exchange rate for the year of the study) to be $76.4\,\$\,t^{-1}$ by Bullard [25], $68\,\$\,t^{-1}$ by Bullard [26] and $58\,\$\,t^{-1}$ by DEFRA [6].

Studies find that harvesting is the most expensive annual operation accounting for over one-third of the delivered costs for switchgrass [17,18,24] and over two-thirds of the farm-gate cost of miscanthus (excluding land costs) [25]; these costs are sensitive to the method of harvesting [27,28]. Costs of production per ton are found to decline as yield increases; a four-fold increase in switchgrass yield would reduce per unit costs by more than half [17] while Bullard estimated that a 50% increase in the yield of miscanthus could reduce per unit costs by about 25% [26].

3. MISCANMOD: a biophysical model for miscanthus

MISCANMOD is a crop-productivity model based on the principles developed by Monteith [29]. Crop specific parameters for *M. x giganteus* were obtained from field trials in Europe over the past 12 years [9]. Under non-water limiting conditions, yield depends on air temperature and solar radiation. Growth begins in the spring when air temperature rises above a base temperature of 10 °C and the length of non-frost season is used to calculate the growing degree days

(GDD). Under water-limited conditions, yield could be constrained by available soil moisture holding capacity (S_{max}). Soil moisture deficit (SMD) is calculated from the difference between the amount of water needed potentially for evaporation and transpiration and the amount of water available from precipitation and needed to return a soil to S_{max}. Yield predictions obtained from MISCANMOD closely approximate observed autumn yields at 15 field trial sites in Europe [9].

To apply the model to Illinois, data on several inputs, such as precipitation, temperature, total solar radiation, soil moisture holding capacity and potential evaporation in Illinois, were obtained and spatially interpolated to generate a 2 km × 2 km grid for each input data set. For the period 1971–2000, monthly mean precipitation was obtained from 186 locations, monthly mean temperature from 116 locations, and the median end of spring frost date and median start of fall frost date from 85 locations [30]. We obtained monthly mean total solar radiation for the period 1991–2000 from 19 stations and soil moisture holding capacity at different depth of soil sampled at 18 stations for the period 1981–2004 [31]. Monthly mean potential evaporation for the period 1970–2000 was obtained for 9 locations from NOAA [32]. Data were spatially interpolated using kriging where datasets had sufficient observations; otherwise inverse distance weighting was the method of choice.

MISCANMOD was used to simulate the annual peak dry matter yield of miscanthus in autumn for each 2 km × 2 km grid cell in Illinois. Land use data from the Illinois Department of Agriculture were used to identify the areas that were cropland in each grid cell in 1999–2000 [33]. Miscanthus yields for all grids that were cropland were averaged to obtain yields at the county level for Illinois.

4. Yields of perennials and row crops in Illinois

Fig. 1 shows the variability in GDD for miscanthus across Illinois obtained as output from MISCANMOD, while Fig. 2 shows that SMD is negative at all locations in Illinois and thus not a limiting factor for miscanthus yield. GDD tends to be highest in the southern and south-western regions of Illinois and lowest in the northern regions. Five year (1998–2002) average crop yields per hectare for corn and soybean were obtained from NASS/USDA [34] for each county in order to estimate the opportunity costs of the land (as explained below). The simulated yield of miscanthus and the 5-year historical yield of corn are shown in Figs. 3a and b. Miscanthus yields range between 30 and 42 t DM ha^{-1}. As expected from the spatial distribution of the GDD across Illinois, we find that yields are about 30–34 t DM ha^{-1} in the northern region, 33–36 t DM ha^{-1} in the central region and 37–42 t DM ha^{-1} in the southern and south-western regions of Illinois. These estimates are within the range of 27–44 t DM ha^{-1} simulated by Heaton et al. [4]. In contrast to the yield pattern for miscanthus, yield of corn and soybeans in Illinois are highest in the west, north-west and central regions of Illinois and lowest in the south and south-west of Illinois. We estimate the costs of producing miscanthus in Table 3 for an average dry matter standing yield of 35.8 t ha^{-1}.

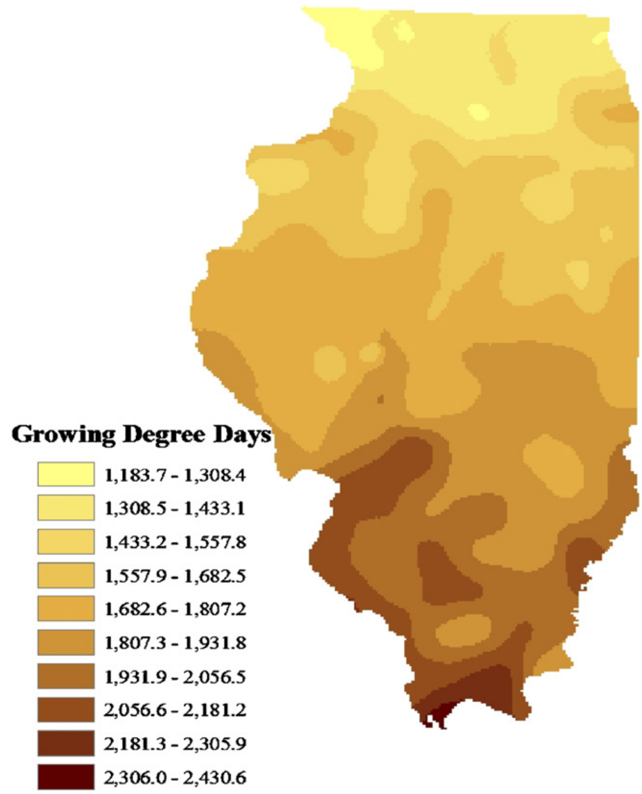

Fig. 1 – Growing degree days.

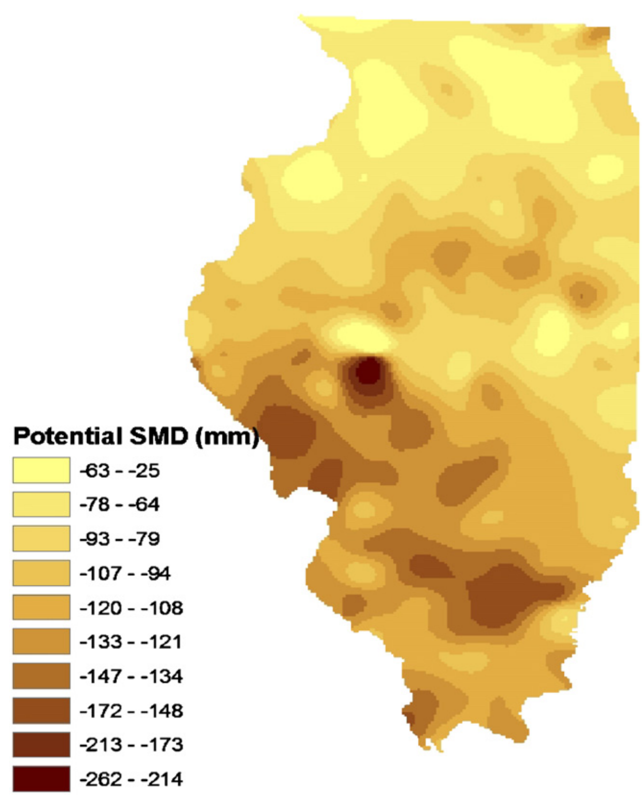

Fig. 2 – Soil moisture deficit.

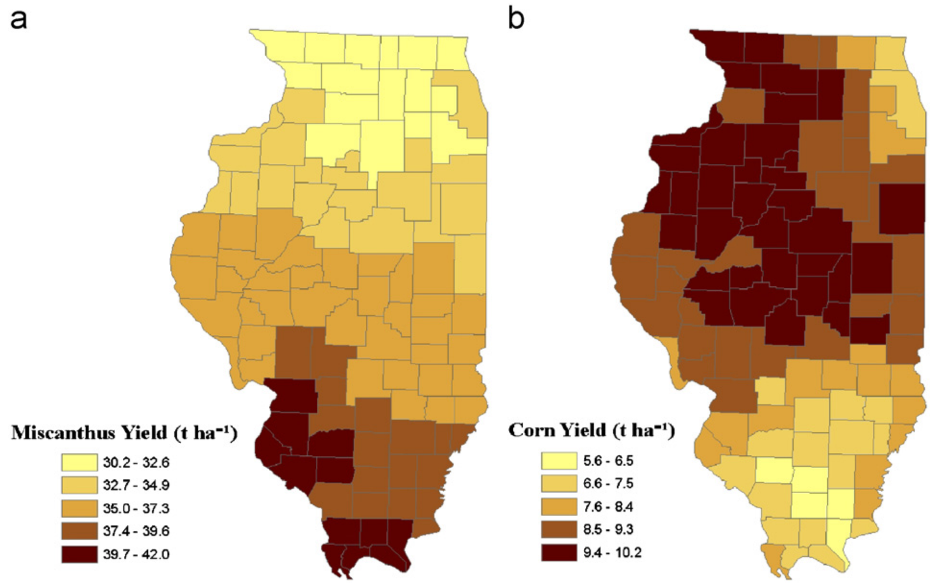

Fig. 3 – (a) Simulated miscanthus yield; (b) 5-year average yield of corn (1998–2002).

In the case of switchgrass, we assume an average yield of 9.42 t DM ha^{-1} for the Cave-in-Rock variety in Illinois [10]. The average yield of corn in Illinois is 9.10 t ha^{-1} while that of soybeans is 3.14 t ha^{-1}. We now discuss the agronomic assumptions that underlie our cost estimates. These assumptions are based on a detailed review of existing studies on switchgrass and miscanthus presented in Tables 1 and 2.

5. Agronomic assumptions underlying costs of production

The costs of producing switchgrass and miscanthus depend on: (i) the costs of inputs, such as chemicals, fertilizers and seeds, (ii) the costs of equipment, (iii) the costs of storage and transportation, and (iv) the opportunity costs of land. The per hectare costs of land, overhead (such as farm insurance and utilities), building repair and depreciation, and farmer's 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 relative profitability of alternative crops. Instead, these are included as the opportunity costs of using existing farmland, labor and capital to produce bioenergy crops. This opportunity cost is measured as the difference between the per-hectare revenues from a corn-soybean rotation and its costs of production and represents the profits foregone by a landowner that uses cropland to produce a bioenergy crop.

Costs in the first year differ from those in subsequent years because they include costs of land preparation and planting to establish the crop. In the second year we assume that there is 25% probability that reseeding/replanting will be needed for switchgrass to replace plants that do not survive the first winter but that there is no need for replanting miscanthus rhizomes (based on field experience with miscanthus in Illinois) [8]. Moreover, 67% of the maximum yield of switchgrass and 50% of the maximum yield of miscanthus can be harvested in the second year [4,7]. From the third year onwards, yields remain constant through the remaining life of the crop, which is assumed to be 10 years for switchgrass and 20 years for miscanthus. To compare costs of production and yields obtained at different points in time over the life of the crop, we compare cost estimates across crops by estimating the discounted value of costs and yields using a discount rate of 4%. The breakeven price of a perennial is then the price per ton of DM in current dollars needed to offset all costs of production incurred over the lifetime of the crop discounted to current prices divided by the discounted value of successive yields. Breakeven price $P = \sum_{t=0}^{T} C_t/(1+d)^t \Big/ \sum_{t=0}^{T} Y_t/(1+d)^t$ where T is the life of the crop, Y_t is yield per hectare in year t, d is the discount rate and C_t is the costs of production per hectare in period t.

5.1. Fertilizer, seed and chemical requirements

Requirements for nitrogen (N) fertilization for switchgrass are expected to be site-specific and vary across studies. Based on current recommendations for the upper Midwest we assume no nitrogen is applied to switchgrass in the first year to prevent weeds and 112 kg N fertilizer ha^{-1} in liquid form is applied annually thereafter (see [7,17]). Trials conducted across the US have not found a positive response of switchgrass yield to applications of potassium (K), phosphorus (P) and calcium. Following Duffy and Nanhou [17] and other studies mentioned in Table 1, we assume that in the establishment year, application rates of P and K are 34 and 45 kg ha^{-1}, respectively. In the subsequent years, P and K application rates should be matched with the nutrients removed by the plant, which range between 0.17–0.97 kg t^{-1} DM for P and 0.72–11.41 kg t^{-1} DM for K in Southern Iowa [35]. We assume that P and K are applied at the lower end of the above ranges since cropland in Illinois is nutrient rich.

Herbicide is required in the first 2 years to combat weeds and applied at the rate of 3.5 L ha^{-1} of Atrazine and 1.75 L ha^{-1}

Table 1 – Assumptions about agronomic practices for switchgrass

Study	Epplin [18]	Ugarte et al. [22]	Turhollow [21]	Hallam [20]	Duffy and Nanhou [35]	Lewandowski et al. [5]	This study
Locational applicability	Oklahoma	Corn Belt	Maryland	Iowa	Southern Iowa	Locations in US and Europe	Illinois
Establishment year							
Seed ($kg\,ha^{-1}$)	8.4	6.5	Not reported	8.1	6.7	9–11	6.73
Reseeding rate			15% replant rate		25–50% replant rate		25% replant rate
Planting time	May–June	Fall	Fall or Spring	May	February–March	Late winter–early May	February–March
Fert. ($kg\,ha^{-1}$)							
Phosphorus	0	16.8	0	36	33.7	0 (Based on soil test)	33.7
Potassium	0	0	0	105	44.9	0 (Based on soil test)	44.9
Nitrogen	0	0	0	0	0	0 (Based on soil test)	0
Lime ($t\,ha^{-1}$)	0	2.24	4.48	0	6.73	–	4.48
Herbicide	1.68 $kg\,ha^{-1}$ 2,4-D	1.12 $kg\,ha^{-1}$ 2,4-D	1.12 $kg\,ha^{-1}$ 2,4-D and 2.24 $kg\,ha^{-1}$ Atrazine	3 $L\,ha^{-1}$ Atrazine	3.52 $L\,ha^{-1}$ Atrazine 1.75 $L\,ha^{-1}$ 2,4-D	2,4-D application	3.52 $L\,ha^{-1}$ Atrazine 1.75 $L\,ha^{-1}$ 2,4-D
Post-establishment years 2–10							
Phosphorus	22 $kg\,ha^{-1}$	0	0	36 $kg\,ha^{-1}$	0.17-.97 $kg\,t^{-1}$ DM	–	0.17 $kg\,t^{-1}$ DM
Potassium	0	28.1[a] $kg\,ha^{-1}$	0	105 $kg\,ha^{-1}$	0.72–11.41 $kg\,t^{-1}$ DM	–	0.72 $kg\,t^{-1}$ DM
Nitrogen	56 $kg\,ha^{-1}$	22.4 $kg\,t^{-1}$ DM	101 $kg\,ha^{-1}$	140 $kgha^{-1}$	112.2 $kg\,ha^{-1}$	50–100 $kg\,ha^{-1}$	112.2 $kg\,t^{-1}\,ha^{-1}$
Herbicide ($L\,ha^{-1}$)	0	0	0	0	3.52 of Atrazine 1.75 of 2,4-D	May apply in year 2	3.52 of Atrazine 1.75 of 2,4-D Year 2 only
Yield ($t\,ha^{-1}$)	9	11.1–15.1 67% of max yield in year 2	11.2 after year 3 30% in year 1; 67% in year 2	10.3	3.36–13.45 100% of yield in year 2	14.75 on average	9.42 on average 67% of max. yield in year 2
Harvest timing and loss in dry matter	Once; July–December	Once	Once; late summer/ Fall	Once; October	Once; after first frost	Once; after first frost; 20% yield loss	Once; after first frost; 20% yield loss

[a] K is applied in years 3, 6 and 9.

of 2,4-D (as in [17]). We assume that 6.73 $kg\,ha^{-1}$ of pure live seed is frost-seeded and that there is a 25% probability of reseeding in the following year (as in [17]). Costs of fertilizer, chemicals and seeds in 2003 prices are: 0.44 $\$\,kg^{-1}$ for N, 0.49 $\$\,kg^{-1}$ for P, 0.31 $\$\,kg^{-1}$ for K, 12.67 $\$\,t^{-1}$ for lime and 15.84 $\$\,kg^{-1}$ of live seed [36].

M. x giganteus has to be propagated vegetatively, typically through mechanical division of rhizomes in the field. We assume that rhizomes are planted in March after the last date of frost at a density of 1 m^{-2}. Studies on several sites in Europe have shown that miscanthus does not respond to N fertilization from the second or third year onwards [37]. We assume that 60 kg N ha^{-1} is applied in year 1 for rhizome development and 50 kg N ha^{-1} is applied subsequently, as in [4]. P and K are applied at rates sufficient to replace the nutrients taken up by the plant. We apply the same amount of herbicides per hectare for miscanthus as for switchgrass in the first year. Field experiments, including those in Illinois, indicate that herbicide does not need to be applied for miscanthus in subsequent years [6]. Cost per propagule is assumed to be 0.034 \$ in 2003 prices (as in [4,15]) which leads to a cost of 335 $\$\,ha^{-1}$.

Table 2 – Assumptions about agronomic practices for miscanthus

Study	Lewandowski et al. [5,15]	Bullard [25,26][a]	DEFRA [6,39][b]	Christian and Haase [37]	Huisman and Kortleve [28]/ Huisman et al. [27]	This study
Locational applicability	Various sites in EU	Various sites in Europe	UK	Various sites in Europe	Netherlands	Illinois
Establishment year						
Planting density and time	1–2 plant/m^2; Spring after frost	1–2 plant/m^2	2 plants/m^2	March–May; after frost	1 plant/m^2; 5–50% replant rate	1 plant/m^2; 0% replant rate; March–April
Fertilizer (kg ha^{-1})						
Phosphorus		12.9				
Potassium		77.9		No recommendation		
Nitrogen	60	103.9				60
Lime	Ca 0.8–1 kg t^{-1} DM	0	–			4.5 t ha^{-1}
Herbicide	Yes; amount not reported	1 application of glyphosate	Yes	Pre-emergence glyphosate	4L ha^{-1} Atrazine and 3L ha^{-1} mineral oil	3.52 L ha^{-1} Atrazine 1.75 L ha^{-1} 2,4-D
Post-establishment years						
Phosphorus	0.3–1.1 kg t^{-1} DM	10 kg ha^{-1}	11–20 kg ha^{-1}	7.4 kg ha^{-1}	50 kg ha^{-1}	0.3 kg t^{-1} DM
Potassium	0.8–1.2 kg t^{-1} DM	60 kg ha^{-1}	95–100 kg ha^{-1}	94.3 kg ha^{-1}	100 kg ha^{-1}	0.8 kg t^{-1} DM
Nitrogen	50–70 kg ha^{-1}	80 kg ha^{-1}	88–130 kg ha^{-1}	No recommendation	75 kg ha^{-1}	50 kg ha^{-1}
Herbicide	None	1 Application of glyphosate post-harvest	Till crop is 1 m in height	None	3L ha^{-1} Glyphosate in year 2	None
Yield	2 years for full estab.; 30 t ha^{-1} (irrigated); 10–25 t ha^{-1} (not irrigated)	12–24 t ha^{-1}	Year 1–2: 2–7 t ha^{-1}Year 3 onwards: 11–15 t ha^{-1}	Year 3 onwards: 10.78 t ha^{-1}	0 In year 1; 7 t ha^{-1} in year 2; 12 t ha^{-1} after that	0 In year 1; 50% in year 2; 100% in years 3–20; 35.8 t ha^{-1} on average
Yield loss due to late Fall/ Spring harvest	3–25% by December 15–25% by March; average loss is 35.5%	Not considered	15–28%			33% by December
Harvest timing and loss in dry matter	March/April harvest; harvest loss 25%; stubble loss 17%	Mid-February to late March; 20% yield loss	15% loss yields due to wastage and stubble			December or early Spring harvest; 0 yield loss during harvest
Life of crop (years)	20–25	19–20	10% yield decline after year 7; plant life: 20	–	15	20

[a] Establishment year application amounts are inferred indirectly from reported cost figures and post-establishment application rates.
[b] The lower limit is from DEFRA Best Practice Guidelines [39] and based on replacement rate to cover nutrient off-take by the stems.

5.2. *Machinery*

The machinery required to establish switchgrass in Illinois in the least costly way (based on estimates in [10]) is through frost seeding using a tandem disk, a harrow, an airflow planter to spread seeds and phosphorus and potassium fertilizer and a self-propelled sprayer to spray the herbicide and spread liquid nitrogen fertilizer. Costs of these operations are obtained from Duffy and Nanhou [17] while those of disking and spraying are obtained from FBFM [38]. In the second year, due to the need for reseeding, annual maintenance and harvesting can only be carried out on 75% of the planted land. Machinery costs for reseeding consist of 25% of the first year's costs of an airflow planter. Machinery costs for preparing the soil for planting miscanthus are based on equipment needs for a chisel plow, harrow, equipment to apply fertilizer and spray herbicides and a semi-automatic potato planter, as in [5,6,27,39]. These cost estimates are obtained from [38,40,41]. Machinery costs are estimated assuming the farmer or group of co-operating farmers is using own machinery, tractors and harvesting equipment. Per hectare costs of owning and operating the equipment are obtained for equipment sizes that are typically used on a 324 ha grain farm (as in FBFM [38] and include overhead (depreciation, interest, insurance, housing and repairs), fuel and labor charges. For implements/operations for which costs were not available from FBFM, we rely on cost estimates from the 2000 Iowa Farm Custom Survey [40]. Since the latter include an allowance for profits, which we assume to be 10% we estimate costs per hectare of owner-operated equipment as 90% of the cost reported in the survey. All costs are converted to costs in 2003 prices using the Gross Domestic Product Deflator Index [42].

Harvesting of switchgrass and miscanthus involves mowing, swathing and baling and can be performed by conventional grass harvesters and balers [35]. We assume a single harvest of switchgrass in the early winter after the first frost so that translocation of nitrogen and other nutrients out of the foliage into the roots reduces overall nutrient use and ash content while improving the suitability of switchgrass as a fuel for combustion [7,43]. This does reduce yields by 20% of dry matter as compared to peak levels in mid-September [5,7] and the moisture content to 15% or less which allows baling to immediately follow mowing/conditioning. For ease of transportation and handling, switchgrass is baled in large rectangular bales, as is current practice in Iowa [44]. Like switchgrass, miscanthus is harvested once a year, but harvesting could be delayed to occur between December and March. Based on field trials in Europe we assume that harvesting miscanthus in December leads to yield losses of 33% of peak yields in October and moisture content of 20% [45,46].

Studies vary in their assumptions about the variation in harvesting costs with biomass yield. We assume the costs of mowing/conditioning and raking are 40.52 $\$\,ha^{-1}$, as in the case of hay, and the costs of making square bales depend on yield at the rate of 15.43 $\$\,t^{-1}$ DM [47]. The costs of renting a tractor, loading it on the field, transporting the bales to the storage area a mile away from the field, unloading and stacking and then reloading the truck/semi-trailer for the final hauling to the power plant are estimated to be 7.34 $\$\,t^{-1}$ [17].

5.3. *Storage and transportation*

We assume that biomass is stored outside on crushed rock on reusable tarp; a method found to be most cost-effective at 3.22 $\$\,t^{-1}$ by Duffy [21]. Storage is assumed to result in 7% loss in yield and to reduce the moisture content of miscanthus bales to 15% through natural ventilation and without any additional drying costs. Estimates for the transportation cost for switchgrass bales per ton-km depend on assumptions about the size of the truck, the number of trips per day, the method used for loading and unloading the container and the roundtrip distance to be covered. For the present study, we assume the cost of transporting switchgrass (with up to 15% moisture) for a round trip distance of 128 km is 8.82 $\$\,t^{-1}$ (based on Duffy [21]). Additionally, there is a cost of 1.102 $\$\,t^{-1}$ which covers the driver's waiting time of 1.5 h for loading and unloading a 20 ton truck, valued at 12 $ per hour in 2002 prices. Converting these costs to 2003 prices, the cost of transportation per ton-km is: $(1.12+0.07d)$ $ where d is the round trip distance in km between the on-farm storage area and the power plant. For a round trip distance of 128 km, these costs amount to 10.1 $\$\,t^{-1}$ in 2003 prices. This cost estimate falls within the range, 9.5–12.25 $\$\,t^{-1}$, actually incurred for transporting switchgrass to the Chariton Valley power plant in Southern Iowa from farms within a radius of 112–128 km [48].

5.4. *Opportunity cost of land*

This is estimated as the foregone profits from the most profitable alternative use of the land that is converted from that use to a perennial grass. Since corn and soybeans are the two dominant row crops grown in rotation with each other in Illinois we assume that a farmer uses half of his hectares for corn and the other half for soybeans in rotation. The profits per hectare from a corn-soybean rotation are estimated as the difference between revenues from a corn-soybean crop valued at the loan rates for each county [49] and the cost of production. Loan rates are used instead of market prices since they play a major role in crop acreage decisions [50]. In 2003 loan rates were in the range of 77.53–85.80 $\$\,t^{-1}$ for corn and in the range of 198.36–206.63 $\$\,t^{-1}$ for soybeans. Other farm subsides are in the form of direct payments that are essentially decoupled from the crop acreage and are not expected to affect the acreage reallocation decisions [51]. The costs of producing corn and soybean consist of the costs of inputs, such as chemicals, fertilizers, and seeds; operating interest on the cost of these inputs; crop insurance; drying and storage costs; and machinery costs. The latter include the costs of repair and maintenance, fuel and lube, labor hire, depreciation and interest on investment as well as transportation of corn to the elevators. We assume that application levels for nitrogen, phosphorus, potassium and seed are yield-based and differ across counties in Illinois. Application rates assumed in this study are the average of the rates provided in FBFM [36]. These are 17.38 kg N, 7.80 kg P, 5.01 kg K and 8265 kernels per ton yield of corn. In the case of soybeans, application rates for phosphorus and potassium are assumed to be 15.11 kg and 23.20 kg per ton yield, respectively. Seed costs are based on the recommended rate of 67.24 $kg\,ha^{-1}$. Interest on all variable input operating costs is paid at the rate of 7% for 8 months. Other costs are assumed to be fixed per hectare and the same across counties.

6. Cost of producing miscanthus and switchgrass

The per hectare total operating costs of miscanthus in the establishment year are more than twice those of switchgrass, primarily due to the larger costs of rhizomes and the machinery needed to plant them as well as to apply nitrogen even in the first year. Pre-harvest machinery costs for miscanthus are almost three times larger (131.09 $ha^{-1}) than those of switchgrass (44.12 $ha^{-1}). Harvesting costs are partly dependent on the yield (with moisture) at the time of harvest. Due to the presence of fixed costs per hectare of mowing and raking, total costs of harvesting do not increase proportionately with yield and in fact the per-ton cost of harvesting falls as harvested yield increases. We estimate harvesting costs per acre to be ($40.52+22.778*harvested yield in wet t ha^{-1}). With 20% of the dry matter of switchgrass lost by the time of harvest, the amount of wet tons (with 15% moisture) harvested per hectare from year 3 onwards is 8.85 t ha^{-1} if the peak yield is 9.4 t DM ha^{-1}. The corresponding figure for miscanthus with 33% loss in dry matter is 29.95 t ha^{-1} (with 20% moisture). After accounting for 7% losses in dry matter during storage, the delivered yield of switchgrass is 8.24 t ha^{-1} (with 15% moisture) and of miscanthus is 27.85 t ha^{-1} (with 20% moisture). The per-ton costs of baling, staging and loading, storage and transportation are assumed to apply to wet tons. Cost for mowing/conditioning, raking, baling and staging/loading the above level of harvested switchgrass is estimated to be 27.38 $ wet t^{-1}. The corresponding cost for harvesting the above yield of miscanthus is 24.11 $ wet t^{-1} (with 20% moisture). Harvesting costs (not including storage costs) account for 61% and 69% of delivered cost of switchgrass and miscanthus, respectively, from year 3 onwards.

The discounted value of operating cost at the farm-gate of miscanthus is much higher than that of switchgrass. On a per ton basis, the cost of miscanthus is much lower (42 $ dry t^{-1}) than that of switchgrass (57 $ dry t^{-1}) because the discounted value of yield per hectare of miscanthus (and therefore expected revenue per hectare) is more than five times larger than that of switchgrass. Transportation costs reported in Table 3 are estimated for a round trip distance of 40 × 2 km between the source of production and the power plant. Storage and transportation together account for 14% and 17% of the delivered cost of switchgrass and miscanthus, respectively (excluding cost of land). The breakeven delivered price of switchgrass is 65 $ dry t^{-1} while that of miscanthus is 50 $ dry t^{-1}. The opportunity cost of the land is estimated to be 192.76 $ ha^{-1}, assuming an average price of corn and soybean of 80.68 $ t^{-1} and 200.72 $ t^{-1}, respectively, and average yield of corn and soybean of 9.10 and 3.14 tons, respectively. After including the opportunity costs of land, the breakeven price of switchgrass is 98 $ DM t^{-1} and of miscanthus is 59 $ DM t^{-1}. Since the yield per hectare of miscanthus is higher than that of switchgrass, the increase in its breakeven price after including fixed costs of land is smaller than that for switchgrass. These breakeven prices represent the minimum price per delivered ton of dry matter that a landowner would need to receive to be willing to switch land to a bioenergy crop and deliver it

Table 3 – Costs of production for switchgrass and miscanthus

Cost items ha^{-1}	Switchgrass ($ ha^{-1})				Miscanthus ($ ha^{-1})			
	Year 1	Year 2	Year 3–10	PV (10 yr)	Year 1	Year 2	Year 3–20	PV (20 yr)
Fertilizer	**86.98**	**60.96**	**52.29**	**484.10**	**97.33**	**36.08**	**36.08**	**571.25**
Nitrogen	0.00	37.07	49.42	355.57	26.46	22.05	22.05	316.06
Phosphorous	16.31	4.66	0.78	25.81	5.20	5.20	5.20	73.55
Potassium	13.84	5.03	2.09	32.22	8.83	8.83	8.83	124.80
Lime	56.83	14.21	0.00	70.49	56.83	0.00	0.00	56.83
Herbicide	**17.89**	**17.89**	**0.00**	**35.09**	**17.89**	**0.00**	**0.00**	**17.89**
Seed	**106.67**	**26.67**	**0.00**	**132.31**	**334.79**	**0.00**	**0.00**	**334.79**
Interest on operating inputs	**14.81**	**7.39**	**3.66**	**45.61**	**31.50**	**2.53**	**2.53**	**64.67**
Pre-harvest machinery	**44.12**	**23.55**	**17.65**	**181.06**	**131.09**	**17.65**	**17.65**	**362.97**
Disking	16.80	0.00	0.00	16.80	23.72	0.00	0.00	23.72
Harrowing	9.06	0.00	0.00	9.06	9.06	0.00	0.00	9.06
Potato planter (for miscanthus planting)	–	–	–	0.00	72.99	0.00	0.00	72.99
Airflow/fertilizer spreader	10.59	15.89	17.65	140.17	17.65	17.65	17.65	249.53
Spraying chemicals (Atrazine and 2,4-D)	7.66	7.66	0.00	15.03	7.66	0.00	0.00	7.66
Harvesting	**0.00**	**146.35**	**271.28**	**1896.93**	**0.00**	**430.32**	**820.12**	**10,396.56**
Mowing/conditioning	0.00	24.09	32.12	231.12	0.00	32.12	32.12	421.90
Raking/swathing	0.00	6.30	8.40	60.45	0.00	8.40	8.40	110.34
Baling	0.00	68.72	136.75	951.35	0.00	231.00	461.99	5845.68
Staging and loading	0.00	32.67	65.02	452.35	0.00	109.84	219.67	2779.52
Storage	0.00	14.57	28.99	201.66	0.00	48.96	97.93	1239.12
Operating costs at farm-gate ($ ha^{-1})	**270.47**	**282.80**	**344.88**	**2775.10**	**612.60**	**486.59**	**876.38**	**11,748.14**
Transportation	0.00	27.83	55.39	385.36	0.00	88.07	176.13	2228.61
Operating cost including transportation ($ ha^{-1})	**270.47**	**310.64**	**400.28**	**3160.46**	**612.60**	**574.65**	**1052.51**	**13,976.75**
Delivered yield (t ha^{-1})	**0.00**	**3.52**	**7.01**	**48.75**	**0.00**	**11.14**	**22.28**	**281.90**
Breakeven farm-gate price excluding land rent ($ t^{-1})				**56.93**				**41.67**
Breakeven delivered price excluding land rent ($ t^{-1})				**64.84**				**49.58**

All estimates are in 2003 prices. Peak dry yield for switchgrass in September and miscanthus in October is assumed to be 9.42 and 35.76 t ha^{-1}, respectively. Figures in bold are summed to get the total operating cost for each column. Present value (PV) of costs is estimated over the life of the crop at a 4% discount rate.

40 km away instead of producing corn and soybeans on that land (Table 4).

7. Sensitivity analysis

We examine the sensitivity of the breakeven price, including the opportunity cost of land, to several assumptions made above (Table 5). The opportunity cost of the land is affected by changes in the price of corn and soybeans and the breakeven price of switchgrass would change by 30% if there was a 25% change in the prices of corn and soybeans. The breakeven price of miscanthus is somewhat less sensitive to the price of corn and soybean because its higher yield per hectare allows changes in fixed costs to be spread over a larger number of tons per hectare. Its breakeven price would change by 14%. Breakeven prices are also very sensitive to assumptions about machinery costs for pre-harvest and harvest operations. A 25% increase in harvest costs would increase the breakeven price of switchgrass by 10% and that of miscanthus by 14%. Changes in fertilizer costs, transportation costs and the discount rate do not have large effects on the breakeven price of either crop. Increase in yield per hectare would reduce breakeven prices of both switchgrass and miscanthus, although less than proportionately, and with a larger effect in the case of switchgrass. We find that peak switchgrass yields would have to increase by more than three times the current yield (to 30 t DM ha^{-1}), with other assumptions held constant, for the breakeven delivered price (including land rent) of switchgrass to be the same as that of miscanthus. If the life of

Table 4 – Annualized costs of production for perennials and row crops

Cost items ($ ha^{-1})	Switchgrass	Miscanthus	Corn	Soybeans
Fertilizer	57.39	40.42	132.47	59.53
Chemicals	4.16	1.27	76.60	88.96
Seed	15.69	23.69	88.96	47.44
Interest on operating inputs	5.41	4.58	13.91	9.14
Storage/drying/crop insurance	23.91	87.67	59.30	27.18
Machinery	222.44	673.59	202.62	172.97
Transportation	45.68	157.68	–	–
Annualized operating cost	374.67	988.88	573.86	405.22
Annualized yield (t ha^{-1})	5.78	19.95	9.10	3.14
Opportunity cost of land	192.76	192.76	–	–
Breakeven delivered cost including opportunity cost of land ($ t^{-1} DM)	98.19	59.24	–	–

Transportation costs for corn and soybean are included in machinery costs and not accounted for separately.
Prices of corn and soybean are assumed as 80.68 and 200.72 $ t^{-1}.

Table 5 – Sensitivity of breakeven prices

	Switchgrass		Miscanthus	
	($ t^{-1})	% Change	($ t^{-1})	% Change
25% Increase in corn-soybean price	127.71	30.1	67.80	14.4
25% Decrease in corn-soybean price	68.68	−30.1	50.69	−14.4
25% Increase in pre-harvest and harvesting machinery costs	107.82	9.8	67.69	14.3
10% Increase in pre-harvest and harvest machinery costs	102.04	3.9	62.62	5.7
25% Decrease in pre-harvest and harvesting machinery costs	88.57	−9.8	50.80	−14.3
25% Increase in transportation costs	100.17	2.0	61.22	3.3
25% Decrease in transportation costs	96.22	−2.0	57.27	−3.3
25% Increase in yield	86.81	−11.6	56.13	−5.3
25% Decrease in yield	117.16	19.3	64.44	8.8
100% higher discount rate	100.76	2.6	60.51	2.1
25% Increase in fertilizer costs	100.85	2.7	59.79	0.9
25% Decrease in fertilizer cost	95.54	−2.7	58.70	−0.9
Reduction in lifetime of miscanthus to 15 years			62.31	5.2

% Change is calculated relative to the breakeven prices in the base case in Table 4.

miscanthus is 15 years instead of 20 years, its breakeven price would increase by 5%.

8. Spatial variability in breakeven prices for perennials in Illinois

The yield of miscanthus for each county is used to calculate the farm-gate breakeven price by county, which varies from 41 to 58 $\$ t^{-1}$. These differences originate from factors associated with the yield of miscanthus and the opportunity cost of land. Breakeven prices are highest in the northwestern counties of Illinois ranging from 51 to 58 $\$ t^{-1}$, due to low yields and high opportunity cost of cropland. In the northeastern counties, these prices are lower (44–55 $\$ t^{-1}$) despite the miscanthus yields being similar to those in the northwest. Since yields of corn and soybeans are higher in the northwest this leads to higher opportunity costs of land. Higher miscanthus yields in central Illinois do not offset the higher opportunity cost of land in that region relative to the northeast. The lowest breakeven prices are in the south and range from 41 to 54 $\$ t^{-1}$.

Table 6 – Determinants of breakeven farm-gate price of miscanthus

Variables	Coefficients
Constant	54.72 (0.466)***
Yield	−0.35 (0.012)***
Opportunity cost of land	0.049 (0.001)***
Adjusted R^2	99.5
No. of observation	102

Standard errors are in parenthesis. *** indicates the coefficient is statistically significant at 1% level.

A regression of the breakeven price on yield and the opportunity cost of land (Table 6) shows that an increase of 10 t ha^{-1} in miscanthus yield would reduce breakeven price by 3.5 $\$ t^{-1}$ all else being constant. An increase in the opportunity cost of land by 1 \$ increases the breakeven cost of miscanthus by 0.05 $\$ t^{-1}$ only.

9. Cost of bioenergy for electricity generation

Next we estimate the cost of delivering miscanthus and switchgrass from each county center to the nearest power plant cluster for co-firing with coal. The 48 existing coal-based power plants in Illinois are grouped at the zip code level to form 24 clusters. The great circle distance between each of these clusters of plants and the nearest county center is estimated using the Haversine formula [52]. The distance between a power plant cluster and the nearest county ranges between 4 and 148 km. The spatial variability in the cost of bioenergy from miscanthus due to differences in distance from each county to the nearest power plant cluster is shown in Fig. 4b. Assuming the energy content of miscanthus is 18 GJ t^{-1} DM [53], the delivered cost per unit of heat energy ranges from 2.45 to 4.42 $\$ GJ^{-1}$ (44–80 $\$ t^{-1}$ DM) across the counties in Illinois. Delivered costs of bioenergy are lowest in counties with a power plant in close proximity indicating that low transportation costs can offset some of the low farm-gate cost advantage of counties with high yields and lower opportunity costs of land (shown in Fig. 4a). The cost of bioenergy from miscanthus is considerably higher than the cost of coal-based energy of 1.123 $\$ GJ^{-1}$ (20.22 $\$ t^{-1}$ DM) paid by power plants in Illinois in 2003 [54]. Additional costs in the form of any changes in infrastructure needed at the power plant to store or process biomass before co-firing or additional costs incurred due to any reduction in boiler efficiency caused by co-firing biomass with coal are not included here. Consideration of such costs would further increase the gap

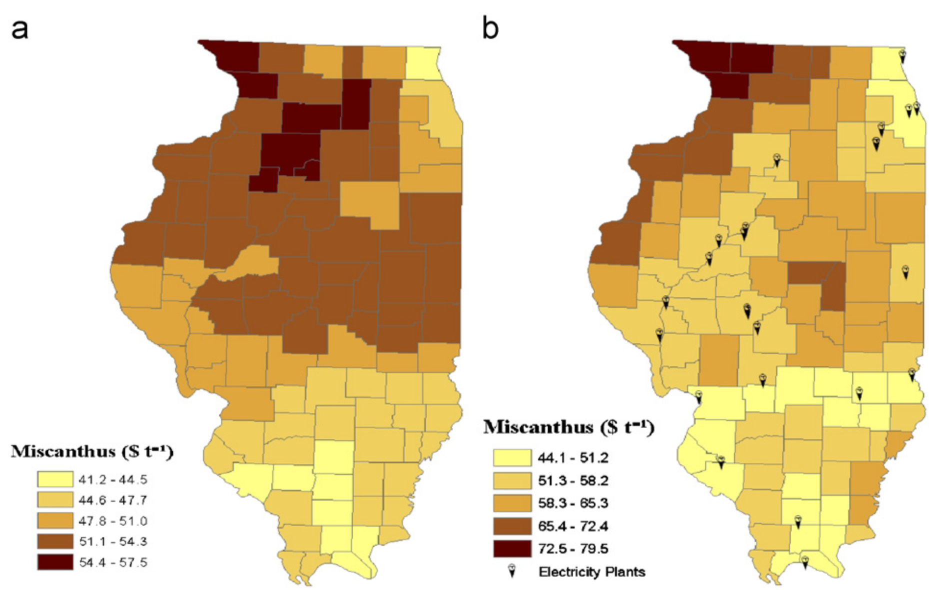

Fig. 4 – (a) Breakeven farm-gate price of miscanthus; (b) breakeven delivered price of miscanthus for electricity generation.

between the breakeven cost of bioenergy and the coal energy-equivalent price for bioenergy that power plants would be willing to pay.

10. Conclusions

In summary, this analysis shows that the breakeven delivered cost of miscanthus for an average yield of 35.76 t ha^{-1} in Illinois is less than two-thirds of the breakeven price of switchgrass with an average yield of 9.4 t ha^{-1}. To the extent that switchgrass yields are positively correlated with miscanthus yields at each location, this suggests that given the present ratio of yields of the two perennials, switchgrass is unlikely to be competitive with miscanthus in Illinois. There is considerable spatial variability in the breakeven farm-gate price of miscanthus, which ranges between 41 \$ t^{-1} and 58 \$ t^{-1} across the various counties in Illinois. This together with differences in the distances miscanthus has to be shipped to the nearest power plant causes variability in the costs of using bioenergy to produce electricity. The breakeven cost of bioenergy for electricity generation is considerably higher than the cost of coal-based energy for power plants in Illinois under current assumptions about costs of producing bioenergy. These estimates may change in the future with new varieties of miscanthus and switchgrass and technological advances in methods of establishment, harvesting and transporting bioenergy crops.

This analysis suggests that currently the market price of bioenergy, based on its heating value relative to coal, is unlikely to be sufficient to induce landowners to grow bioenergy crops in Illinois for co-firing in power plants given current costs of production for these crops and the price of coal. The production of miscanthus in Illinois and/or their use for co-firing with coal by power plants would have to be subsidized. The magnitude of these subsidies could be related to the environmental benefits obtained by the production and use of bioenergy crops, such as their potential to enhance the sequestration of carbon in agricultural soils, reduce nutrient run-off and increase wildlife habitat. The use of biomass by power plants also reduces air pollutants and carbon emissions; environmental regulations could therefore create incentives for power plants to pay more for biomass than the coal energy-equivalent price.

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