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An integrated biogeochemical and economic analysis of bioenergy crops in the Midwestern United States

ATUL K. JAIN*, MADHU KHANNA†, MATTHEW ERICKSON* and HAIXIAO HUANG‡

*Department of Atmospheric Sciences, University of Illinois, Urbana, IL, USA, †Department of Agricultural and Consumer Economics, University of Illinois, Urbana, IL, USA, ‡Energy Biosciences Institute, University of Illinois, Urbana, IL, USA

Abstract

This study integrates a biophysical model with a county-specific economic analysis of breakeven prices of bioenergy crop production to assess the biophysical and economic potential of biofuel production in the Midwestern United States. The bioenergy crops considered in this study include a genotype of Miscanthus, *Miscanthus* × *giganteus*, and the Cave-in-Rock breed of switchgrass (*Panicum virgatum*). The estimated average peak biomass yield for miscanthus in the Midwestern states ranges between 7 and 48 metric tons dry matter per hectare per year ($t\,DM\,ha^{-1}\,yr^{-1}$), while that for switchgrass is between 10 and $16\,t\,DM\,ha^{-1}\,yr^{-1}$. With the exception of Minnesota and Wisconsin, where miscanthus yields are likely to be low due to cold soil temperatures, the yield of miscanthus is on average more than two times higher than yield of switchgrass. We find that the breakeven price, which includes the cost of producing the crop and the opportunity cost of land, of producing miscanthus ranges from $\$53\,t^{-1}$ DM in Missouri to $\$153\,t^{-1}$ DM in Minnesota in the low-cost scenario. Corresponding costs for switchgrass are $\$88\,t^{-1}$ DM in Missouri to $\$144\,t^{-1}$ DM in Minnesota. In the high-cost scenario, the lowest cost for miscanthus is $\$85\,t^{-1}$ DM and for switchgrass is $\$118\,t^{-1}$ DM, both in Missouri. These two scenarios differ in their assumptions about ease of establishing the perennial crops, nutrient requirements and harvesting costs and losses. The differences in the breakeven prices across states and across crops are mainly driven by bioenergy and row crop yields per hectare. Our results suggest that while high yields per unit of land of bioenergy crops are critical for the competitiveness of bioenergy feedstocks, the yields of the row crops they seek to displace are also an important consideration. Even high yielding crops, such as miscanthus, are likely to be economically attractive only in some locations in the Midwest given the high yields of corn and soybean in the region.

Keywords: breakeven cost of biomass, crop yield model, Miscanthus, switchgrass

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Introduction

Concerns about energy security, exhaustible oil supplies and global warming in the United States have led to an ambitious Renewable Fuel Standard (RFS) of producing 136 billion liters of biofuels by 2022 under the Energy Independence and Security Act (EISA), 2007. Although corn has been the main feedstock used for ethanol production, there is growing recognition that relying on corn as the only feedstock for ethanol is not sustainable because of its impact on the environment and food prices (Abbott *et al.*, 2008; Khanna *et al.*, 2009). As a result, the RFS mandates that 79 billion liters of biofuels should come from noncorn feedstocks and at least 61 billion liters from cellulosic feedstocks, such as crop residues, dedicated energy crops and wood products. Moreover, these dedicated energy crops and crop residue must be harvested from agricultural land cleared or cultivated before December 2007 to qualify for renewable fuel credit under RFS.

Although conversion of cellulosic biomass to fuel is not yet commercially viable, considerable research is underway on high-yielding feedstock sources that could provide abundant biomass for large scale cellulosic biofuel production in the United States and minimize the amount of land that needs to be diverted from food to fuel production. Two perennial C_4 crops, switchgrass (*Panicum viragatum*) and miscanthus (*Miscanthus*

Correspondence: Atul K. Jain, e-mail: jain@atmos.uiuc.edu

$\times$ *giganteus*), have been identified as among the best choices for low-input and high dry matter yield per hectare in the United States and Europe (Lewandowski *et al*., 2003; Gunderson *et al*., 2008; Heaton *et al*., 2008). There has been field research on switchgrass in the United States since 1991 (McLaughlin & Kszos, 2005). Research on miscanthus in the United States, on the other hand, was initiated in 2002 following the establishment of field trials of miscanthus and switchgrass at the University of Illinois Agricultural Research and Education Centers (Heaton *et al*., 2008).

Switchgrass is a warm season perennial grass native to North America that has historically been used as forage. The Cave-in-Rock Switchgrass cultivar (hereinafter referred to as switchgrass) studied here is an upland variety that originated in Southern Illinois with excellent potential in the northern states of the United States (Lewandowski *et al*., 2003). [Cave-in-Rock is more cold tolerant and suited for the Midwest than the more high yielding lowland varieties like Alamo (T. Voigt, personal communication, University of Illinois, Urbana-Champaign)] Miscanthus is a perennial rhizomatous grass; the miscanthus variety being evaluated here as a feedstock for biofuels is the sterile hybrid genotype *Miscanthus* $\times$ *giganteus* (hereinafter referred to as miscanthus). It has been studied extensively through field trials in several European countries but is nonnative to the United States. [*Miscanthus* $\times$ *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 Long *et al*., 2007).] The majority of growth for switchgrass occurs during the warm summer months June to August, whereas miscanthus biomass accumulation normally peaks between August and October. These grasses have high efficiency of converting solar radiation to biomass and in using nutrients and water, and have good pest and disease resistance (Semere & Slater, 2007; Clifton-Brown *et al*., 2008). Field trials indicate that miscanthus has relatively high yields in the US Midwest, more than twice those of switchgrass and higher than miscanthus yields observed in Europe (Heaton *et al*., 2008; Miguez *et al*., 2008).

While these perennial grasses have great biophysical potential to help meet future energy needs, the extent to which this potential can be realized will depend on the economic viability of converting existing cropland to produce these crops, as required by the RFS. Farmers will produce these crops only if they can receive an economic return that is at least equivalent to net returns from the most profitable conventional crops. The economic viability of bioenergy crops is likely to differ across locations due to variations in yields, which depend on location specific climatic and biogeochemical conditions, costs of production, and the opportunity costs of land.

This paper examines the biophysical and economic potential of producing bioenergy crops (switchgrass and miscanthus) and the determinants of spatial variability in this potential in the Midwestern US (Iowa, Illinois, Indiana, Michigan, Minnesota, Missouri, Ohio, Wisconsin). This research is interdisciplinary and requires linking biogeochemical models that can simulate energy crop yields with economic decision models that reflect the incentives of landowners to adopt crops that lead to the highest return to the land. Biophysical model simulations are conducted at 0.1° scale, using the Integrated Science Assessment Model (ISAM), and then aggregated to a county level to obtain average yields at the county level for each of these energy crops. These yields are used to calculate the county-specific costs of production and the breakeven price of producing bioenergy crops. This study seeks to advance our understanding of the spatial and temporal dynamics of bioenergy crop yields together with the spatial variability in the breakeven farm-gate price of bioenergy crops across the Midwestern United States.

Few crop productivity modeling studies have estimated the yields for miscanthus and switchgrass. The MISCANMOD has been used in conjunction with a GIS to calculate yields of miscanthus across Europe (Clifton-Brown *et al*., 2004). The ALMANAC model (Kiniry *et al*., 1992) is a general crop growth model that has been used in several site-specific studies to estimate the yields of switchgrass (Kiniry *et al*., 1996, 2005; McLaughlin *et al*., 2006), but is primarily a single-point model. More recently, Gunderson *et al*. (2008) used results from various switchgrass growth studies across the United States to statistically estimate the potential for switchgrass production.

Many studies have developed estimates of the costs of producing switchgrass at specific locations in the United States under given assumptions about the yield potential of the crop, such as Iowa (Duffy, 2007), Arkansas (Popp, 2007), Tennessee (Mooney *et al*., 2009; Epplin *et al*., 2007) and Indiana (Brechbill *et al*., 2008). Others report yield and cost data obtained from field experiments in regions, such as Iowa (Hallam *et al*., 2001), the northern plain states (Perrin *et al*., 2008), Oklahoma (Haque *et al*., 2008) and Wisconsin (Vadas *et al*., 2008). [The assumed switchgrass yield in these studies varies between 9.0 (Duffy, 2007) and 12.3 metric tons dry matter per hectare ($\mathrm{t\,DM\,ha^{-1}}$) (Epplin *et al*., 2007) whereas the observed yields in field trials range widely from 5 t DM ha^{-1} in the Upper Plain states (Perrin *et al*., 2008) to 28 t DM ha^{-1} in Mississippi (Busby *et al*., 2007). The reported farm-gate costs of switchgrass production also vary significantly from study to study with \$90.7 t^{-1} DM in Duffy (2007) being the highest and \$38.9 t^{-1} DM in Hallam *et al*. (2001) being the lowest. A few studies have compared the costs of growing switchgrass with other potential cellulosic feedstocks including other herbaceous crops (Hallam *et al*., 2001), willow and poplar (Turhollow, 2000; Ugarte *et al*., 2003) and short rotation woody crop (Downing & Graham, 1996), and found these costs to be lower. Busby *et al*. (2007) compare the costs of growing miscanthus and switchgrass in Mississippi and Oklahoma using data from field trials and find that while the former has a yield and cost advantage in Oklahoma, the latter has an advantage in Mississippi. Khanna *et al*. (2008) compare the costs of producing switchgrass and miscanthus and their spatial variability across counties in Illinois and find that miscanthus has a consistent cost advantage over switchgrass across Illinois. James *et al*. (2010) compare the breakeven prices of several herbaceous and woody biomass crops, including switchgrass and miscanthus in Michigan.

This paper builds upon and extends the approaches of previous studies. While we use a similar crop growth modeling approach, we calibrate and evaluate model parameters using observed field data for miscanthus and switchgrass from experimental trials in Illinois. Following calibration and validation, we use this model in combination with measured climate and solar radiation data to predict the potential yields and breakeven prices for miscanthus and switchgrass for a larger geographical area and to provide insights on the factors influencing the spatial variability in these costs across counties in the Midwestern United States.

Models and methods

Crop growth model description

The annual peak dry matter yields (Y_p) of miscanthus and switchgrass for each 0.1° × 0.1° grid cell in the United States. Midwestern region are calculated using equations based on the principal developed by Monteith (1977) and used by Clifton-Brown *et al*. (2000, 2004) to estimate the yield of miscanthus for Ireland:

$$Y_p = S_t \varepsilon_i \varepsilon_c, \quad (1)$$

where S_t is the integral of incident solar radiation (MJ m^{-2}); ε_i is the efficiency with which the radiation is intercepted by crop canopy, which is defined as a function of radiation extinction coefficient and leaf area index (LAI) (Clifton-Brown *et al*., 2000).

$$\varepsilon_i = 1 - e^{-k^* \mathrm{LAI}}, \quad (2)$$

and ε_c is the efficiency with which the intercepted radiation is converted into biomass energy. The model is used to calculate the yields across the Midwestern region of the United States under both limiting and nonlimiting water resources. The soil water balance between daily rainfall and potential and actual evaporations are calculated using climatic water budget model of Pastor & Post (1985) as implemented by Jain & Yang (2005). The soil hydraulic characteristics for the soil moisture function and the water balance calculations are derived from soil depth and texture information for each FAO soil type (Zobler, 1986, 1999) and relationships between soil texture and water content at the critical pressure (Rawls *et al*., 1982).

Model input

The Y_p equation described above is calibrated using observed yields of miscanthus and switchgrass from data collected in 2005 and 2006 crop years from the experimental field trial site located at the University of Illinois Agriculture Research and Education Centers (UIAREC), Urbana, IL site. The model was evaluated for six UIAREC sites across Illinois: DeKalb, Havana, Orr, Brownstown, Fairfield and Dixon Springs. The field trials for DeKalb, Urbana and Dixon Springs were established in year 2002 (Heaton *et al*., 2008) and for the other sites in year 2004. The data for the Urbana site is available starting 2003, DeKalb and Dixon Springs starting 2005, and for the rest of the sites starting 2006. The seven field sites used in this study are located in North, Central and Southern Illinois, spanning almost 5° of latitudes, about 5 °C variation in mean temperature and a range of soils. Although the data are from Illinois, they are applicable to most of the Midwestern United States, given the similarity of cropland and cropping systems in this region (Heaton *et al*., 2008). Measures of canopy light interception, leaf area index, intercepted photosynthetic active radiation (PAR), and aboveground biomass are used to calibrate the model as discussed next.

The daily temperature and precipitation data for the years 2000 through 2007 at 0.1° × 0.1° are generated from a monthly 4 km × 4 km resolution grid climate dataset from the PRISM Group continental US analysis (PRISM Group, 2009). Monthly solar radiation is obtained by interpolating point measurements from the US National Solar Radiation Database over 1961–2005 (NREL, 1995, 2007). The daily values for temperature and precipitation are calculated using a climate generator built on MODAWEC (Liu *et al*., 2009), where monthly precipitation, maximum and minimum temperature, and wet days data are used as an input. Lastly, daily solar radiation is calculated using the WXGEN weather generator implemented in the EPIC productivity model (Sharpley & Williams, 1990).

As shown by Clifton-Brown & Lewandowski (2000), miscanthus rhizomes are killed in laboratory freezing tests in which the specimen is kept at −3 °C for 3 h. The same study also reports the cold effect on the miscanthus yield for four different sites, showing that miscanthus rhizome dies when temperature reaches on average about −3 °C. To account for this, we used data from the NASA Global Land Data Assimilation System (Rodell *et al*., 2004) to modify miscanthus yields to zero at grid points where the 6 h average soil temperature over the period of 2002–2007 in the 4.5–9 cm soil layer reaches −3 °C. In the case of switchgrass, Nobumasa *et al*. (2002) find that switchgrass rhizomes die if chilled down to −20 °C. These soil temperatures are not seen in the study region, so we do not account for this effect for switchgrass. Since there are no field trials in the United States high latitudes where the soil temperature could routinely reach this critical temperature, we have estimated yields for with and without cold effect (see 'Model estimated yield for biofuel crops for the US Midwest region').

Model calibration and evaluation

Following the method of Clifton-Brown *et al*. (2000) and using the data discussed above, four model parameters are calibrated. First, we calibrated thermal leaf area coefficient (*thc*) by regression of LAI on accumulated degree days above base temperature (DD_{TB}) (i.e., LAI = $thc \times DD_{TB}$). The DD_{TB} is calculated with daily minimum and maximum air temperatures. Based on the correlation between LAI and DD_{TB} for different base temperature, we find the highest correlation coefficient of $r^2 = 0.90$ with a base temperature of 12 °C for miscanthus and $r^2 = 0.91$ with a base temperature of 10 °C for switchgrass (Table 1). Using these DD_{TB}, the regression values of *thc* coefficients are found to be 0.0192 for miscanthus and 0.0127 for switchgrass (Fig. 1a and 1c and Table 1).

Table 1 Crop growth model parameters for miscanthus and switchgrass that were calibrated using the measured data

Parameter	Miscanthus	Switchgrass
Base temperature (°C)	12	10
Thermal leaf area coefficient (unitless)	0.019	0.013
Light extinction coefficient (unitless)	0.57	0.44
Radiation use efficiency (g MJ^{-1} PAR_i)	3.4	1.7

Second, the radiation extinction coefficient k is calculated using the relationship between LAI and radiation intercepted coefficient (ε_i) [Eqn (2)].The calculated k for switchgrass and miscanthus is 0.44 and 0.57, respectively (Table 1). As shown in Fig. 1b and e, an *LAI* of about 5 for switchgrass and 4 for miscanthus is sufficient to intercept about 90% of the incident radiation.

Third, the radiation use efficiency (ε_c) is estimated from the regression of the aboveground dry matter on intercepted radiation (Fig. 1c and f). The estimated ε_c for switchgrass and miscanthus is 1.7 and 3.4 g MJ^{-1} of intercepted PAR (PAR_i), respectively (Table 1).

Fourth, thermal time to maturity is calculated by establishing a relationship between latitude and peak biomass. At the Urbana site, with latitude of 40.11°N, the thermal time for miscanthus was determined to be 1260 DD_{TB}, with switchgrass requiring 1320 DD_{TB} to reach maturity.

Finally, the length of growing season is determined by the number of days between the last spring air frost and the first autumn air frost. The air frost threshold temperature is assumed to be 0 °C.

Overall, the model was able to replicate the observed peak yields of switchgrass and miscanthus for the calibration and evaluation sites in Illinois. Considering all six evaluation sites, modeled miscanthus yields were approximately 12% higher, and switchgrass yields were 4% higher than the observed data (see Fig. 2). Average observed peak yields were 37.2 metric tons of dry matter per hectare per year (t DM ha^{-1} yr^{-1}) for miscanthus and 14.7 t DM ha^{-1} yr^{-1} for switchgrass, whereas average modeled yields were 42.5 t DM ha^{-1} yr^{-1} for miscanthus and 15.3 t DM ha^{-1} for switchgrass.

The modeled yields of miscanthus at DeKalb, Urbana and Fairfield are found to be in close agreement with the observed data, with differences being <2%; whereas the modeled yields for switchgrass are in close agreement with observations at the DeKalb, Urbana and Orr sites, with the difference at these sites being <2%. However, we found large differences in calculated (43 t DM ha^{-1}) and observed (17 t DM ha^{-1}) yield for miscanthus at the Brownstown site; the model yields overestimated observed yields by 60%. This can be attributed to poor soil conditions at the site, causing very low observed yields in every year of sample data (F. Dohleman, personal communication). If we exclude the Brownstown site for calculation of average error in miscanthus production, the average error in miscanthus estimation drops to 4%. The largest percentage difference (12%) for switchgrass was found at Brownstown as well. However, the difference between measured and modeled yields is not as large as for miscanthus, suggesting that the poor soil quality effect is greater

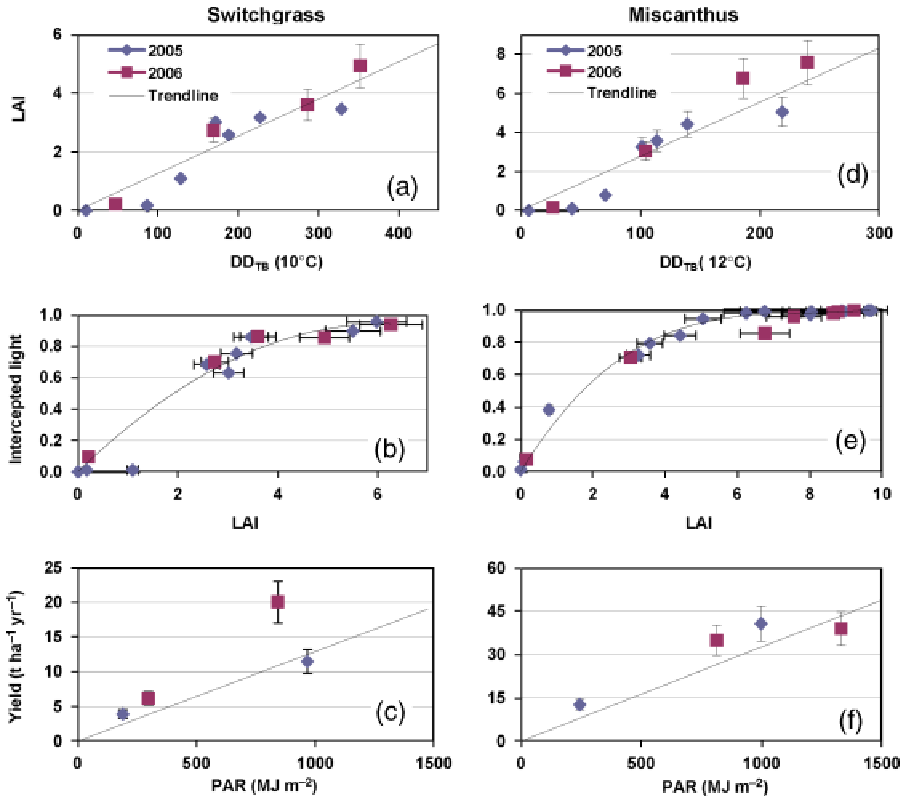

Fig. 1 Relationship between (a and d) leaf area index (LAI) and above 10 °C for switchgrass and 12 °C for miscanthus (DD_{TB}), (b and e) intercepted light and LAI, and (c and f) above ground peak yield and intercepted photosynthetic active radiation (PAR). The left panel represents the relationships for switchgrass and the right panel for miscanthus. These relationships are derived using data collected in years 2005 and 2006 from the experimental field trial site located at the University of Illinois Agriculture Research and Education Centers (UIAREC), Urbana, IL site.

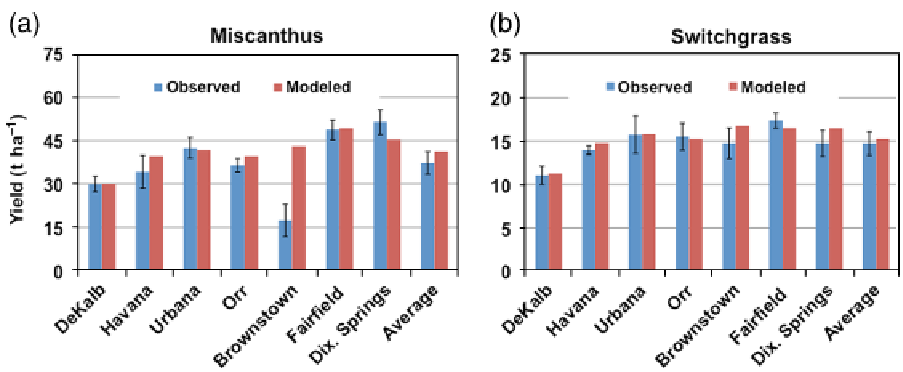

Fig. 2 Comparison of model estimated yields for miscanthus and switchgrass with observation data collected at six UIAREC sites across Illinois: DeKalb, Havana, Orr, Brownstown, Fairfield and Dixon Springs, as well as average for all sites. The value for Urbana is averaged for the period 2005–2006 and for the rest of the sites the values are averaged for the period 2006–2007.

for miscanthus than for switchgrass, which our model is not able to capture.

We also compare our model estimated yields of switchgrass with those observed at two other sites in the Midwest. Casler & Boe (2003) estimate Cave-in-Rock switchgrass yield at a site in Arlington, WI (lat. 43.33°, long. −89.38°) to be 13.3 t DM ha^{-1}. Lemus *et al.* (2002) report Cave-in-Rock switchgrass yield of 12.5 t

DM ha^{-1} yr^{-1} at the McNay Farm, IA (lat. 40.97°, long. −93.43°). Both studies reported the measured yield in the third year after planting. Our model estimated yield at both sites is 13.4 t DM ha^{-1} yr^{-1}, which is in close agreement with the observed yields.

Agronomic and economic data

We develop county-specific enterprise budgets of the costs of production of switchgrass and miscanthus over their lifetime for each of the Midwestern states. Switchgrass stands can live for 15–20 years in a native state, but in cultivated conditions the US Department of Energy is estimating stand-life at 10 years (http://southwestfarmpress.com/energy/121107-switchgrass-challenges/, http://www.osti.gov/bridge/servlets/purl/771591-9J657S/webviewable/771591.pdf). A 10-year life span is also commonly assumed for analyzing the costs of production of switchgrass (see Qin *et al*., 2006; Duffy, 2007; Brechbill *et al*., 2008; Perrin *et al*., 2008; Mooney *et al*., 2009). Miscanthus is also a long-lived grass with the oldest plantation being an 18-year-old stand in Denmark (Lewandowski *et al*., 2003). Field experiments provide evidence of long term productivity of 14–16-year-old miscanthus stands in Europe (Hansen *et al*., 2004; Clifton-Brown *et al*., 2007; Christian *et al*., 2008). In the United States, the oldest miscanthus stands include those growing at the University of Illinois Landscape Horticulture Research Center since 1988 and at the Chicago Botanic Garden since 1970 (Heaton *et al*., 2008). We assume a life span of 10 years for switchgrass and 15 years for miscanthus for our economic analysis and examine the sensitivity of our costs of production to a shorter life span of 10 years for miscanthus.

Both costs and yields of biomass during the establishment years differ from those over the remaining lifetime of these crops. To compare costs of production at different points in time over the life of the crop, and across crops with different lifetimes, we first calculate the present discounted value $\sum_{t=0}^{T}\frac{C_t}{(1+d)^t}$ of the sequence of annual costs, C_t, over the life of each crop using a discount rate of 4%. We similarly calculate the present value of yields, given the sequence of annual yields over the life of the crop, $\sum_{t=0}^{T}\frac{Y_t}{(1+d)^t}$ using the same discount rate as above. Note that Y_t is yield after losses during harvesting and storage in year t and we refer to the annualized yields after losses during harvesting and storage as yield at farm-gate. The breakeven farm-gate price P_B (\$ t^{-1} DM) for each crop is the minimum price per dry metric ton of the bioenergy crop that a cropland owner would need to receive each year to cover all the costs of production over the life of the crop. This price would result in the present value of revenues from the crop being just equal to the PV of costs of producing it over its life as follows:

$$P_B\left[\sum_{t=0}^{T}\frac{Y_t}{(1+d)^t}\right]=\sum_{t=0}^{T}\frac{C_t}{(1+d)^t}. \quad (3)$$

Thus,

$$P_B=\frac{\sum_{t=0}^{T}\frac{C_t}{(1+d)^t}}{\sum_{t=0}^{T}\frac{Y_t}{(1+d)^t}}, \quad (4)$$

where T is the life of the crop, C_t is the cost of the bioenergy crop per hectare in period t, d is the discount rate and Y_t again is yield per hectare after harvesting and storage losses in year t. C_t includes the cost of producing the crop at time t (C_{pt}) and opportunity cost of land (C_{Lt}), both measured in \$ ha^{-1}. We estimate C_{Lt} as follows:

$$C_{Lt}=(P^*_{ct}Q_{ct}-C_{ct}+P^*_{st}Q_{st}-C_{st})/2, \quad (5)$$

where P_{ct}, Q_{ct} and C_{ct} are the price (\$ t^{-1}), yield (t ha^{-1}) and production cost of corn (\$ ha^{-1}), respectively, whereas P_{st}, Q_{st} and C_{st} are the corresponding values for soybeans at time t.

The farm-gate production cost (C_{pt}), of switchgrass and miscanthus include (i) the cost of inputs, such as chemicals, fertilizers and seeds, (ii) the cost of field operations, such as planting and harvesting, and (iii) the costs of storage. Costs of production for each county are obtained using state-specific input prices and machinery costs for 2007. The per hectare costs of land, overhead (such as farm insurance and utilities), building repair and depreciation, and 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.

The agronomic assumptions about the temporal pattern of crop yields, reseeding rates and input application rates are based on a review of existing agronomic and economic studies presented in Khanna *et al*. (2008, 2009) and supplemented with information in Brechbill *et al*. (2008) and Duffy (2007) and experimental field research conducted at UIAREC. Application rates are assumed to be the same across all states in the Midwestern US and are given in Table 2. Some input application rates are dependent on yield and thus their application rate per hectare varies across counties. Other input application rates per hectare do not vary across counties. In practice, fertilizer application rates, replanting probabilities, second-year yields and harvest losses may differ across locations. To allow flexibility in input requirements for these variables we consider two

Table 2 Agronomic assumptions for miscanthus and switchgrass production

	Miscanthus low-cost – high-cost scenarios	Switchgrass low-cost – high-cost scenarios
	Establishment year	
Planting density (rhizome m^{-1})	1	–
Seeding rate (kg ha^{-1})	–	6.5–11
Planting time	March–April	February–March
Nitrogen (kg ha^{-1})	30–60	0
Phosphorus (kg ha^{-1})	7	33.7
Potassium (kg ha^{-1})	100	44.9
Lime (t ha^{-1})	2.3–4.5	0–6.7
Atrazine (Herbicide) (L ha^{-1})	3.5	3.5
2,4-D (Herbicide) (L ha^{-1})	1.8	1.8
	Postestablishment year	
Replanting rate in year 2	15–50%	15–50%
Nitrogen (kg ha^{-1})	25–50	56–140
Phosphorus (kg ha^{-1})	7	0.42–0.97*
Potassium (kg ha^{-1})	100	9.47–11.40*
Atrazine (Herbicide) (L ha^{-1})	0	0–3.5
2,4-D (Herbicide) (L ha^{-1})	0	1.8
Percent of peak biomass yield		
Year 1 (%)	0	100–30
Year 2 (%)	50–40	100–67
Year 3 and after (%)	100	100
Yield loss (%)	20–40	20
Harvest timing	December or early Spring	After first frost
Moisture at harvest (%)	15	15
Farm-gate yield (t DM ha^{-1})***	19.2–14.1	9.4–8.4
Life of crop (years)	15	10

*Application rate is measured in kg t^{-1} DM of biomass removed.
**Assumptions about harvesting costs between the low cost and high cost scenarios are also different as explained in the text.
***Farm-gate yield is defined as annualized yield after losses during harvesting and storage.

alternative scenarios, a low-cost and a high-cost scenario. The agronomic assumptions for these two scenarios are described in Table 2. The low-cost scenario considers a low fertilizer application rate, low replanting probability, high second-year yield and low harvest loss and economies of scale in harvesting costs whereas the high-cost scenario captures the opposite case of production. In particular, in the high-cost scenario we assume that the costs of baling per ton are the same for switchgrass and miscanthus; thus baling costs per hectare are much higher for miscanthus than for switchgrass given its higher yield per hectare. In the low-cost scenario, we differentiate between the fixed costs of baling (for tractor and other implements) and variable costs (fuel, lube and labor); thus baling costs per ton of dry matter decrease as the tons of biomass per hectare increases [see Figure S1 in the Supporting Information (SI) provided]. These assumptions are used together with input prices and costs of various field operations obtained from Khanna *et al*. (2008), Duffy (2007), Brechbill *et al*. (2008) and FBFM (2007, 2008) to construct costs of production for switchgrass and miscanthus in each of the Midwestern states. The costs of production differ in the establishment phase (year 1 for switchgrass and years 1 and 2 for miscanthus) and the maintenance years, defined by the remaining life of the crop (see Table S1 for the breakdown of these costs for various field operations for Illinois). Similar methods were used for calculating the costs for other states, together with state-specific prices of inputs and yields. (Details of the costs of production of miscanthus and switchgrass for the other Midwestern states are available from the authors on request.) These prices are provided in Table S2. Annualized breakdown of costs of production for each crop for each of the Midwestern states, under the assumption of a 10-year life of switchgrass and 15-year life of miscanthus and in the low and high-cost scenarios, are reported in Tables S3 and S4, respectively.

There is considerable uncertainty about the cost of miscanthus rhizomes as they are not yet commercially available for large scale plantations. Personal communication with developers and producers of miscanthus varieties, rhizomes and plugs indicates that they expect miscanthus plugs to cost between $0.30 and

\$0.80 plug^{-1} as they begin commercial sales in 2010 and close to \$0.25 plug^{-1} by 2011. For a large scale plantation with 10 000–12 000 plugs ha^{-1}, the costs of establishment (including labor, equipment and chemicals) are expected to be \$3000–\$4000 ha^{-1}. (Personal communication with representatives from Pyramid Farms Ltd, Ontario, Canada, Mendel Biotechnology, California and with Tom Voigt, University of Illinois.) Plugs are vegetatively produced from rhizomes and have a dominant meristem. Costs are expected to be lower for rhizomes compared with plugs and to decrease as the scale of production increases. Cost of propagating rhizomes at the University of Illinois is estimated to be \$0.10 rhizome^{-1}. We assume a rhizome cost of \$0.25 and a planting rate of 10 000 rhizomes ha^{-1}. Our costs of establishment, including planting, fertilizer and chemical costs amount to \$2957 ha^{-1} in Illinois. We examine the sensitivity of the breakeven prices of miscanthus to a doubling of the cost of rhizomes by considering a scenario with \$0.50 rhizome^{-1}. We also consider a scenario where these costs are \$0.10 rhizome^{-1}.

We define C_{Lt} as the foregone profits per hectare from the next best alternative use of that land. In the case of cropland, this alternative use is defined by choice of crop, rotation and tillage practice. A landowner is assumed to be using the land in its most profitable use, which in turn depends on the yields of the alternative crops, their prices and costs of production (which in turn depend on prices of inputs such as fertilizers and chemicals). The most profitable land use and the opportunity cost of the land is likely to change over time (with changes in input and output prices and yields) and across locations (due to spatial variation in yields of alternative crops).

We estimate the costs of corn and soybean production for each county in the Midwestern United States using information from the crop budgets compiled for that state by state extension services. The revenue from corn and soybean production is estimated using the county-specific 5-year (2003–2007) average yields and state-level price statistics published by the National Agricultural Statistics Service (NASS) for 2007. The sources for this data and the assumptions underlying the estimation of the opportunity costs of land under representative conditions for each of the Midwestern states are reported in Table S2. For comparison, we also estimated the profits from wheat and hay production (Table S2). We find that, with the exception of Michigan, a corn–soybean rotation with conventional tillage is the most profitable land use on average in each of the Midwestern states. (Corn production with conventional tillage or no-till typically involves about the same costs per hectare. However, soybean production costs with no-till are typically higher than with conventional till due to higher seed and chemical costs which more than offset the lower fuel and machinery costs. We assume that yields per hectare for each crop are the same under conventional till and no-till. For more details regarding input and fuel uses under different types of till, see http://www.ers.usda.gov/Data/ARMS/app/Crop.aspx and http://ecat.sc.egov.usda.gov/.) Average profits range between \$366 ha^{-1} in Michigan and \$785 ha^{-1} in Illinois (Table S2). Not surprisingly, it has a dominant share in total crop acreage in the Midwest. In Iowa, its share in total crop acreage is 84%; on average its share is 53% in total crop acreage in the eight Midwestern states (Padgitt *et al*., 2000). An exception to this is Michigan in which only 22% of acreage is in a corn–soybean rotation; on average, we find that hay alfalfa is about 13% more profitable (on average) than the corn–soybean rotation.

Given the diversity of observed crops, rotations and tillage practices within and across locations in the Midwest, it is evident that a corn–soybean rotation with conventional tillage is not the most profitable land use in all locations. To the extent that other land uses are more profitable than a corn–soybean rotation, the opportunity cost of converting that land to bioenergy crops would be higher. We use representative profits (for each county) from a corn–soybean rotation with conventional tillage to provide an estimate of the cost of converting land currently under a corn–soybean rotation to bioenergy crops in a county. This opportunity cost would be higher if corn residues have value as a feedstock for biofuels or biopower. We discuss the sensitivity of our breakeven price estimates to assumptions about the discount rate, input and output prices, yields and the use of corn residues below.

Even with a corn–soybean rotation, the opportunity cost of land differs across counties in a state since the yields and production costs of corn and soybeans differ across counties. The map in Fig. 3a shows the spatial variation in the per hectare yield of corn across the Midwestern United States. Yields of corn are much higher in central and northern Illinois and in Iowa and relatively lower in Missouri. The spatial distribution of soybean yields per hectare is highly correlated with corn yields per hectare and is not shown for brevity. Figure 3b shows the estimated opportunity cost of corn–soybean land in terms of dollars per hectare in this region. In general, states with a high corn and soybean yield per hectare also have a high opportunity cost per hectare of using that land for bioenergy crops. Illinois has the highest opportunity costs of land as its corn and soybean yields per hectare and prices are high while the costs of production of corn and soybeans per hectare are relatively low. On the other hand, Michigan has the lowest opportunity cost of land per hectare

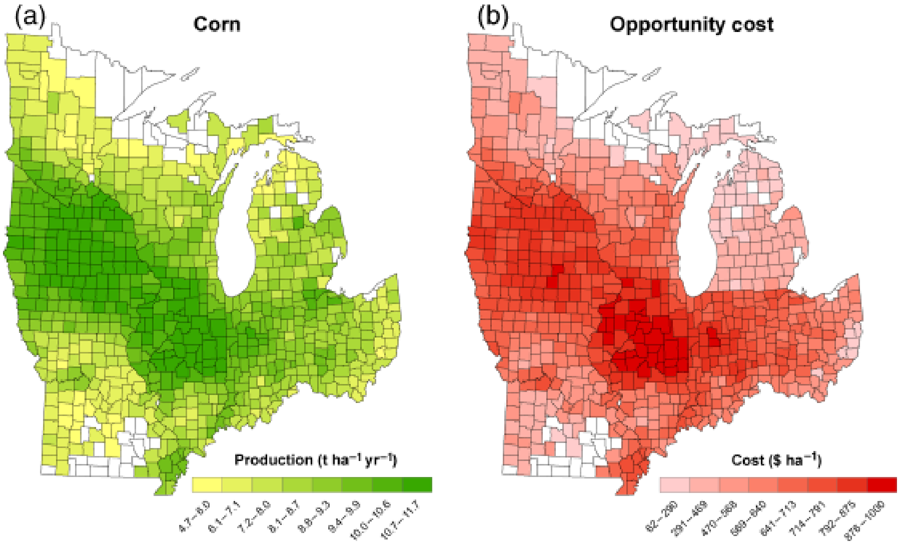

Fig. 3 Average corn yields for the period 2003–2007 and the opportunity cost of land in 2007 prices.

under a corn–soybean rotation due to its low corn and soybean yields per hectare and relatively high costs of production per hectare of these crops.

Results

Model estimated yield for biofuel crops for the US Midwest region

While the model was run for the entirety of the continental United States, this paper presents estimates for the Midwestern United States only. In regions such as the Midwest, model results are largely driven by input temperature and solar radiation. On a per hectare basis, our model results suggest that the miscanthus peak biomass yield in the Midwest is about three times the yield of switchgrass. The estimated peak biomass yield for miscanthus in the Midwest ranges between 0 and 62 t DM ha^{-1} yr^{-1} and for switchgrass ranges between 8 and 40 t DM ha^{-1} yr^{-1}. The model results show a north to south gradient, which suggest that yields in this region are largely driven by temperature and solar radiation (Fig. 4). As such, Missouri and the southern portions of Illinois and Indiana show strong yields for miscanthus and switchgrass, with northern Minnesota and Michigan's Upper Peninsula being the region where the estimated yields for both biofuel crops are the lowest (Fig. 4). As discussed in Clifton-Brown & Lewandowski (2000), extremely cold soil temperatures will kill rhizomes of *Miscanthus* $\times$ *giganteus*. Using the criteria implemented in the model, most of Minnesota, Wisconsin and the Michigan Upper Peninsula are shown to be very poor performers in miscanthus production, with averaged county-level production being zero for much of this region of the Midwest. Given the lack of field data from these regions and uncertainty of the degree to which there is cold tolerance, yields could be in between the range of values provided here.

Water limitation, as implemented in the model has only a small effect on yields of miscanthus and switchgrass. Over the study region, the average yield increases by 1.0 t DM ha^{-1} for switchgrass and 3.1 t DM ha^{-1} yr^{-1} for miscanthus when water limitation is disabled. The spatial pattern of yield is the same with and without water limitation across the Midwest.

Without some frost in late autumn, miscanthus does not senesce properly (Clifton-Brown *et al*., 2001a), reducing translocation of nutrients from the aboveground biomass to the rhizome. This can result in nutrient limitation as the aboveground biomass is harvested along with the necessary nutrients for next year's growth. This effect is simulated within the model, but it does not affect yields within the study region. While year to year variations in climate do not change the regional pattern of yield they do affect peak yield levels, our model results indicate that the variation in peak yields for the two biofuel crops was between $\pm$5% and 10% due to variations in local climate over the period 2003–2007 (Table 3).

Cost of bioenergy crops in Midwestern United States

The state-level estimates of costs as well as breakeven prices in the low-cost and the high-cost production scenarios are reported in Table 4 and the results of the low-cost production scenario are also depicted in Fig. 5.

The costs of production of switchgrass in the low-cost scenario ranges from \$39 to \$58 t^{-1} DM across this region while the costs of miscanthus vary more widely between \$34 and \$80 t^{-1} DM among the Midwestern states. In the high-cost scenario, these costs range between \$62 and \$90 t^{-1} DM for switchgrass and \$58 and \$131 t^{-1} DM for miscanthus. In general, the costs of production for miscanthus are considerably lower than those for switchgrass (Table 4) except for the Northern Midwestern states such as Minnesota and Wisconsin, which have significantly low miscanthus yields. Although the establishment cost for miscanthus is much higher than for switchgrass, its annualized cost of production per dry ton is still lower than that of switchgrass primarily because of its higher yield (more than twice that of switchgrass on average) and longer lifetime (15 years instead of 10 years for switchgrass). As a result of the difference in yield per hectare of miscanthus and switchgrass, the opportunity cost of land per dry ton for these two crops differs greatly at any location. It accounts for a large part of the total cost per dry ton in the Midwest. This opportunity cost of land also differs across states due to differences in the productivity of conventional crops across these states.

The opportunity costs of land per dry ton range between \$46 and \$92 t^{-1} DM across the Midwestern states in the low-cost scenario for switchgrass and between \$19 and \$74 t^{-1} DM in the case of miscanthus. Some states have much higher opportunity costs of land per dry ton for switchgrass or miscanthus because they have a much lower yield per unit of land than others (Fig. 4). Iowa has the highest opportunity cost of land ranging between \$92 and \$103 t^{-1} DM for switchgrass and Minnesota has the highest opportunity cost of land for miscanthus at \$74–\$103 t^{-1} DM across the low and high-cost scenarios. Michigan has the lowest opportunity cost of land ranging between \$46 and \$54 t^{-1} DM for switchgrass and Missouri has the lowest cost of land for miscanthus at \$19 and \$27 t^{-1} DM.

A comparison across states shows that Missouri has the lowest breakeven price per dry ton for both bioenergy crops; Minnesota and Iowa have the highest breakeven price per dry ton for switchgrass due to its high opportunity cost of land and Minnesota and Wisconsin have highest breakeven costs for miscanthus due to their much lower miscanthus yield levels (Table 4). In Missouri, the breakeven price of production

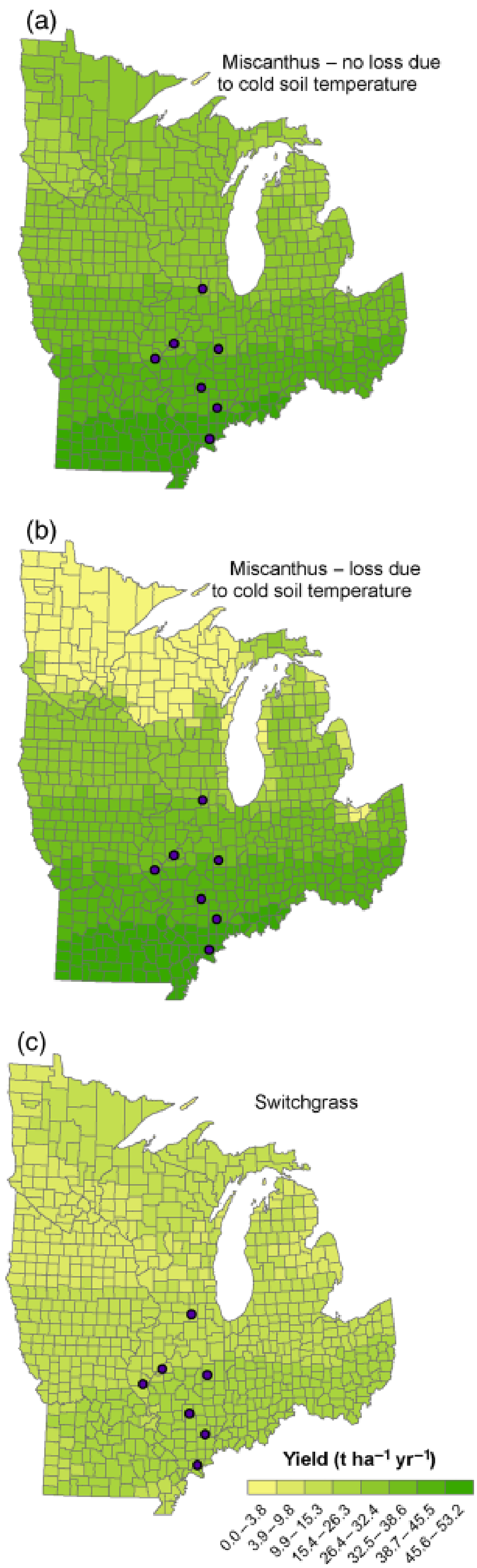

Fig. 4 Estimated peak yields (t/ha) for (a) miscanthus – no loss due to cold soil temperature, (b) miscanthus – loss due to cold soil temperature and (c) switchgrass in the Midwestern United States. The values are averaged for the period 2005–2006. The dots are showing the locations for the measured miscanthus and switchgrass yields.

Table 3 Crop growth model estimated peak miscanthus and switchgrass biomass yields averaged for the period 2003–2007

	Miscanthus			Switchgrass	
State/region	Cold effect yield ($t\,DM\,ha^{-1}\,yr^{-1}$)	SD	No cold effect yield ($t\,DM\,ha^{-1}\,yr^{-1}$)	Yield ($t\,DM\,ha^{-1}\,yr^{-1}$)	SD
Iowa	31.23	2.7	31.23	11.32	0.9
Illinois	39.97	3.2	40.26	14.57	1.0
Indiana	42.53	3.5	42.53	15.51	1.2
Michigan	16.61	3.1	27.33	10.40	1.1
Minnesota	7.38	2.4	25.65	9.90	0.8
Missouri	47.70	3.5	47.70	15.39	1.0
Ohio	39.44	2.8	41.00	15.34	1.0
Wisconsin	9.93	2.6	26.79	10.10	0.9
US Midwest	29.35	2.7	35.31	12.82	0.9

of switchgrass ranges between \$88 and 118 t^{-1} DM whereas that of miscanthus ranges between \$53 and 85 t^{-1} DM. The average breakeven price of switchgrass, across all Midwestern states, is \$115 t^{-1} DM whereas that of miscanthus is \$88 t^{-1} DM, in the low-cost scenario (Table 5).

Corresponding figures for the high-cost scenario are \$151 t^{-1}DM for switchgrass and \$136 t^{-1}DM for miscanthus.

If miscanthus is more cold tolerant than assumed here, the average yield of miscanthus would change from <10 to 25.65 $t\,DM\,ha^{-1}\,yr^{-1}$ in Minnesota and to 26.79 $t\,DM\,ha^{-1}$ in Wisconsin (Table 3). At these new yield levels, the breakeven prices of miscanthus would decrease dramatically (by about 45%) from \$153–\$234 t^{-1} DM to \$86–\$134 t^{-1} DM in Minnesota and from \$140–\$211 t^{-1} DM to \$78–\$120 t^{-1} DM in Wisconsin. If we exclude Minnesota and Wisconsin, then the breakeven price of production of miscanthus across the remaining states ranges between \$53–\$79 t^{-1} DM in the low-cost scenario and \$85–\$128 t^{-1} DM in the high-cost scenario. When the two states are excluded, the average breakeven price of miscanthus in the remaining Midwestern states is \$68 t^{-1}DM in the low-cost scenario and \$107 t^{-1}DM in the high-cost scenario.

Mooney *et al*. (2009) estimate the costs for the Alamo variety in Tennessee with a yield of 17.7 $t\,DM\,ha^{-1}\,yr^{-1}$ to range between \$46 and 67 t^{-1} DM. This includes an estimate of land costs in Tennessee that ranges between \$9 and 19 t^{-1} DM. Our estimates for the costs of switchgrass production per ton (excluding land costs) for Missouri, in Table 4, are very similar to Mooney *et al*. (2009) (\$39–62 t^{-1} DM). However, our estimated breakeven price in Missouri is higher than their estimate for Tennessee, partly due to a somewhat lower yield (15.5 t $DM\,ha^{-1}\,yr^{-1}$) and partly due to a much higher cost of land (\$49–56 t^{-1} DM of switchgrass). Our breakeven prices for switchgrass production in Indiana, \$103–138 t^{-1}, are more than twice as high as those in Brechbill *et al*. (2008), \$54–57 t^{-1}, in large part due to our higher costs of land (\$61–67 t^{-1} DM as compared with their cost of land of \$14 t^{-1} DM). James *et al*. (2010) estimate of switchgrass breakeven price of \$115 t^{-1}DM in Michigan (with a yield of 9 $t^{-1}\,DM\,ha^{-1}\,yr^{-1}$) is within the range we find for Michigan, between \$102 and \$142 t^{-1} DM (with an average yield of 10 $t\,DM\,ha^{-1}\,yr^{-1}$). Their estimate of the breakeven price of miscanthus in Michigan ranges between \$45 and \$200 t^{-1}DM as rhizome costs vary between \$0.5 and \$1.80 $rhizome^{-1}$ and qwith an assumed life of 10 yrs and a yield of 22.4 $t^{-1}\,DM\,ha^{-1}\,yr^{-1}$for miscanthus. Our breakeven prices for miscanthus production in Michigan range between \$79 and \$128 t^{-1}DM; while we have lower rhizome costs and a longer lifetime for miscanthus, we also consider a lower yield of 17 $t\,DM\,ha^{-1}\,yr^{-1}$ that raises costs of production.

The spatial distribution of county-level breakeven prices of the bioenergy crops under the low-cost scenario is shown in Fig. 6. In general, switchgrass is more costly to produce than miscanthus in most of the Midwestern counties but for some counties in Minnesota, Wisconsin and Michigan, miscanthus is much more expensive than switchgrass due to the lack of yield advantage and its high establishment cost. Southern Missouri has the lowest breakeven price of energy crop production (\$40 t^{-1} DM of miscanthus) and in most Midwestern counties, the breakeven prices of miscanthus are $<$\$80 t^{-1} DM. On the other hand, the breakeven prices of switchgrass in most of the Midwestern counties are around \$100 t^{-1} DM or above and; as these are largely determined by the opportunity cost of land, the breakeven prices in Iowa and Northern Illinois are the highest while in Missouri and Northern Minnesota and Wisconsin the breakeven prices of

Table 4 Costs of bioenergy crop production (US$ t^{-1})

State	Switchgrass				Miscanthus			
	Production cost (US$ t^{-1} DM)	Opportunity cost of land (US$ t^{-1} DM)	Breakeven price (US$ t^{-1} DM)	Share of opportunity cost in breakeven price (%)	Production cost (US$ t^{-1} DM)	Opportunity cost of land (US$ t^{-1} DM)	Breakeven price (US$ t^{-1} DM)	Share of opportunity cost in breakeven price (%)
Illinois	44–70	73–82	117–151	62–54	37–63	31–43	69–106	46–40
Indiana	42–71	61–67	103–138	59–49	36–65	29–39	65–104	44–38
Iowa	48–75	92–103	140–178	66–58	41–69	37–51	78–120	48–42
Michigan	56–88	46–54	102–142	45–38	53–91	26–37	79–128	33–29
Minnesota	58–90	86–98	144–188	60–52	80–131	74–103	153–234	48–44
Missouri	39–62	49–56	88–118	56–48	34–58	19–27	53–85	36–32
Ohio	42–67	56–62	98–130	57–48	38–65	27–36	65–101	41–36
Wisconsin	46–70	82–91	127–162	64–57	68–114	72–98	140–211	51–46

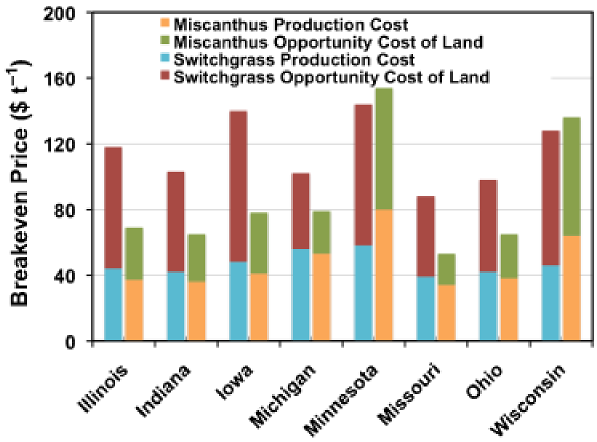

Fig. 5 The estimated breakeven price for switchgrass and miscanthus in the Midwest United States. The values are in 2007 prices.

switchgrass are the lowest. These results suggest that there is considerable spatial variation in the breakeven prices of cellulosic feedstocks in the Midwest and that some areas are better suited to provide low price and high yield feedstock than others and will specialize in the production of different bioenergy crops. Bioenergy crops are more likely to be attractive to landowners in locations with high yields of bioenergy crops and with low yields and high costs of production of conventional crops they seek to displace.

Sensitivity analyses

We analyze the sensitivity of the breakeven price, including the opportunity cost of land, to several assumptions made above (Table 5). We report and discuss the results for the low-cost scenario only since there is not much difference between the effects in the low and high-cost cases. The opportunity cost of the land is affected by changes in the price of corn and soybeans and a 25% change in the prices of corn and soybeans changes the breakeven price (on average across states) by 27% (ranging between 16% and 32%) for switchgrass and 20% (between 11% and 23%) for miscanthus. 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. Breakeven prices are not sensitive to assumptions about costs for preharvest and harvest operations. A 25% increase in preharvest costs would increase the breakeven price of switchgrass and miscanthus by only 0.4% on average (between 0.3% and 0.5%) and the same percentage increase in harvest costs

Table 5 Sensitivity of breakeven prices for the low cost scenario*

		Switchgrass			Miscanthus		
		Mean	Minimum	Maximum	Mean	Minimum	Maximum
Baseline	(US$ t^{-1} DM)	115.01	88.27	144.19	87.81	53.25	153.47
25% Increase in corn-soybean price	(US$ t^{-1} DM)	145.60	110.22	183.02	105.69	61.85	186.86
	% Change	27	16	32	20	11	23
25% Decrease in corn-soybean price	(US$ t^{-1} DM)	84.42	66.32	105.36	69.94	44.65	120.08
	% Change	−27	−32	−16	−20	−23	−11
25% Increase in preharvest cost	(US$ t^{-1} DM)	115.42	88.62	144.69	88.16	53.44	154.12
	% Change	0.4	0.3	0.5	0.4	0.3	0.5
25% Decrease in preharvest cost	(US$ t^{-1} DM)	114.61	87.93	143.69	87.47	53.06	152.82
	% Change	−0.4	−0.5	−0.3	−0.4	−0.5	−0.3
25% Increase in harvest cost	(US$ t^{-1} DM)	122.10	94.97	151.94	93.75	58.72	160.31
	% Change	6	5	8	7	4	10
25% Decrease in harvest cost	(US$ t^{-1} DM)	107.93	81.57	136.44	81.88	47.78	146.63
	% Change	−6	−8	−5	−7	−10	−4
25% Increase in fertilizer price	(US$ t^{-1} DM)	118.68	90.58	149.85	89.33	53.78	157.83
	% Change	3	2	5	2	1	3
25% Decrease in fertilizer price	(US$ t^{-1} DM)	111.35	85.96	138.54	86.30	52.72	149.11
	% Change	−3	−5	−2	−2	−3	−1
10% Increase in bioenergy crop yield	(US$ t^{-1} DM)	106.79	82.34	133.72	81.62	50.20	141.31
	% Change	−7	−8	−7	−7	−8	−6
10% Decrease in bioenergy crop yield	(US$ t^{-1} DM)	125.06	95.53	156.99	95.39	56.98	168.34
	% Change	9	8	9	8	7	10
Change discount rate from 4% to 8%	(US$ t^{-1} DM)	115.56	88.69	144.88	95.00	56.96	167.13
	% Change	0.5	0.4	0.7	7.9	6.7	9.6
Change rhizome price from US$0.25 to US$0.50 $rhizome^{-1}$	(US$ t^{-1} DM)	115.01	88.27	144.19	104.89	62.39	185.33
	% Change	NA	NA	NA	19	15	25
Change rhizome price from US$0.25 to US$0.10 $rhizome^{-1}$	(US$ t^{-1} DM)	115.01	88.27	144.19	77.57	47.77	134.35
	% Change	NA	NA	NA	−11	−15	−9
Change life time from 15 to 10 years for miscanthus	(US$ t^{-1} DM)	115.01	88.27	144.19	99.11	59.08	174.96
	% Change	NA	NA	NA	12	11	15
Inclusion of corn stover profits in opportunity cost of land	(US$ t^{-1} DM)	123.02	90.51	158.63	91.31	52.95	166.99
	% Change	6.5	2.5	10.8	2.6	0†	8.8

*Percentage changes are calculated relative to the breakeven price for that crop in the baseline case provided in row 1 of this table.
†This reflects the lack of change in opportunity cost of land for Missouri where corn stover production is not profitable at the breakeven price of miscanthus of US$52.95 t^{-1} DM calculated here.

would increase the breakeven price by about 6% on average (between 5% and 8%) for switchgrass and 7% (between 4% and 10%) for miscanthus. A 25% increase in fertilizer costs also has only small effects on the breakeven price of either crop, which would increase on average by 3% (between 2% and 5%) for switchgrass and around 2% (between 1% and 3%) for miscanthus. Changing discount rate from 4% to 8% would have a very modest impact on the breakeven price of switchgrass (0.5% increase on average and varying between 0.4% and 0.7%) but a more remarkable impact on the price of miscanthus (7.9% increase and varying between 6.7% and 9.6%) because miscanthus has much higher establishment costs. A 10% increase in bioenergy crop yield per hectare reduces the breakeven prices of both switchgrass and miscanthus by 7% on average. When the lifetime of miscanthus is shortened from 15 to 10 years, the breakeven price of miscanthus would increase on average by 12% (between 11% and 15%). Moreover, the breakeven price of miscanthus is also very sensitive to rhizome price. If rhizome costs are $0.50 $rhizome^{-1}$ instead of $0.25 $rhizome^{-1}$, the breakeven price of miscanthus would increase on average by 19% (between 15% and 25%). If the rhizome price is $0.10 $rhizome^{-1}$ then the breakeven price of miscanthus would decrease by 11% on average. In general, the breakeven price of bioenergy crops is more sensitive to the assumptions examined above in the states with

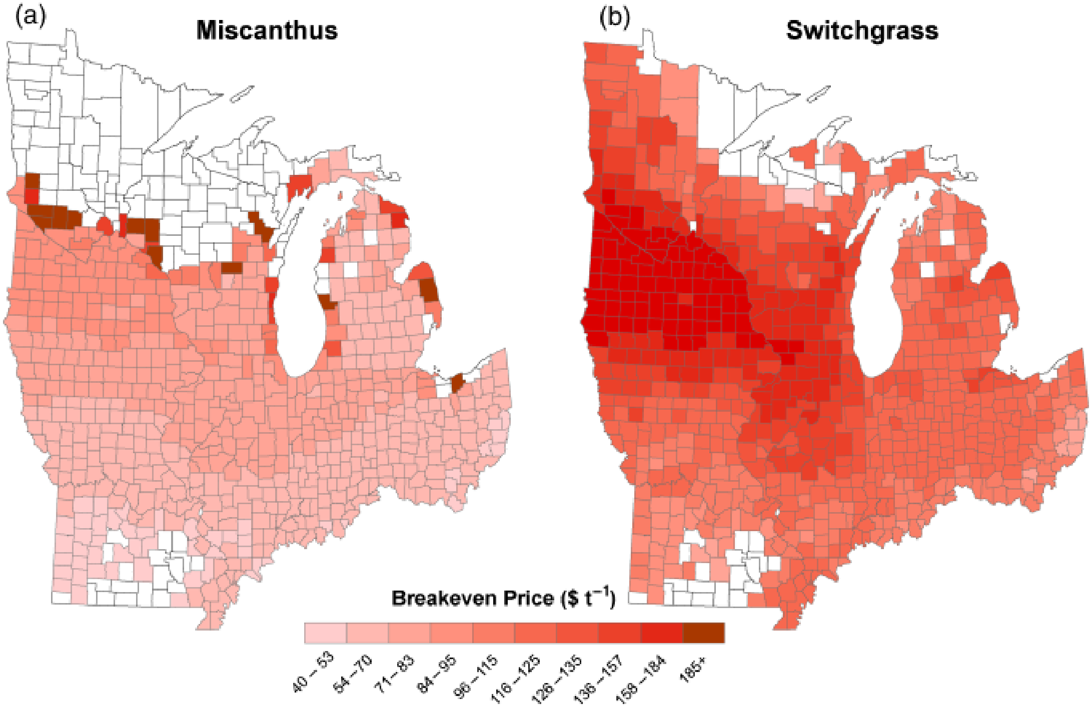

Fig. 6 Estimated breakeven price of (a) miscanthus and (b) switchgrass in the Midwest United States in 2007 prices.

low-crop yields than in the states with high-crop yields. We also find that in all scenarios examined here, the average (and the minimum) breakeven price of switchgrass is higher than that of miscanthus in the Midwestern states (Table 5). However, in almost all cases, the maximum estimated price of switchgrass is lower than the maximum price for miscanthus. These high prices for miscanthus are typically those observed in two states, Minnesota and Wisconsin, where yields are very low.

In addition to the factors considered above, such as crop prices and fertilizer prices, the opportunity cost of land for bioenergy crops will also be affected by the value placed on corn stover for cellulosic biofuel production. We examine the impact of including this value in the opportunity cost of land per dry ton for energy crops using the approach in James *et al*. (2010) and calculate the breakeven price of perennial grasses assuming equal biomass price across cellulosic sources. Corn stover costs depend on a number of factors: stover yields, the amount of replacement nutrients to be applied, the proportion of the residue that can be sustainably harvested and the price of the corn stover. We estimate the costs of harvesting stover, using assumptions about yields and nutrient replacement rates in Sheehan *et al*. (2003), a residue collection rate of 30% with a corn–soybean rotation and conventional tillage in each state. We then find the breakeven price of perennial grasses assuming the same price would apply to stover . We find that the inclusion of corn stover in the opportunity cost of land raises the average breakeven price for switchgrass by 7% and for miscanthus by 3% across the Midwestern states. The maximum increase in the breakeven price is 11% for switchgrass and 9% for miscanthus. (The breakeven price for miscanthus is relatively low in Missouri while the costs of harvesting corn stover are relatively high. As a result, inclusion of corn stover production does not add value to the opportunity cost of land in Missouri) (see last row, Table 5).

Conclusions

This paper integrates a biophysical model of bioenergy crop yields with economic analysis of the breakeven prices of bioenergy crop production to assess how these prices differ across bioenergy crops and across different locations in the Midwestern United States. The crop growth model was calibrated with a range of site-specific observed field data for miscanthus and switchgrass. This model is then used in combination with measured climate and radiation data to obtain yields of switchgrass and miscanthus in the Midwestern United States. This together with information about returns to land from existing crops (corn and soybeans) grown in the Midwestern states is used to calculate the breakeven

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prices of these bioenergy crops at a county-specific level.

Our crop yield model shows that miscanthus yields on average were more than two times higher than those of switchgrass. The estimated yields were substantially higher in southern counties and lower in northern counties. Our modeling results suggest that the continental climate of the United States. Midwest with warmer and wetter summers drive higher yields while its consistently cold winters allow greater translocation of nutrients to the rhizome, which stimulates productivity of biofuel crops. However, extremely cold temperatures in the north could freeze the soil deep enough to kill miscanthus rhizomes over the winter, limiting the crop's potential in northern latitudes. Our model results suggest that rainfall in the US Midwestern states is normally a nonlimiting factor for biofuel crop growth, although peak yield amount could vary from year to year depending upon other climate conditions.

A comparison of model-calculated yields with observed data shows close agreement between the two on average and at a site-specific level for most sites in the study. The model's limitations in explaining yields at some sites, such as the Brownstone site in Illinois, may be because the model does not capture the yield-limiting effects of soil nutrient deficits. Better parameterization of the effects of soil nutrient limitations on the growth of perennial grasses may be required to improve model performance.

Our economic analysis shows that breakeven prices of bioenergy crops are critically dependent on the yields of bioenergy crops and the yields of the annual crops they are likely to displace. High yields of bioenergy crops reduce the per ton opportunity cost of land. The latter is particularly high in locations where the yields of corn and soybeans are high and a land owner would need to forgo considerable returns by switching to an energy crop. Moreover, low fertilizer application rate, low replanting probability, high second-year yield, and low harvest loss also play a significant role in reducing the breakeven prices of bioenergy crop production. We find that the breakeven price, which includes the cost of producing the crop and the opportunity cost of land, of miscanthus ranges from \$53 t^{-1} DM in Missouri to \$153 t^{-1} DM in Minnesota in the low-cost scenario. Corresponding costs for switchgrass are \$88 t^{-1} DM in Missouri to \$144 t^{-1} DM in Minnesota. Breakeven prices at the upper end of this range are primarily due to high opportunity cost of land or low yields of bioenergy crops. On average, the breakeven price of switchgrass in the Midwest is \$115 t^{-1} DM whereas that of miscanthus is \$88 t^{-1} DM in the low-cost scenario. If we exclude Minnesota and Wisconsin as being unviable for producing miscanthus due to their low yields per hectare, then the average breakeven price of miscanthus in the remaining Midwestern states is \$68 t^{-1} DM in the low-cost scenario and \$107 t^{-1} DM in the high-cost scenario.

We find that the breakeven prices of miscanthus and switchgrass are sensitive to factors that change the net returns to corn and soybean and thus the costs of converting that land to bioenergy crops. The additional value added to the value of land by including the net returns to corn stover depends critically on assumptions about the cost of corn stover, but is likely to be relatively small compared with the value of the land derived from corn and soybeans. The returns to miscanthus are also sensitive to the cost of rhizomes and the life span of miscanthus. In all the scenarios examined, we find that the breakeven prices per ton are on average lower for miscanthus than for switchgrass.

Our economic analysis underestimates the breakeven prices in several ways. It does not consider other land uses (besides corn–soybean rotation) that might be more profitable in some parts of these states. It also does not consider the effects of diverting land towards bioenergy crops and reducing production of corn and soybeans, thereby raising their prices and the opportunity cost of converting that land. In other cases, our analysis could be overestimating these breakeven prices. We do not consider other sources of returns to bioenergy crops, such as the value of carbon credits generated through the soil carbon sequestration achieved by them or the savings in greenhouse gas emissions realized by using these crops as feedstocks to produce biofuels and displacing gasoline. We also do not include other returns from bioenergy crops, such as the value of switchgrass for forage or seed production and the potential to produce biochemicals. The opportunity cost of land considered here could be lower if marginal land or pasture land is used for bioenergy crop production; this would result in lower breakeven prices of bioenergy crops.

Our analysis focused on the farm-gate breakeven prices and did not take into account the cost of transporting biomass from farm to the biorefinery or biomass-fired power plant. Searcy *et al.* (2007) estimate this cost to be \$12.75 t^{-1} DM for a 100 km roundtrip. As this cost is the same for switchgrass and miscanthus, it will not affect their relative breakeven price per ton if they are transported over the same distance. However, to the extent that the transportation distance for miscanthus and switchgrass differ due to the size of the catchment area from which biomass is collected to meet the needs of a biorefinery/power plant, the relative costs of the two grasses could be affected.

Our analysis does, however, show some of the factors that influence the breakeven prices of bioenergy crops and explains the causes of differences in breakeven prices across two bioenergy crops and across locations in the Midwestern United States. We can use the breakeven price estimates provided here to project the breakeven prices of biofuel derived from switchgrass and miscanthus. With an average breakeven price of miscanthus of \$68 t^{-1} DM in the low-cost scenario and \$107 t^{-1} DM in the high-cost scenario (for the Midwest excluding Minnesota and Wisconsin), the cost of cellulosic ethanol is estimated to range between \$\$0.63 L^{-1} for the low-cost scenario and \$0.74 L^{-1} for the high-cost scenario. [This calculation is based on the assumption of 330 L of biofuels per ton of dry matter of biomass and a cost of fuel conversion minus coproduct credit for a biorefinery with 189 million liter annual capacity of \$0.38 L^{-1} and is based on pilot demonstrations by National Renewable Energy Laboratory (NREL) (Wallace *et al*., 2005). It includes the round-trip cost of \$12.75 t^{-1} DM of transporting biomass from the farm to a biorefinery located at a distance of 50 km.] In comparison, the breakeven price for biofuel from switchgrass ranges between \$0.77 and \$0.88 L^{-1} in the low and high-cost scenario, respectively, with an average breakeven price of switchgrass of \$115 t^{-1}DM in the low-cost scenario and \$151 t^{-1}DM in the high-cost scenario across all Midwestern states. Our analysis shows that the costs of cellulosic biofuel production will depend on the yield of the feedstock used, the region where that feedstock is produced and the existing land uses it displaces as well as on the agronomic and economic production conditions that emerge with large scale production of these bioenergy crops.

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References

Abbott PC, Hurt C, Tyner WE (2008) *What's driving food prices?* Farm Foundation Issue Report, July 2008, Farm Foundation, Oak Brook, IL.

Brechbill SC, Tyner WE, Ileleji KE (2008) The economics of biomass collection and transportation and its supply to Indiana cellulosic and electric utility facilities. In: *Proceedings Risk, Infrastructure and Industry Evolution Conference, June 24–25, 2008, Berkeley, CA* (eds English BC, Menard RJ, Jensen K), pp. 105–115. Farm Foundation, Oak Brook, IL.

Busby D, Little RD, Shaik S *et al*. (2007) *Yield and Production Costs for Three Potential Dedicated Energy Crops in Mississippi and Oklahoma Environments*. Southern Agricultural Economics Association Meeting, Mobile, Alabama, February 4–7, 2007.

Casler MD, Boe AR (2003) Cultivar × environment interactions in switchgrass. *Crop Science*, **43**, 2226–2233.

Christian DG, Riche AB, Yates NE (2008) Growth, yield and mineral content of *Miscanthus × giganteus* grown as a biofuel for 14 successive harvests. *Industrial Crops and Products*, **28**, 320–327.

Clifton-Brown JC, Brewer J, Jones MB (2007) Carbon mitigation by the energy crop *Miscanthus*. *Global Change Biology*, **13**, 2296–2307.

Clifton-Brown J, Chiang Y-C, Hodkinson TR (2008) Miscanthus: genetic resources and breeding potential to enhance bioenergy production. In: *Genetic Improvement of Bioenergy Crops* (ed. Vermerris W), pp. 273–294. Springer Science + Business Media, LLC, New York.

Clifton-Brown JC, Jones MB, Breuer J (2001a) Yield performance of *M × giganteus* during a 10 year field trial in Ireland. *Aspects of Applied Biology*, **65**, 153–160.

Clifton-Brown JC, Lewandowski I (2000) Overwintering problems of newly established Miscanthus plantations can be overcome by identifying genotypes with improved rhizome cold tolerance. *New Phytologist*, **148**, 287–294.

Clifton-Brown JC, Neilson BM, Lewandowski I, Jones MB (2000) The modelled productivity of *Miscanthus × giganteus* (GREEF et DEU) in Ireland. *Industrial Crops and Products*, **12**, 97–109.

Clifton-Brown JC, Stampfl P, Jones MB (2004) Miscanthus biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions. *Global Change Biology*, **10**, 509–518.

Downing M, Graham R L (1996) The potential supply and cost of biomass energy crops in the Tennessee valley authority region. *Biomass and Bioenergy*, **11**, 283–303.

Duffy M (2007) *Estimated Costs for Production, Storage and Transportation of Switchgrass*, University Extension Report PM 2042, Iowa State University, Ames, IA.

Epplin FM, Clark CD, Roberts RK, Hwang S (2007) Challenges to the development of a dedicated energy crop. *American Journal of Agricultural Economics*, **89**, 1296–1302.

FBFM (2007) *Farm Economics Facts and Opinions. Farm Business and Farm Management Newsletters*. Department of Agricultural Economics, University of Illinois at Urbana Champaign.

FBFM (2008) *Machinery Cost Estimates: Forage Field Operations. Farm Business and Farm Management Newsletters*. Department of Agricultural Economics, University of Illinois at Urbana Champaign.

Gunderson AC, Davis EB, Jager IH *et al*. (2008) *Exploring Potential U.S. Switchgrass Production for Lignocellulosic Ethanol. ORNL/TM-2007/183*. Oak Ridge National Laboratory, Oak Ridge, TN.

Hallam A, Anderson I, Buxton D (2001) Comparative economic analysis of perennial, annual, and intercrops for biomass production. *Biomass and Bioenergy*, **21**, 407–424.

Hansen E, Christensen B, Jensen L, Kristensen K (2004) Carbon sequestration in soil beneath long-term Miscanthus plantations as determined by 13C abundance. *Biomass and Bioenergy*, **26**, 97–105.

Haque M, Epplin FM, Aravindhakshan S, Taliaferro C (2008) *Cost to Produce Cellulosic Biomass Feedstock: Four Perennial Grass Species Compared*. Paper presented at Southern Agricultural Economics Association Annual Meeting, Dallas, TX.

Heaton EA, Dohleman FG, Long SP (2008) Meeting US biofuel goals with less land: the potential of Micanthus. *Global Change Biology*, **14**, 2000–2014.

Jain AK, Yang X (2005) Modeling the effects of two different land cover change data sets on the carbon stocks of plants and soils in concert with CO2 and climate change. *Global Biogeochemical Cycles*, **19**, 1–20.

James LK, Swinton SM, Thelen KD (2010) Profitability of cellulosic energy crops compared with corn. *Agronomy Journal*, **102**, 675–687.

Khanna M, Dhungana B, Clifton-Brown J (2008) Costs of producing Miscanthus and Switchgrass for bioenergy in Illinois. *Biomass and Bioenergy*, **32**, 482–493.

Khanna M, Önal H, Chen X, Huang H (2009) Meeting biofuels targets: implications for land use, greenhouse gas emissions and nitrogen use in Illinois. In: *Transition to a Bioeconomy: Environmental and Rural Development Impacts, Proceedings of Farm Foundation/USDA Conference, St. Louis, MO, October 15–16 2008* (ed. Khanna M), pp. 18–35. Farm Foundation, Oak Brook, IL.

Kiniry JR, Cassida KA, Hussey MA *et al*. (2005) Switchgrass simulation by the ALMANAC model at diverse sites in the southern U.S.. *Biomass and Bioenergy*, **29**, 419–425.

Kiniry JR, Sanderson MA, Williams JR *et al*. (1996) Simulating Alamo switchgrass with the ALMANAC model. *Agronomy Journal*, **88**, 602–606.

Kiniry JR, Williams JR, Gassman PW, Debaeke P (1992) A general process-oriented model for two competing plant species. *Transactions of the ASAE*, **35**, 801–810.

Lemus R, Brummer CE, Moore KJ, Molstad NE, Burras LC, Barker MF (2002) Biomass yield and quality of 20 switchgrass populations in southern Iowa, USA. *Biomass and Bioenergy*, **23**, 433–442.

Lewandowski I, Scurlock JMO, Lindvall E, Christou M (2003) The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. *Biomass and Bioenergy*, **25**, 335–361.

Liu J, Williams JR, Wang X *et al*. (2009) Using MODAWEC to generate daily weather data for the EPIC model. *Environmental Modelling & Software*, **24**, 655–664.

Long SP, Dohleman F, Jones MB, Clifton-Brown J, Jørgensen U (2007) *Miscanthus – panacea for energy security and the midwest economy or another kudzu?* The Illinois Steward Magazine; 16(1). Available at: http://ilsteward.nres.uiuc.edu/Issues/2007/Spring/energy.htm

McLaughlin SB, Kiniry JR, Taliaferro C, Ugarte D (2006) Projecting yield and utilization potential of switchgrass as an energy crop. *Advances in Agronomy*, **90**, 267–297.

McLaughlin SB, Kszos LA (2005) Development of switchgrass (*Panicum virgatum*) as a bioenergy feedstock in the United States. *Biomass and Bioenergy*, **28**, 515–535.

Miguez FE, Villamil MB, Long SP, Bollero GB (2008) Meta-analysis of the effects of management factors on *Miscanthus* × *giganteus* growth and biomass production. *Agricultural and Forest Meteorology*, **148**, 1280–1292.

Monteith JL (1977) Climate and the efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society of London Series B*, **281**, 277–294.

Mooney DF, Roberts RK, English BC, Tyler DD, Larson JA (2009) Yield and breakeven price of ‘Alamo’ Switchgrass for Biofuels in Tennessee. *Agronomy Journal*, **101**, 1234–1242.

Nobumasa I, Takayoshi N, Liu G, Li D, Huang J (2002) The relation between soil temperature and the number of over-wintering plants of switchgrass (*Panicum virgatum* L.), quack-grass (*Agropyron repens* Beauv.) and johnsongrass (*Sorghum halepense* Pers.) in hilly land on a Loess Plateau. *Journal of Weed Science and Technology*, **47**, 74–78.

NREL (1995) *National Solar Radiation Database (1961–1990)*. NREL/TP-463-5784, Final Technical Report. National Renewable Energy Laboratory, Golden, CO.

NREL (2007) *National Solar Radiation Database 1991–2005 Update: User's Manual. NREL/TP-581-41364*. National Renewable Energy Laboratory, Golden, CO.

Padgitt M, Newton D, Penn R, Sandretto C (2000) *Production Practices for Major Crops in U.S. Agriculture, 1990–97*. Statistical Bulletin No. (SB969), Economic Research Service, US Department of Agriculture, September.

Pastor J, Post WM (1985) *Development of a linked forest productivity-soil process model*. Tech. Rep. ORNL/TM-9519, Oak Ridge Natl. Lab., Oak Ridge, TN.

Perrin R, Vogel K, Schmer M, Mitchell R (2008) Farm-scale production cost of switchgrass for biomass. *Bioenergy Research*, **1**, 91–97.

Popp MP (2007) Assessment of alternative fuel production from switchgrass: an example from arkansas. *Journal of Agricultural and Applied Economics*, **39**, 373–380.

PRISM Climate Group, Oregon State University, Available at: http://www.prismclimate.org (accessed 13 May 2009).

Qin X, Mohan T, El-Halwagi M, Cornforth G, McCarl BA (2006) Switchgrass as an alternate feedstock for power generation: an integrated environmental, energy and economic life-cycle assessment. *Clean Technologies and Environmental Policy*, **8**, 233–249.

Rawls WJ, Brakensiek DL, Saxton KE (1982) Estimation of soil water properties. *Transactions of the ASAE*, **25**, 1316–1328.

Rodell M, Houser PR, Jambor U *et al*. (2004) The global land data assimilation system. *Bulletin of the American Meteorological Society*, **85**, 381–394.

Searcy E, Flynn P, Ghafoori E, Kumar A (2007) The relative cost of biomass energy transport. *Applied Biochemistry and Biotechnology*, **136–140**, 639–652.

Semere T, Slater F (2007) Invertebrate populations in miscanthus (*Miscanthus × giganteus*) and reed canary-grass (*Phalaris arundinacea*) fields. *Biomass and Bioenergy*, **31**, 30–39.

Sharpley A, Williams JR (1990) *Epic, erosion, productivity impact calculator: 1. Model documentation*. Technical Bulletin 1768, U.S. Dept. of Agriculture.

Sheehan J, Aden A, Paustian K, Killian K, Brenner J, Walsh M, Nelson R (2003) Energy and environmental aspects of using corn stover for fuel ethanol. *Journal of Industrial Ecology*, **7**, 117–146.

Turhollow A (2000) *Costs of producing biomass from riparian buffer strips*. Available at: http://www.ornl.gov/~ webworks/cpr/v823/rpt/108548.pdf

Ugarte D G D L T, Walsh M E, Shapouri H, Slinsky SP (2003) *The economic impacts of bioenergy crop production on U.S. agriculture*. Agricultural Economic Report No. 816. U.S. Department of Agriculture, Office of the Chief Economist, Office of Energy Policy and New Uses.

Vadas PA, Barnett KH, Undersander DJ (2008) Economics and energy of ethanol production from Alfalfa, corn, and switchgrass in the Upper Midwest, USA. *Bioenergy Research*, **1**, 44–55.

Wallace R, Ibsen K, McAloon A, Yee W (2005). *Feasibility study for co-locating and integrating ethanol production plants from corn starch and lignocellulogic feedstocks*. NREL/TP-510-37092 Revised January Edition: USDA/USDOE/NREL.

Zobler L (1986) *A world soil file for global climate modeling*. NASA Tech. Memo. 87802, 32 pp.

Zobler L (1999) Global Soil Types, 1-Degree Grid (Zobler), data set, Distrib. Active Arch. Cent., Oak Ridge Natl. Lab., Oak Ridge, TN.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Relationship between biomass harvest costs and yield levels.
Table S1. Costs of production for energy crops in Illinois.
Table S2. Input prices and opportunity costs of Land.
Table S3. Annualized costs of production for Switchgrass (SW) and Miscanthus (MIS) for low-cost scenario.
Table S4. Annualized costs of production for Switchgrass (SW) and Miscanthus (MIS) for high-cost scenario.

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