Profitability Analysis of Cellulosic Energy Crops Compared with Corn

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ABSTRACT

The expected profitability of six cellulosic feedstock crops is compared with two corn (*Zea mays* L.)-based systems under southern Great Lakes region conditions over a projected 10-yr period. At 2006–2009 costs and yields from literature, none would be more profitable than the corn-based systems. Comparative breakeven price analysis identifies the cellulosic feedstock price that would make crops equally profitable with continuous corn. Breakeven prices of cellulose are \$110 to \$130 Mg^{-1} for poplar (*Populus* spp.), switchgrass (*Panicum virgatum* L.), and mixed grasses. For miscanthus (*Miscanthus* × *giganteus* J.M. Greef & Deuter ex Hodk. & Renvoize), breakeven cellulose prices are \$200 Mg^{-1} at current costs, but only \$45 Mg^{-1} if rhizome costs fall to near European levels, well within the range of temporary U.S. farm bill cost share levels for biomass harvest, transportation, and storage. Without targeted subsidies, native prairie and fallow old field systems would not be competitive with corn or the other four cellulosic crops reviewed at current yields and foreseeable prices. Comparative breakeven yields at a cellulose price of \$60 Mg^{-1} would require yield gains above benchmark literature values of 50% for switchgrass, 60% for poplar and mixed grasses, 140% for fallow old fields, 180% for native prairie, and 190% for miscanthus at current rhizome costs, but no added yield for miscanthus with rhizomes at plausible reduced cost.

Cellulosic ethanol has emerged as a leading candidate biofuel that could contribute significantly to meeting U.S. liquid fuel demand while reducing net greenhouse gas emissions. Feasibility of large-scale cellulosic ethanol production depends not only on the development of cost-effective processing methods, but also on the availability of large quantities of cellulosic biomass for conversion to ethanol (Perlack et al., 2005). The impact of a biofuel economy on the U.S. agricultural landscape is potentially huge. To derive a significant portion of U.S. energy use from cellulosic biomass requires a half billion to a billion metric tons of plant products annually (National Research Council, 2009; Perlack et al., 2005). The resulting high demand for land will have unknown consequences for sustaining food and fiber production for human populations, for biodiversity in managed and unmanaged ecosystems, and for the biogeochemical processes that underlie regulation of the biosphere (Robertson et al., 2008). The environmental and economic consequences of large-scale cellulosic biomass production will depend in part on which species are cultivated and how they are managed.

Profitable production of cellulosic biofuel feedstock is a precondition for large-scale biofuel production to become feasible. But as other authors have made clear, for revenues to exceed costs by itself is not a sufficient condition for growers to switch to cellulosic biomass crops (Tyner and Taheripour, 2007; Tyner, 2008). Farmers will also need to cover the opportunity cost of the crops that are displaced by cellulosic biomass crops.

Broad inquiry into sustainable cellulosic biomass production should include a range of biomass sources, including trees, mixed grasses, native prairie, and natural succession species. Switchgrass has long been considered a promising biofuel, with yields ranging from an average of 3.4 Mg ha^{-1} in field studies (Brummer et al., 2000) to 21.6 Mg ha^{-1} (McLaughlin and Kzsos, 2005). Other studies have shown that miscanthus is a likely candidate for commercial scale production of cellulosic biomass, with yields in Europe ranging from 2 Mg ha^{-1} to 44 Mg ha^{-1} (Lewandowski et al., 2000). Average yields in Illinois are very promising, having consistently achieved nearly 30 Mg ha^{-1} (Heaton et al., 2008; Pyter et al., 2007). Short-rotation woody crops, especially hybrid poplar, have also been considered for biomass production. Poplar is expected to yield between 7.8 and 11.76 Mg ha^{-1} in the Lake States (De La Torre Ugarte et al., 2003), though trials have achieved yields as high as 20 to 42 Mg ha^{-1} on good soil (Perlack et al., 1996). Poplar 'NM6' (*P. nigra* × *P. maximowiczii*) yielded 8.4 Mg ha^{-1} in the Upper Peninsula of Michigan over 10 yr (Miller and Bender, 2008). Mixed prairie systems are usually planted to restore biodiversity and improve soil structure and maintenance, and are not usually harvested for biomass. However, a field experiment by Tilman et al. (2006) in Minnesota demonstrated an increase in energy per hectare given an increase in species diversity. Plots with 16 grassland species (low-input, high diversity or LIHD) achieved 238% more bioenergy (measured as biomass times energy release on combustion) per hectare than monoculture switchgrass on highly degraded soil with low fertilization. Under this management scenario, Tilman

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Abbreviations: BCAP, biomass crop assistance program; GLBRC, Great Lakes Bioenergy Research Center; OC_{CG}, opportunity cost of continuous corn (grain).

Biofuels

et al. (2006) achieved a 3.7 Mg ha^{-1} yield, and estimated a 6 Mg ha^{-1} yield on fertile soil. Another experiment in Minnesota, of controlled prairie restoration, demonstrated yields between 5.3 Mg ha^{-1} and 7.3 Mg ha^{-1} among unfertilized and fertilized plots after 3 yr of growth (Camill et al., 2004).

Economic studies of biofuel feedstocks have tended to focus on the most promising crops, often corn stover, switchgrass, and recently miscanthus (Brechbill and Tyner, 2008; Mooney et al., 2009; Heaton et al., 2008; Perrin et al., 2008). Different studies have shown costs per unit dry matter for corn stover and miscanthus to be lower than that estimated for switchgrass production. Brechbill and Tyner (2008) found that cost per ton for corn stover ranged from $39 to $44, while costs per ton for switchgrass ranged from $58 to $64, under differing production scenarios. Khanna et al. (2007) estimated that miscanthus produced in Illinois had a breakeven price of \$59 Mg^{-1}, \$39 Mg^{-1} less than switchgrass, when taking into account the opportunity cost of corn-soybean [*Glycine max* (L.) Merr.] production. A comparison by De La Torre Ugarte et al. (2003) estimated average switchgrass production at 10.8 Mg ha^{-1} and \$22.12 Mg^{-1}, compared to hybrid poplar production of 9.9 Mg ha^{-1} at \$22.32 Mg^{-1} in the Great Lakes region.

This paper presents enterprise budgets and comparative breakeven analysis for eight potential biofuel crop systems for Michigan as indicative of the southern Great Lakes region. Analysis of the budgets highlights key parameters that drive their potential profitability. To assess the adoption potential of each system, the paper analyzes the comparative breakeven price and yield at which each cellulosic feedstock production system would displace continuous corn as the benchmark crop system.

OBJECTIVES OF THIS STUDY

Building from the assumption that land managers (farmers in particular) aim to maximize expected profitability from crop production, this study evaluates the relative profitability of eight crop systems. This study estimates profitability of these eight production systems via the following steps: (i) construct capital budgets for each system over a 10-yr period; (ii) compare annualized costs and revenues across systems; (iii) calculate breakeven prices and yield for each alternative system relative to a continuous corn production system that yields both grain and stover; (iv) assess the likelihood of adoption of these systems based on their expected profitability (including opportunity cost of displacing continuous corn).

In general, the study intends to answer the research questions: (i) How profitable are these alternative crop systems expected to be? (ii) If they are not more profitable than continuous corn, then what price or yield of cellulosic biomass would be required for them to become at least as profitable as continuous corn?

Production Systems

The eight production systems whose expected profitability is evaluated here are the subject of field research at the Great Lakes Bioenergy Research Center (GLBRC) intensive research sites at the Kellogg Biological Station (KBS) in Hickory Corners, Southwest Michigan, as well as the University of Wisconsin agronomic research station at Arlington in south-central Wisconsin. The research design contrasts agronomic systems across several important management attributes: annual vs. perennial, monoculture vs. polyculture, woody vs. herbaceous, cultivated vs. natural, and intensive management vs. low-input management. The model systems for experimental evaluation were selected across a gradient of management intensity in farmer control of nutrients, pests, tillage, and harvest intensity (proportion of biomass harvested). Future research will evaluate the cropping systems in terms of biogeochemistry (carbon balance, nitrogen loss, greenhouse gas flux, soil erosion), biodiversity (plant, animal, microbial), and economics (profitability, risk, environmental trade-offs, and policy interventions).

Biofuel production systems based on existing annual grains fit most easily into farmers' current cropping systems, but they may not be the most productive or sustainable in the long term. Therefore, in addition to evaluating annual corn monoculture and rotational systems for biofuel production, the GLBRC experimental design also includes six alternative systems that incorporate perennials. Perennial-based systems include monocultures of the warm-season grasses switchgrass and miscanthus, as well as a mixture of cool-season C3 and warm-season C4 grasses (including switchgrass), a woody monoculture system (short-rotation poplar clones), a native grassland (prairie) system, and a native successional treatment (old field system). These systems are being studied intensively at the molecular, plant, rhizosphere, and landscape levels to provide the basis for understanding responses important for designing sustainable bioenergy cropping systems. A complete list of the cropping systems being studied is available in Appendix 1. Further details on the scientific names for the species involved are available in Appendix 2.

MATERIALS AND METHODS

Relative Profitability Analysis

Because six of the production systems under review are perennial systems, the profitability analysis is based on long-term capital budgets. These budgets track annual cash flows of revenues and expenditures over a 10-yr period, including land preparation, planting, pest control, harvest, drying, baling, bale transport to loading site, and transportation, as relevant for each system.[1] The capital budgeting approach used here is based on standard practice (Boehlje and Eidman, 1984), but it omits costs that are invariant across experimental treatments, following the standard approach for partial enterprise budget analysis of agronomic experiments (CIMMYT, 1988). Examples of such costs are land rental and management remuneration. Hence, the results reported here are valid for comparison across the systems included, but they do not account for all costs faced by growers. The resource base underpinning the enterprise budgets is assumed to be a representative farm with medium- to high-quality land in southern Michigan facing 2006–2009 prices. The purpose of the analysis is to estimate typical profitability under commercial farming conditions, so the agronomic management assumed in the budgets sometimes varies slightly from GLBRC experimental practices, which are designed for plot-based research.

Following Erickson et al's (2004) finding that U.S. farms averaged a 5% rate of return on capital during 1960–2001, we use a 5% discount rate to represent a typical farmer's real

[1] Note that storage costs are not included. The model assumes that product is immediately transported to a buyer.

Table 1. Agronomic protocol used in this study.

Crop	Planting material†	N‡	P	K	Pest control§
			kg ha^{-1}		
Corn	74,100 sd ha^{-1}	194	60	132	Lexar, 8.4L ha^{-1}
Corn (rotation)	74,100 sd ha^{-1}	157	72	149	Lexar, 8.4L ha^{-1}
Soybean	469,300 sd ha^{-1}	0	45	118	glyphosate, 2.34 L ha^{-1}; insecticide, label rate
Canola	5.6 kg ha^{-1}	112	90	112	trifluralin, 2.34 L ha^{-1}; insecticide, label rate
Switchgrass	5.6 kg PLS ha^{-1}	67	0	0	warm season grass herbicide, label rate
Miscanthus	11,240 rhiz ha^{-1}	0	0	0	pendamethalin, 3.51 L ha^{-1}; 2,4-D, 4.68 L ha^{-1}
Grass mix	9 kg PLS ha^{-1}	0	0	0	warm season grass herbicide, label rate
Poplar	2720 cut ha^{-1}	0	0	0	glyphosate, 2.34 L ha^{-1}; pendamethalin, 3.51 L ha^{-1}
Prairie	8.4 kg PLS ha^{-1}	0	0	0	warm season grass herbicide, label rate
Old field	none	0	0	0	none

† cut = cutting; PLS = pure live seed; rhiz = rhizome; sd = seed.

‡ Nitrogen application begins after first harvest for perennial systems. Nitrogen for corn systems includes replacement for stover removal.

§ Used in Year 1 and Year 2 only for perennial systems. *Warm Season grass herbicide* is a generic term referring to any combination of the following: glyphosate, pendimethium (Prowl), 2,4-D, atrazine, dicamba (Clarity), aminopyralid (Milestone), S-methachlor (Dual Magnum), clopyralid (Transline), imazapic (Journey). Average price per application is used as the input cost. See Appendix 2 for a complete listing of chemical names for pest control.

opportunity cost of capital. Prices are held constant across all 10 yr, so it was not necessary to compensate for inflation.

This study compares the profitability of different production systems by calculating an annualized net return from the present value of the total net revenue from each system that is generated by the production budgets. The annualized net return is calculated by applying a standard financial annuity formula to the present value of the 10-yr sum of annual net returns. The formula generates a constant annual payment that sums over the 10-yr time horizon to have the same present value as the sum of the estimated annual returns. The annuity formula (Ross et al., 2008), can be expressed as

$$A = PV\left[\frac{r(1+r)^{T}}{(1+r)^{T}-1}\right]$$

The annuity, A, is calculated by multiplying the present value of 10 yr of production returns over costs that vary (PV) by a standard annuity formula based on interest rate (r) and time horizon (T). In this study, r is equal to 5%, and T is equal to 10 yr.

Within the 10-yr time horizon, the number of times a production cycle repeats will vary by system. Continuous corn, for example, grows in a 1-yr cycle, so is repeated 10 times. The corn-soybean-canola (*Brassica* spp.) rotation is considered one system, and its annualized present value was calculated assuming a balanced rotation where a third of available land is planted to each crop in each year. We assume a single 10-yr cycle for both miscanthus and switchgrass, although it is possible that the stand for either crop could last well beyond that end date (Pyter et al., 2007; Department for Environmental, Food and Rural Affairs, 2003). For both of these perennial grasses, biomass yields ramp up from no harvestable yield in the establishment year to maximum yield in Year 3. Poplar stands have been grown in rotations of 5 to 15 yr and beyond, depending on the purpose of the crop (wood chips, pulpwood, and sawlogs are three common uses) (Alig et al., 2000). This analysis uses a single 10-yr cycle, and the average annual biomass yield is based on findings from previous studies on short-rotation poplar over 10-yr intervals (Miller and Bender, 2008; Miller and Bloese, 2002; Stanturf et al., 2001). Revenue from poplar sales is a one-off event in Year 10, which is smoothed to an annualized measure of profitability, comparable with the other systems.

Production Practices and Yield Levels

For each cropping system, a complete agronomic protocol was created, based on current expert recommendations and modified according to information from producers. Because these budgets are intended to represent commercial production of each crop, they do not conform to the exact research procedures followed at the GLBRC intensive field research sites in Hickory Corners, MI, and Arlington, WI. The cropping system protocols in each budget describe the mechanical treatments, seeding rate, amount of fertilizer, field labor, and other inputs attributed to each system for this study. Key input levels for each system are presented in Table 1.

All systems in this study are assumed to be tilled in the first year and then converted to a no-till regime for Years 2 through 10. Input levels therefore correspond to best practices for no-till systems where distinct practices are appropriate.

A number of reliable sources are available for established production practices for traditional crops. This study uses yield assumptions and production recommendations for corn and soybean from the most recent Michigan State University Extension production recommendations (Dartt and Schwab, 2001), with the exception of pesticide application, nutrient replacement to account for stover removal, and stover yield. Pesticide usage is instead based on farmer interviews conducted in Michigan during July 2008. Canola production practices were adapted from recommendations for Ontario based on information from a Michigan State University agronomist specializing in canola production (personal communication, R. Freed, Professor, Michigan State University, July 2008). For annual crops, all costs and revenues are the same each year, with the exception of the first year when fields are tilled, adding an additional cost. Chemical compounds used in pest management for all crops are listed in Appendix 3.

Stover collection falls outside standard corn production practices, but could be an important byproduct of corn grain production, given a market for cellulose. At the same time, stover left on the field plays an important role in maintaining soil structure and preventing erosion. A recent study estimates that up to 70% of stover is collectible from no-till fields while still keeping soil erosion at levels deemed "tolerable" by the USDA (Sheehan et al., 2004). However, most other estimates of safe removal rates are far lower.

Table 2. Switchgrass fertilizer rates and yields reported in recent literature.

Nitrogen†	Phosphorus‡	Potassium‡	Yield	Location	Source
kg ha^{-1}	kg Mg^{-1}		Mg ha^{-1}		
Plot trials					
67.0	0.0	0.0	10.6- 22.9	TN	Mooney et al., 2009
0.0	0.0	0.0	4.8	ND, SD, MN	Tober et al., 2007
112.0	n/a§	n/a	9.3	IA	Lemus et al., 2002
quantity not reported	no yield response	no yield response	15.0	VA	McLaughlin, 2005
n/a	n/a	n/a	10.3	US/EU	Heaton et al., 2004
Commercial-scale production					
75.0	n/a	n/a	7.0	ND, SD, NE	Perrin et al., 2008
112.0	6.1	25.6	3.4	IA	Brummer et al., 2000
0.0	0.0	0.0	6.4	MI	MI State Game Area practices
0.0	0.0	0.0	no harvest	MI	Michigan CRP farmers
Production models					
89.7	1.6	6.6	11.2	IN	Brechbill et al., 2008
112	0.2	0.7	9.4	IL	Khanna et al., 2007
107.6	0	9.3	10.8	Lakes States	De la Torre Ugarte et al., 2003

† Nitrogen application begins following first harvest.
‡ Phosphorus and potassium are harvest-year rates.
§ n/a, not available.

Lindstrom (1986) showed that soil runoff rates increase only slightly up to 30% removal, when they start to rise more rapidly. Walters and Yang show sustainable stover collection must remain below 28% (Walters and Yang, 2008). Recommended stover removal rates are likely to depend on soil characteristics, climate, management practices, and other factors (Anderson, 2006). This study assumes a 38% stover collection rate, which can be achieved with a bale-only harvest system (no raking) (Brechbill and Tyner, 2008). Fertilizer application rates are also increased to compensate for nutrient loss due to stover removal. Replacement rates per short ton stover removed are 7.95 pounds nitrogen, 2.95 pounds phosphorus, and 14.97 pounds potassium (Brechbill and Tyner, 2008).

Establishing a production protocol and estimated yield for the biomass crops was more difficult, as less is known about commercial scale production of these crops. Switchgrass has been grown in the United States for decades, both as a forage crop and to provide habitat for wildlife, but relatively little is known about growing switchgrass for biomass. Fertilizer rates and yields from recent studies investigating switchgrass grown for biomass vary widely and lack a consistent pattern in relation to geographic location, weather, or variety. For this study, the researchers set yield levels at 9 Mg ha^{-1}, slightly below small-plot research yields in the Corn Belt (Table 2), given the shorter growing season, colder temperatures, and poorer soil of the Great Lakes states. The benchmark yield is assumed to come from more fertile cropland than the average yield of 7 Mg ha^{-1} from 3- to 5-yr-old commercial-scale switchgrass on marginal lands in the Great Plains (Perrin et al., 2008).

Whereas information on switchgrass production for biomass varies widely, there is very little information available on miscanthus production for biomass in the United States. The miscanthus production protocol used here is based on recommendations from the University of Illinois (Pyter et al., 2007). Illinois trials have consistently achieved yields much higher than those normally seen in Europe, where miscanthus production is more common. This is not surprising given the high fertility of Illinois soil. The global yield average of 22 Mg ha^{-1} reported by Heaton et al. (2004) is used as the expected yield in this study. Lower than Illinois yields (Heaton et al., 2008), this figure takes into account Michigan's generally less fertile soil, fewer growing degree days, and colder winters.[2] It is likely that miscanthus yields could be increased substantially once the crop is more intensively studied, improved varieties are developed, and farmers learn what management regimes work best. Nevertheless, the modest yield used for this study is an appropriate baseline for current conditions in the southern Great Lakes region. Table 3 reports fertilizer rates and yields from recent miscanthus trials and models in the United States and Europe.

Management protocols for the grass, prairie, and poplar systems were adjusted from current practices used to grow these plants for wildlife habitat or other purposes, according to recommendations from experts familiar with Michigan conditions. For native grass and prairie systems, growers interviewed expected that yearly harvests would eliminate the need for herbicides once the field was established. Prairie growers noted that reseeding of forbs and other nongrass species was often necessary in native species mixes, since the grasses tend to dominate in the early years (personal communication, M. Bishop, Michigan Department of Natural Resources Technician, July 2008). However, as the reseeding would add nothing to total biomass production, it is assumed a commercial farmer would not make the investment, and so these costs have been omitted from the budget. Finally, *old field* refers to natural successional regrowth on fallow land with no agronomic inputs, and no production costs beyond harvest and handling.

Yields for mixed grass, prairie, poplar, and old field are estimates from various sources. The mixed grasses crop is comprised of small grass species such as indiangrass and clover (*Trifolium* spp.). Lacking data on yields of these grasses produced for biofuel feedstock, we have estimated the yield at 1.12 Mg ha^{-1} (0.5 ton acre^{-1}) below switchgrass yields. Prairie biomass yields are difficult to determine, given the large number of species that will react in different ways to different phenomena. Tilman (2006) noted high yields from polyculture crops on degraded land and estimated a yield of 6 Mg ha^{-1} for fertile land. A separate study

[2] Studies in Europe have found anecdotal evidence that young miscanthus plants are highly susceptible to cold. See Lewandowski et al. (2000) and Clifton-Brown et al. (2001).

Table 3. Miscanthus fertilizer rates and yields reported in recent literature.

Nitrogen†	Phosphorus‡	Potassium‡	Yield	Location	Source
kg ha^{-1}	kg Mg^{-1}		Mg ha^{-1}		
60.0	0.3–1.1	4.0–8.0	10–25	Europe	Lewandowski et al., 2000
60.0	1.7	4.2	13.8–37.8	Europe	Clifton-Brown et al., 2001
n/a§	n/a	n/a	22.4	global	Heaton et al., 2004
0.0	0.0	0.0	30.7	Illinois	Pyter et al., 2007
25.0	n/a	n/a	29.6	Illinois	Heaton et al., 2008

† Nitrogen application begins following first harvest.
‡ Phosphorus and potassium are harvest-year rates.
§ n/a, not available.

in Minnesota found an average yield of 5.3 Mg ha^{-1} on agricultural-quality land (Camill et al., 2004). We chose a yield value that was below the controlled experiment value on fertile land but above the value for degraded land, of 4.8 Mg ha^{-1}. Poplar yields were set at 11.2 Mg ha^{-1}, adjusted down from the 13.5 Mg ha^{-1} yr^{-1} average of small-plot research in the Lansing area in 2002, to reflect less meticulous commercial care (Miller and Bloese, 2002). Old field yields are taken from early successional plots at the Kellogg Biological Station in southwestern Michigan, from 1989 to 1999 (Long-Term Ecological Research, 1999).

Labor time requirements in this document reflect only field labor hours and marketing time. Field hours for machine operations are based on the standards of the American Society of Agricultural and Biological Engineers for effective field capacity for common agricultural machinery (American Society of Agricultural and Biological Engineers, 2006). Other labor requirements, such as for hand-planting poplar trees, are drawn from recent literature. Table 4 shows labor hours per hectare by crop.

Table 4. Annual field labor time requirements by crop system.

Crop	Annual average†
	h ha^{-1}
Continuous corn + stover	3.95
Corn-soybean-canola	2.99
Switchgrass	1.46
Miscanthus	1.70
Grass mix + clover	1.32
Poplar	5.28
Native prairie	1.48
Old field	1.02

† All values based on machine operations in-field, calculated using American Society of Agricultural and Biological Engineers (2006) machine standards.

Input Costs

Cost data for this study were collected from a variety of primary and secondary sources, and generally represent 2008–2009 conditions in the Great Lakes region. Whenever possible, input prices represent actual prices observed in Michigan (or available to Michigan farmers, as in the case of seed ordered online) during summer 2008. These prices were collected through informal surveys of state retailers, manufacturer-recommended pricing sheets, producer surveys, and published quotes. In some cases, Michigan-specific data were not available, and data from neighboring states or the USDA National Agricultural Statistical Survey monthly price list for April 2008 were used instead. Because fertilizer prices in particular rose steeply in 2008, average fertilizer prices for 2006–2008 for the region (National Agricultural Statistics Service, 2008a, 2006) were used in place of 2008 prices. Machine rates are based on estimates for custom rates in Michigan, which incorporate labor costs (Stein, 2008). In cases where no market price exists, costs were adopted from previous studies. For example, the miscanthus planter cost is calculated based on costs in a 2007 study from the University of Illinois (Khanna et al., 2007). Table 5 shows prices for key inputs.

Two miscanthus scenarios are presented in this study, to reflect the extreme difference in planting material costs between the United States, where there is currently little demand for

Table 5. Crop production input prices and data sources.

Input	Unit	Price	Source
		U.S. $	
Corn seed	80,000 kernel	184.00	National Agricultural Statistics Service, 2008a, 2008b
Soy seed	210,000 seed	40.00	National Agricultural Statistics Service, 2008a, 2008b
Canola seed	kg	21.80	Ontario Ministry of Agriculture, Food and Rural Affairs, 2008
Switchgrass seed	kg PLS	24.92	Average price cited by seed suppliers in Mid-West region
Miscanthus rhizomes	rhizome	1.80	Kurt Bluemel Nursery, Baldwin, MD (GLBRC KBS receipts)
Miscanthus rhizomes	rhizome	0.05	hypothetical; represents expected reduction in price due to rapid increase in supply
Grass seed mix	kg PLS	81.59	Prairie Moon Nursery, Winona, MN
Poplar cuttings	cutting	0.22	Average price cited by nurseries in Great Lakes region, 2008
Prairie seed mix	kg PLS	143.00	Prairie Moon Nursery, Winona, MN
Nitrogen	kg	1.16	Average price cited by fertilizer suppliers in Michigan, 2008
Phosphorous	kg	1.28	Average price cited by fertilizer suppliers in Michigan, 2008
Potassium	kg	0.67	Average price cited by fertilizer suppliers in Michigan, 2008
Pesticides	varies	varies	Syngenta, Suggested Dealer Pricing, Jan 2008 and National Agricultural Statistics Service, 2008a, 2008b
Machinery–custom hire	varies	varies	Stein, 2008 Machine Work Rates for Saginaw, MI, and Edwards and Smith, 2008 Iowa Custom Rate Survey

miscanthus, and the more mature market in the European Union. The *costly rhizomes* scenario uses the amount paid by the GLBRC research trial at the Kellogg Biological Station in 2008, $1.80 per ×*giganteus* rhizome purchased from Pennsylvania. However, given that recent EU prices that have been used in other studies are much lower (as low as 0.5¢ per rhizome) (Khanna et al., 2007; Bullard et al., 1997; Heaton et al., 2004; Scurlock, 1999), the *cheap rhizomes* scenario assumes a price of 5¢ per rhizome as what might be expected once U.S. markets for miscanthus rhizomes develop.

Output Prices

The crop revenues used in the relative profitability analysis are based on output prices for the 2009–2010 marketing year drawn from 2009 projections by the USDA Economic Research Service (Baker et al., 2009; Ash et al., 2009). For corn grain, which underpins the continuous corn baseline cropping system, the price was $132 Mg^{-1} ($3.35 per bushel) (Baker et al., 2009). (For the breakeven analyses, the current price of corn is replaced by prices corresponding to $2.50, $3.50, and $4.50 per bushel.)

Determining a price for cellulosic feedstock for ethanol production is more challenging, as no active market exists. This study considers sets the upper bound at the price of hay, which has similar production costs to many biomass crops and so can serve as a reasonable alternative from the grower's viewpoint. Non-alfalfa hay in Michigan averaged $110 Mg^{-1} from 2006 to 2009 (National Agricultural Statistics Service, 2008b). Because biomass crops would not require the mineral content, palatability, or other attributes of hay, prices can be expected to be lower. A lower bound on cellulosic feedstock price would be the biorefiner's willingness to pay. Solomon et al. (2007) used private sector investment projections to estimate the production cost allocable to feedstock at $72 Mg^{-1}. Jiang and Swinton (2009) used oil prices of $50 to $85 per barrel along with subsidies from the Farm, Conservation and Energy Act of 2008 to estimate a biorefiner's maximum affordable biomass prices from $19 to $63 Mg^{-1}. Given the range from a supply-side opportunity cost of $110 Mg^{-1} to a demand-side willingness to pay as low as $19 Mg^{-1}, this study elected to use prices of $30, $60 and $90 Mg^{-1}. The upper end of the range approaches the upper limit of the USDA Biomass Crop Assistance Program (BCAP), which will pay a 1:1 match up to $50 Mg^{-1} for a maximum of 2 yr. Prices for cellulosic feedstocks were assumed equal across all types of material.[3] Base output prices for all crops are shown in Table 6. The complete budgets for each crop system, showing input prices and yields over a 10-yr cycle, are available as supplemental tables to this article. See Supplemental Tables 1–11.

[3] Note, however, that different feedstock prices are possible, even likely. For example, a 2003 USDA study noted that the energy content of poplar wood would justify prices for hybrid poplar feedstock that are 9.6% higher than for switchgrass feedstock (De La Torre Ugarte et al., 2003).

Comparative Breakeven Cellulosic Feedstock Price Analysis for Changing Crops

Given that markets do not currently exist for cellulosic biomass as an ethanol feedstock, any specific assumed price is somewhat arbitrary. For cellulosic biomass crops to become attractive, they would have to generate net income at least as great as what farmers earn from their current systems. To determine the price at which a cellulosic biomass crop would overtake the profitability of traditional crops, a comparative breakeven price was calculated for each system. The analysis compared the returns to cellulosic biomass from each system to the returns from a monoculture corn system harvesting both grain and 38% of available stover (Brechbill and Tyner, 2008). Comparative breakeven prices differ from simple breakeven prices because comparative breakeven prices require that the new crop cover not only its direct costs of production, but also the opportunity cost of giving up the net returns from the crop being replaced. Previous work by Mooney et al. (2009) reported simple breakeven prices to cover the cost of switchgrass production, but not the opportunity cost of replacing another crop. The formula to calculate the breakeven price (P_{BE}) of cellulosic biomass required for the new cellulosic crop to generate the same net return as continuous corn is adapted from Hilker et al. (1987):

$$P_{BE} = \frac{VC_N + OC_{CG}}{Y_{N_{avg}} - Y_{CS}}$$

in which the subscript N refers to the new, or challenger, system, and the subscript CG refers to continuous corn (raised for grain and stover), the "defender" system in our analysis. VC_N is the variable cost of producing the new, cellulosic biomass crop in U.S. $ ha^{-1}, and OC_{CG} is the annual opportunity cost of lost net revenue from the corn grain production. Net revenue is defined as the grain-only revenue above all costs associated with the production and harvest of both grain and stover, including increased nutrient application

Table 6. Crop yields, prices, and data sources.

Output	Yield	Price†	Source of yield value
	Mg ha^{-1}	U.S. $	
Corn-on-corn–grain	8.5	138	Dartt and Schwab, 2001
Corn-on-corn–stover	3.2	60	Calculated based on Walters and Yang, 2008
Corn (rotation)–grain	9.4	138	Dartt and Schwab, 2001
Corn (rotation)–stover	3.6	60	Calculated based on Walters and Yang, 2008
Soybean	2.8	334	Dartt and Schwab, 2001
Canola	2.2	358	Ontario Ministry of Agriculture, Food and Rural Affairs, 2008
Switchgrass	9.0	60	Adjusted below average for Midwest region
Miscanthus	22.4	60	Adjusted below Illinois reported yields
Grass mix	7.8	60	Adjusted below switchgrass yields, given the smaller plant size of other grass species
Poplar	11.2	60	Adjusted below results in MI field trials (Miller and Bloese, 2002)
Prairie mix	4.8	60	Tilman et al., 2006
Old field	3.9	60	KBS Early successional biomass production rate, 1989–1999

† Prices for traditional crops are taken from the USDA Economic Research Service outlook reports for 2008–2009 marketing year (Baker et al. 2009; Ash et al. 2009). The price for biomass is the base value assumed in this study (see text).

and stover harvest and removal. The opportunity cost of continuous corn (OC_{CG}) is calculated as the annuity payment needed to equal the present value of total net returns over 10 yr.[4] Y_{Navg} represents average annual yield over 10 yr of the new cellulosic crop in dry Mg ha^{-1}. Y_{CS} represents the stover yield from the monoculture corn system (assuming 38% of stover is harvested). In the denominator, Y_{CS} is deducted from the biomass yield of the new system to measure the challenger crop's net gain in cellulosic biomass above what continuous corn would offer (assuming equal prices across cellulosic biomass sources). In this analysis, the OC_{CG} is a based on an assumed corn grain yield of 8.5 Mg ha^{-1}, and varies as the analysis varies the price of corn grain. The corn stover yield (Y_{CS}) is set at 3.2 Mg ha^{-1} (calculated based on Lang, 2002). Hence, the breakeven price for cellulosic biomass from a crop other than continuous corn requires that the alternative crop yield more cellulosic biomass than the 3.2 Mg ha^{-1} stover harvest assumed for this system.

The corn grain price plays a key role in determining the OC_{CG} system. Corn markets have been highly volatile over the past 3 yr. When the price for oil rises above $60 per barrel, ethanol becomes profitable and the markets for oil and corn become linked (Tyner and Taheripour, 2007). High oil prices over the last few years, therefore, have driven corn grain prices to levels unprecedented in recent times (McPhail and Babcock, 2008; Jiang and Swinton, 2009). Given this recent shift in the corn markets, we did not use historical average prices in our analysis. For the relative profitability calculation, we used the corn market outlook midpoint price of $132 Mg^{-1}. The USDA Economic Research Service's 10-yr projections put corn prices near $138 Mg^{-1} ($3.50 bu^{-1}) (USDA-ERS, 2009); therefore, $138 Mg^{-1} is used as the base price to estimate breakeven prices and yields. To capture the likely range of variability, we also calculated breakeven prices against low and high potential corn grain prices of $98 and $177 Mg^{-1} ($2.50 and $4.50 bu^{-1}).

Comparative Breakeven Cellulosic Feedstock Yield Analysis

The breakeven yield analysis estimates the mature-stand cellulosic yield level necessary for biofuel crops to generate net returns equivalent to continuous corn. Using the same notation as above and a biomass price (P_N), the breakeven yield (Y_{BE}) is the yield that would be required from a dedicated cellulosic crop to generate the same 10-yr present value of cumulative net returns as from continuous corn with a 38% stover removal yielding Y_{CS} quantity of corn stover:

$$Y_{BE} = \left(\frac{VC_N + OC_{CG}}{P_N} + Y_{CS} \right) \left(\frac{10}{T_{Y_{mat}}} \right)$$

Because many of the cellulosic biomass crops are perennials that require several years to reach full, or mature, annual yield, the final term in this equation divides the 10-yr time horizon by the number of full yield-equivalent years for that crop ($T_{Y_{mat}}$). $T_{Y_{mat}}$ is calculated as the total production over 10 yr divided by the expected mature annual yield. For annual crops, $T_{Y_{mat}}$ is simply 10. For a perennial crop that takes more than 1 yr from planting to reach full yield potential, the number is <10 (e.g., miscanthus and native prairie = 8.5, switchgrass and mixed grass and clover = 8.67, poplar = 9.67). T

$$T_{Y_{mat}} = \frac{\sum_{t=1}^{10} Y_{Nt}}{Y_{N_{mat}}}$$

[4] The annuity payments smoothe the slightly lower return from Year 1 with the yearly returns for Years 2–10. The lower revenue is Year 1 is due to the added cost of field tillage.

RESULTS

Relative Profitability

The relative profitability was calculated using the midpoint outlook prices for 2009–2010: corn at $132 Mg^{-1} ($3.35 bu^{-1}), soybean at $334 Mg^{-1} ($9.10 bu^{-1}), and canola at $358 Mg^{-1} ($16.25 bu^{-1}) (Ash et al., 2009; Baker et al., 2009), and assuming a biomass price of $60 Mg^{-1}. Under these conditions, the miscanthus system with cheap rhizomes earned net annualized revenue of $550 ha^{-1}, 1.7 times the net revenue of the continuous corn system ($320 ha^{-1}), and 1.8 times the net revenue of the corn rotation system ($300 ha^{-1}). In contrast, the miscanthus with costly rhizomes is the worst earner, at negative net revenue of –$1860 ha^{-1}. Switchgrass, grass mix, and old field earned positive net revenues between $70 and $100 ha^{-1}. Poplar and native prairie also failed to earn positive revenue, at –$130 ha^{-1} and –$90 ha^{-1}, respectively. Figure 1 shows total expenses that vary and gross revenues for each system (rounded to nearest $10).

Comparative Breakeven Prices for Replacing Continuous Corn

Comparative breakeven prices for cellulosic biomass are the prices that would be needed for continuous corn farmers to earn equal revenue from a dedicated cellulosic feedstock crop system. Figure 2 reports the comparative breakeven cellulose biomass prices for these systems, assuming a corn grain price of $138 Mg^{-1}. The miscanthus with cheap rhizomes system had the lowest breakeven price, at approximately $45 Mg $^{-1}$. Of the other cellulosic systems, poplar, switchgrass, and the grass mix system are the next most promising, but at a price from $110–130 Mg^{-1}, they exceed the likely affordable price range for refiners, and meet or exceed the price of hay. Miscanthus with costly rhizomes breaks even at $200 Mg^{-1}. Native prairie, which only barely exceeds the cellulosic yield of the 38% corn stover harvest, would require a cellulose price of $580 Mg^{-1} to break even. The unfertilized old field system cannot break even at all, because it produces less biomass than the 38% corn stover harvest. Indeed, the native prairie system would also fail to break even if the corn stover harvest were nudged upward from 38 to 50%.

The profitability of cellulosic biomass production is highly sensitive to the price of corn grain. Table 7 shows the breakeven prices by crop over a range of corn grain prices, from $98 Mg^{-1} ($2.50 bu^{-1}) to 177 Mg^{-1}($4.50 bu^{-1}). Denoted cells are prices that meet or exceed the price of non-alfalfa hay ($110 Mg^{-1}). Miscanthus with cheap rhizomes offers the lowest breakeven prices for cellulose at all prices of corn modeled. At a corn grain price of $98 Mg^{-1}, switchgrass, grass mix, and poplar have breakeven prices lower than the benchmark price of hay. However, at corn prices of $138 Mg^{-1} and higher, it is difficult for any of the biomass crops other than miscanthus with cheap rhizomes to compensate for the value of income from corn grain. Also noteworthy is that crops with the highest yields, regardless of cost,

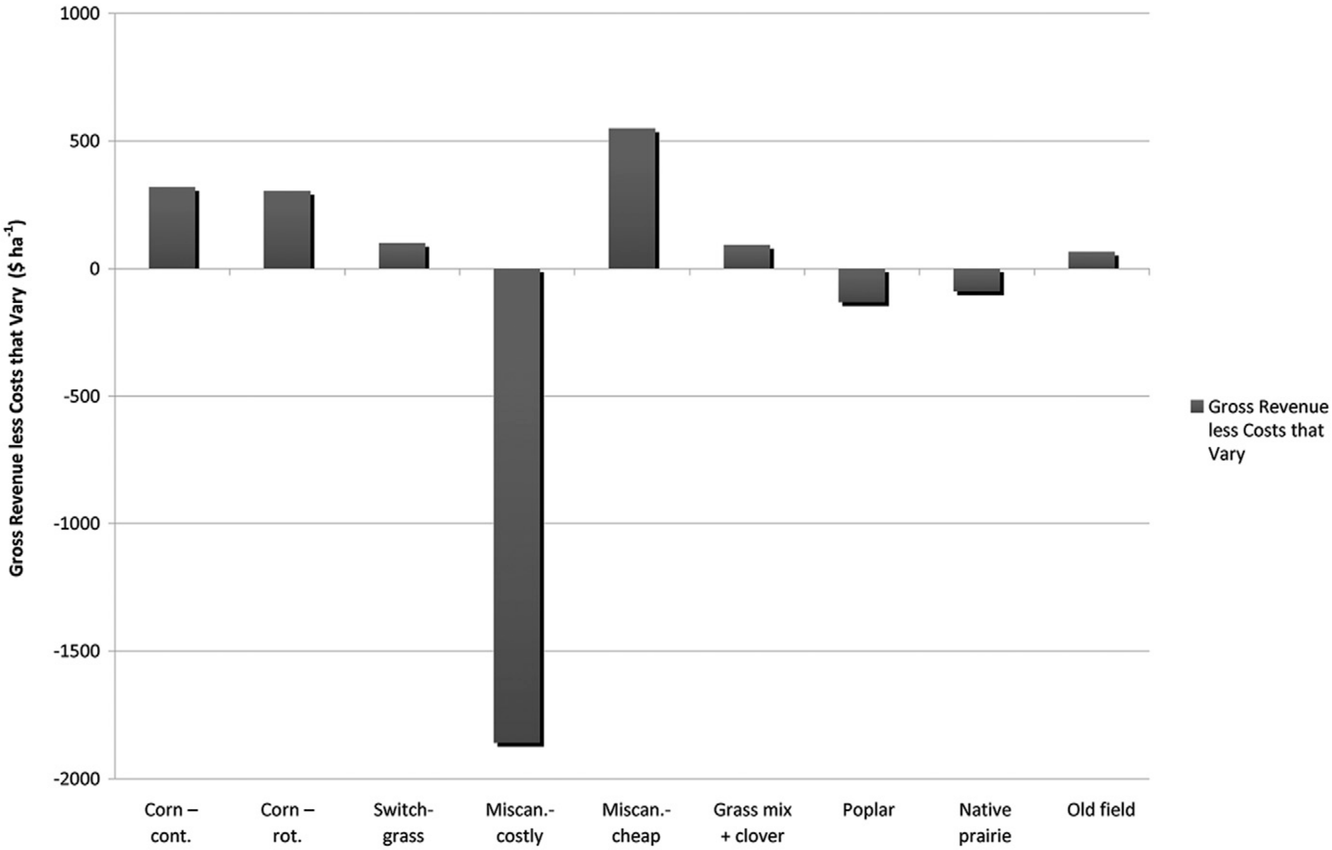

Fig. 1. Relative profitability of cellulosic feedstock crops (costs that vary across treatments vs. gross revenue).

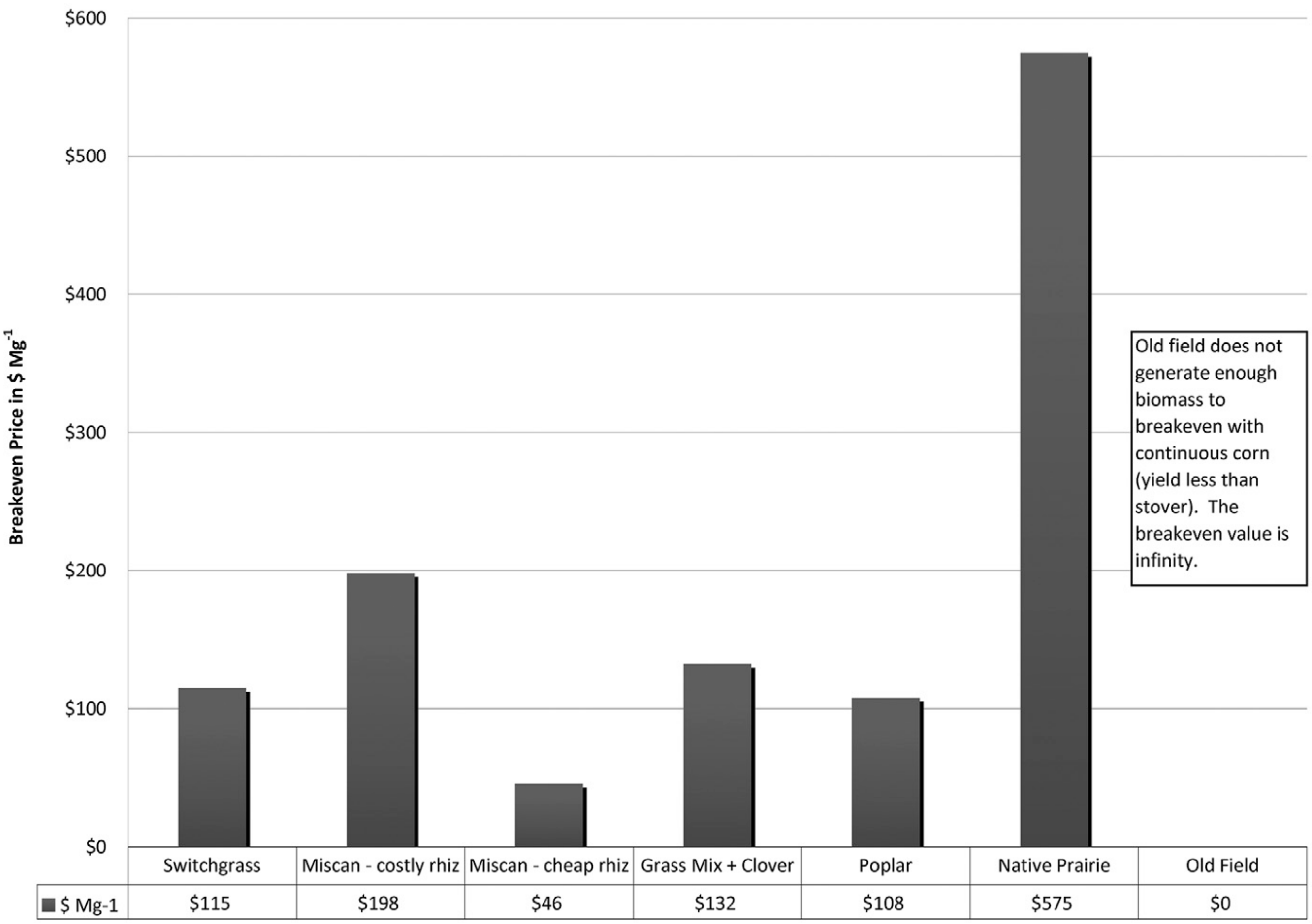

Fig. 2. Comparative breakeven prices for dedicated cellulosic crops to replace continuous corn (grain + 38% stover harvested).

showed the least sensitivity to changes in corn price. Miscanthus is a case in point, showing the flattest increments.

Comparative Breakeven Yield for Replacing Continuous Corn

A comparative breakeven yield, assuming a biomass price of \$60 Mg^{-1} and corn price of \$138 Mg^{-1}, shows the minimum yield required for a biomass crop to generate net revenue equal to continuous corn. Note that for perennial crops, the yield numbers refer to the mature-stand yield, not the yield average over 10 yr. However, it is not the absolute yield, but rather the relative increase required over current yield estimates, that is most relevant. For example, as shown in Fig. 3, the crop with the lowest breakeven yield is that with the lowest maintenance cost, unfertilized fallow old field. However, because its estimated cellulosic yield is so low, this crop requires a yield increase that is proportionately large—140%. By contrast, three crops with seemingly high breakeven yields need relatively low percent yield increases to break even: switchgrass (13.8 Mg ha^{-1}, a 50% increase), poplar (17.5 Mg ha^{-1}, a 60% increase) and grass mix (12.8 Mg ha^{-1}, a 60% increase). Miscanthus with costly rhizomes, which has the highest breakeven price, also shows the highest breakeven yield at 65.1 Mg ha^{-1}, which is nearly three times the expected yield for Michigan. Miscanthus with cheap rhizomes, on the other hand, is the most economically feasible competitor to corn + stover. The breakeven yield for this crop, 18 Mg ha^{-1}, is actually below the expected yield for Michigan, 22.4 Mg ha^{-1}.

Table 7. Breakeven price sensitivity with respect to corn grain price.

Cellulosic crop	Corn price, U.S. \$ Mg^{-1}† 98	138	177
Switchgrass	45	115‡	184‡
Miscanthus–costly rhizomes	178‡	198‡	218‡
Miscanthus–cheap rhizomes	26	46	66
Grass mix + clover	44	132‡	220‡
Poplar	66	108	149‡
Native prairie	208‡	575‡	942‡
Old field	n/a§	n/a	n/a

† Prices correspond to \$2.50, \$3.50, and \$4.50 per bushel.
‡ Exceed typical non-alfalfa hay prices.
§ n/a, not applicable.

Sensitivity of Breakeven Yield to Changes in Biomass Price

At \$60 Mg^{-1} and above, miscanthus with cheap rhizomes has a breakeven yield that is actually below the current expected yield. However, it is the only crop that shows a breakeven yield at or below the expected yield for Michigan across the price range of \$30 to \$90 Mg^{-1} for cellulosic biomass. There are two notable patterns evident as the price for biomass increases. First, as the price increases, those crops with higher yields, regardless of input costs, become more competitive. Thus, at \$30 Mg^{-1}, switchgrass has a breakeven yield closer to its expected yield than poplar, but at \$90 Mg^{-1}, the relationship is reversed. Second, as the biomass price increases, the incremental change in the percent yield increase required to breakeven declines. For example, the

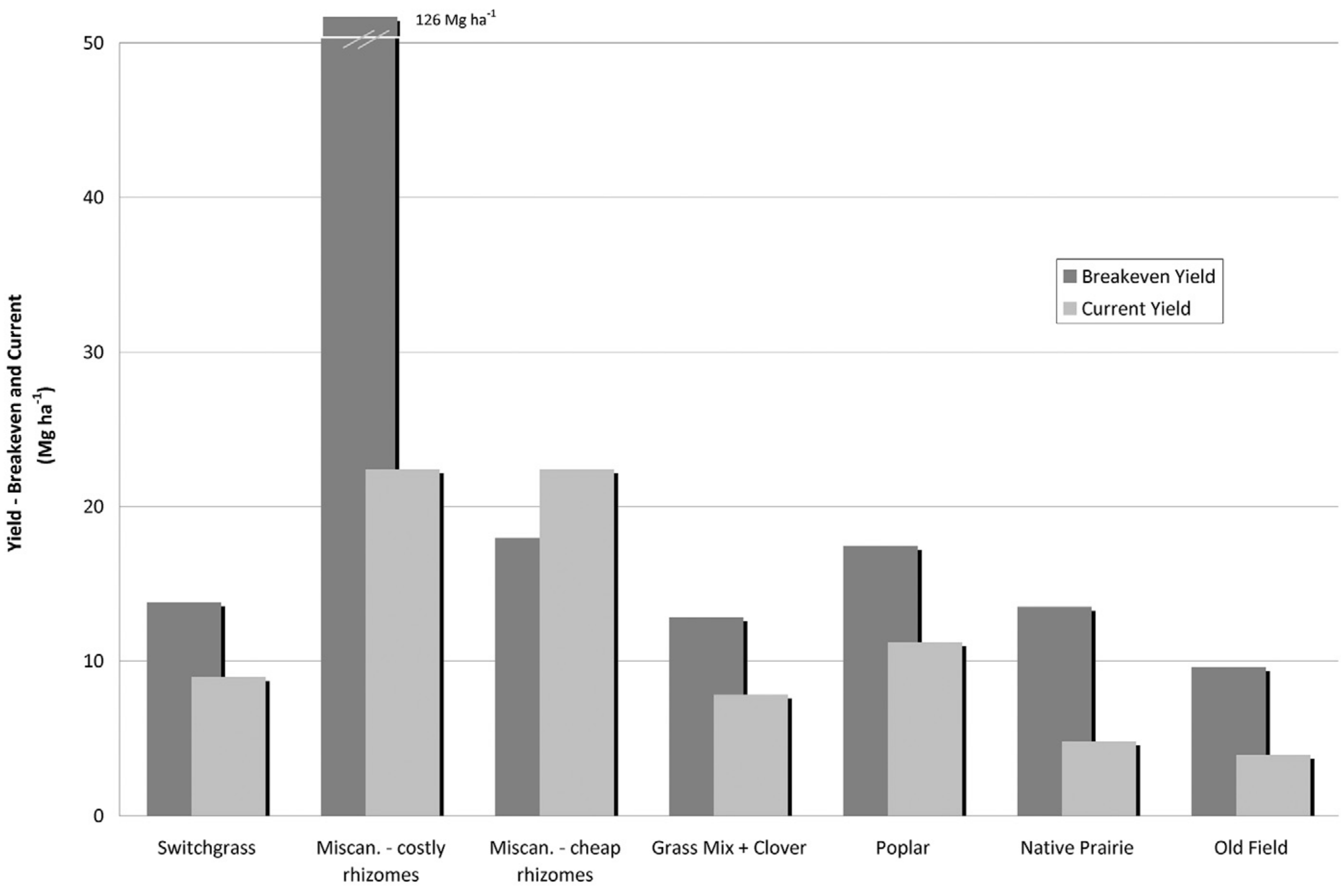

Fig. 3. Comparative breakeven yields for dedicated cellulosic crops to replace continuous corn at \$60 Mg^{-1} (Note: corn system includes grain + 38% stover harvested).

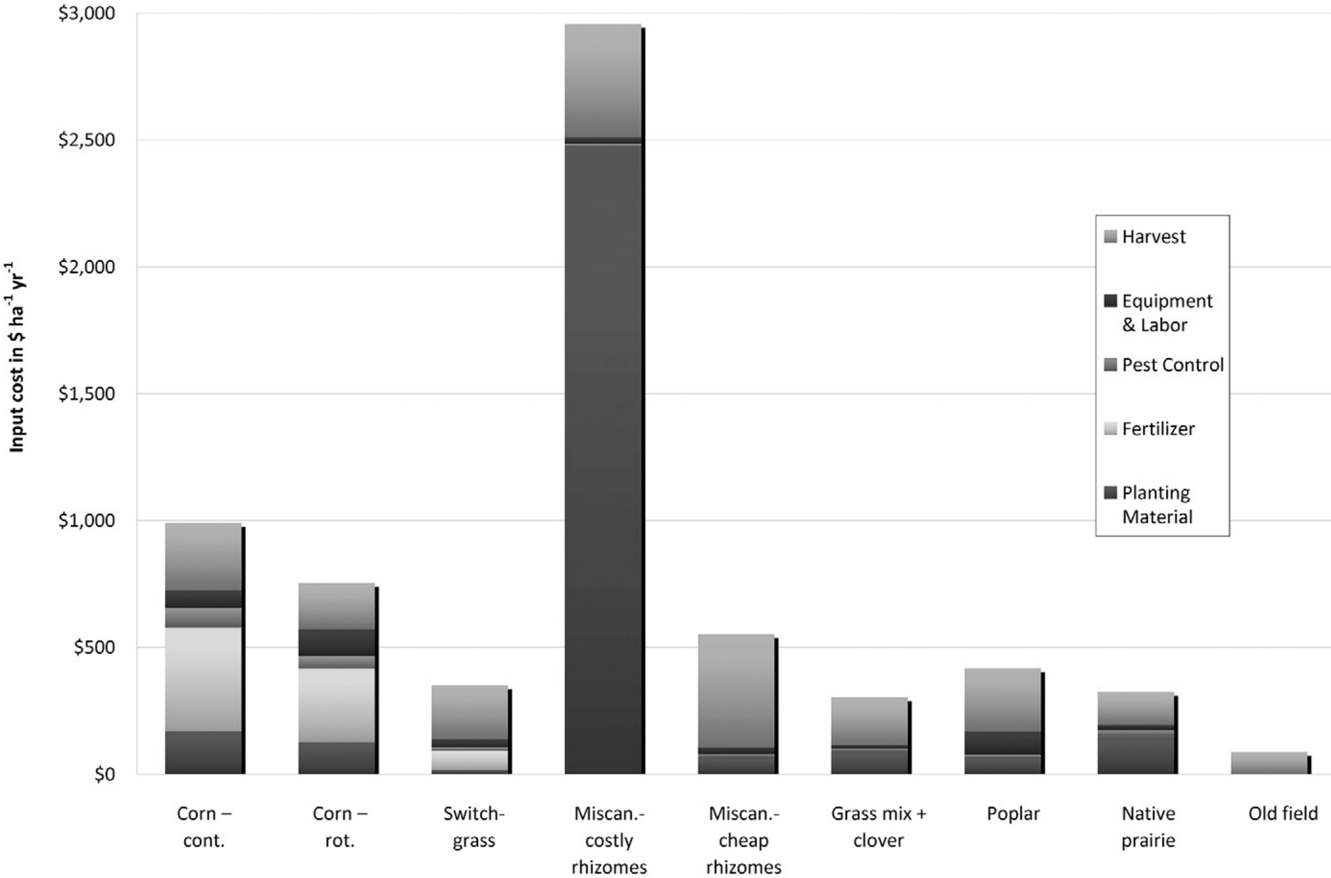

Fig. 4. Relative cost of inputs by cellulosic crop.

breakeven yield of switchgrass falls by over 110% of the baseline yield value as the price for cellulose rises from \$30 to 60 Mg^{-1}, but falls just 36% of the baseline value as the biomass price goes from \$60 to 90 Mg^{-1}. This pattern is evident for all systems.

The percentage yield increase over the baseline yield needed to break even as the price for cellulose rises shows a relationship similar to that of the breakeven price sensitivity analysis. Miscanthus with cheap rhizomes is the most attractive crop from a profitability standpoint, while miscanthus with costly rhizomes, native prairie, and old field are the least attractive. Poplar, switchgrass, and the grass mix are the mid-range options.

Sensitivity of Results to Changed Input Costs

Extreme shifts in input prices could significantly impact both the breakeven prices and breakeven yields presented above. Figure 4 illustrates the proportion of total production expense attributable to different categories of inputs, including planting material, fertilizers, pest control, equipment and labor, and harvest costs (which include transportation) by crop system. Each of these categories is a significant driver of production expense for corn. However, costs for biofuel crops are dominated by harvest expenses. Harvest expenses include mowing, baling, handling and transportation. Biomass crops under the production protocols assumed in this study are not sensitive to fertilizer prices, with the exception of switchgrass. However, because harvest is mechanically intensive and biomass is extremely bulky to transport, biomass crop production costs are sensitive to increases in oil prices.

DISCUSSION

At current yields and foreseeable prices, the profitability of dedicated cellulosic biofuel crops in the southern Great Lakes region falls far short of continuous corn. The value of the corn grain product makes corn stover the likely cellulosic feedstock for this region under a wide range of cost, price, and output scenarios.

The OC_{CG}, a major factor in the breakeven prices and yields estimated here, hinges on soil fertility. Yet the yield and associated profitability of annual row crops such as corn and soybean is particularly sensitive to field conditions including slope, soil type, and fertility levels (Kravchenko et al., 2005). The profitability of these row crops can be greatly reduced on marginal lands. Little information is currently available on the profitability of cellulosic biomass crops relative to corn under marginal field conditions, where the perennial root systems of switchgrass, miscanthus, and poplar may provide a significant yield advantage.

Among feedstock crops, the most likely cellulosic feedstock alternative to corn stover is miscanthus, despite the fact that it is the least competitive given current input costs in the United States. If reduced rhizome costs can be realized, then miscanthus already breaks even at current expected yields and the assumed price of \$60 Mg^{-1}. Though not yet a reality, what makes this possibility significant is that the cost reduction has already been demonstrated in European markets. Indeed, overseas, the rhizome price is reportedly ten times lower than the "cheap rhizome" scenario analyzed here (Lewandowski et al., 2000; Bullard et al., 1997; Khanna et al., 2007). The variability of production methods and yields observed in the literature for switchgrass, poplar and indicate that there is potential for production costs to decline relative to output in these crops as well.

Native prairie and fallow old field, two biomass feedstock sources often found on marginal or degraded land, are the least likely to displace corn on fertile crop land. The costs and returns of prairie as a crop differ from monoculture switchgrass in three important respects—the presence of forbs in the mix reduces the need for fertilizer, lowering costs; the mix of uncommon seeds is more costly, and yields are likely be lower than a switchgrass monoculture. The cost reduction of the first quality is overwhelmed by the greater expense and reduced revenue of the latter two qualities. In our analysis, native prairie shows a breakeven yield of 13.5 Mg ha^{-1}, which is 280% above the expected yield. Prairie does provide ecological services that monoculture crops—even native, perennial ones—do not. However, without a policy targeted at subsidizing these services, farmers have scant incentive to provide them.

The static picture given in this analysis does not take into account the potential for technological change. However, the potential for technological innovation in the form of improved genetic material, refined agronomic practices, and advances in the process to produce cellulosic ethanol is high for biomass feedstock crops, given their novelty as commercial crops. Advances in their production or processing traits could enhance their profitability. The required yield increases implied by the breakeven yield analysis are well within the range of increases achieved for other crops. For example, U.S. corn yields increased 4.6-fold from 1900 to 1998 (Larson and Cardwell, 1999). Hybrid poplar has been intensively bred using traditional methods over the last several decades, but it has not been bioengineered on a commercial scale, nor bred specifically for conversion to liquid transportation fuel. Switchgrass, though it has long been used as a hay crop, has only begun to be optimized for biomass. Miscanthus research for biofuel purposes is in its infancy.

Though this analysis focuses on price and yield, biomass crop profitability is also affected by production costs. Total production cost for dedicated biomass crops is generally lower and based on fewer inputs than total production cost for traditional annual field crops. For example, with the exception of switchgrass, biomass crops require little fertilizer, making them relatively immune to fertilizer price volatility. On the other hand, harvest costs, primarily machinery costs, range from 50 to 100% of total production costs for the different biomass crops (with the exception of miscanthus with costly rhizomes). But harvest costs are just 23% of the production cost for corn grain + stover, and only 19% of total costs for the rotation system. Harvest costs, together with planting material costs for some crops, are the only areas where significant costs savings can be achieved for biomass crop production. Nevertheless, the opportunity is there for reductions in the cost of planting material and improvements to harvest technology and transport systems to improve the profitability of the crop.

The yield response of biomass crops to fertilization is potentially very significant. In a detailed comparison of 21 studies on switchgrass and miscanthus performance in the United States and Europe, Heaton et al. (2004) found that miscanthus on average produced twice the biomass produced by switchgrass. In addition, switchgrass was found to benefit from moderate nitrogen applications where miscanthus did not. However, while miscanthus stands have been known to produce at extremely high yields with no fertilization for years beyond the 10-yr limit set by this study (Pyter et al., 2007), the evidence is anecdotal and needs to be more intensively researched. It is reasonable to expect that any crop system that exports nutrients via regular harvests will eventually require some replacement fertilization to maintain soil fertility, especially on marginally productive soils. Incorporating fertilizer into the budgets for biomass crops would obviously impact their profitability and sensitivity to corn and biomass prices.

Finally, it is important to note that the profitability of any crop is influenced by policy. The high OC_{CG} is due indirectly to U.S. policies ranging from the sugar quota to the ethanol blender tax credit and ethanol import tariff. Cellulosic feedstock production has received supports more recently via mandatory ethanol blending quantities in the Energy Independence and Security Act of 2007 and the BCAP program in the Food, Energy and Conservation Act of 2008 (commonly known as the 2008 Farm Bill, U.S. Congress, 2008). The BCAP subsidies, which are not available to corn producers, are not incorporated into this analysis, but may alter the conclusions presented here if program funds are appropriated and made easily accessible to farmers.

Environmental stewardship is encouraged by farm bill cost share and payment for environment service programs (e.g., Environmental Quality Incentives Program and the Conservation Security Program). Future policy changes in these areas could create not only direct profitability effects via changed costs and revenues, but also indirect effects on prices induced by changes in supply or demand.

Other Factors Affecting Farmers' Willingness to Grow Cellulosic Feedstock Crops

In informal interviews conducted during summer 2008, five Michigan farmers were asked what reservations they might have before switching to a perennial crop. The primary concerns centered on availability of markets for cellulosic feedstocks, uncertainty about prices, and negative cash flows while awaiting mature yields from perennial biofuel crops. Another major concern was the lack of adequate storage infrastructure for cellulosic biomass. The analysis here assumes that a farmer transports cellulosic biomass directly to the refinery, with no storage costs incurred. However, storage is likely to be a significant issue should demand for biomass increase. Consider storage needs from one hectare of cropland. A switchgrass yield of 9 Mg ha^{-1} means about 60 m^3 of product (Wright, 2004); 9.4 Mg ha^{-1} of corn, on the other hand, equals about 13 m^3. Clearly, significant investment will be required to transport and store the biomass feedstock inventory just for an individual biorefinery, much less an entire industry. Current corn grain ethanol plants have been unwilling to invest in storage facilities or hold large amounts of inventory (Roti, 2007). If cellulosic biomass were stored in bales on farm fields, farmers would incur significant losses due to flaking, decomposition, and pest damage, not to mention the cost of the land areas and structures dedicated to storing bales.

Another concern related to production of switchgrass is its potential to become an invasive weed. Farmers in Michigan have requested that state wildlife agents not use switchgrass in habitat restoration projects that adjoin corn fields, because farmers fear the switchgrass will invade and become difficult to remove (M. Bishop, personal communication, July 2008). Indeed, herbicides are considered necessary for commercial switchgrass production only during the first 2 yr because a well-established stand will suppress most plant competitors. However, there is no evidence that switchgrass can establish itself in an annually tilled field, or even a no-till annual cropping system. *Miscanthus ×giganteus* is a sterile hybrid, and hence unlikely to spread on its own.

A final potential deterrent to farmer adoption of dedicated cellulosic crops is the potentially high cost of removing perennial crops to replace them. Miscanthus has an extensive woody rhizomatous root system, and once established in a field, could be very difficult to eliminate if a farmer should choose to return to annual cropping. Similarly, after coppicing, poplar tree crops would require stump removal before returning to rotational crops.

At least two noteworthy factors would favor adoption of dedicated cellulosic crops. First, most of them require relatively little labor apart from initial establishment and harvest. Poplar and native prairie require very little attention after establishment, so they may be attractive to part-time farmers. Switchgrass and miscanthus require more labor than traditional grain crops, due almost entirely to the demands of harvest and baling. However, due to the time sensitive nature of harvest, a farmer may chose to custom hire the harvest of biofuel crops.

Environmental benefits from dedicated cellulosic crops represent another set of factors potentially favoring adoption. Untilled perennial systems remove carbon from the atmosphere while emitting little or no greenhouse gasses, especially compared with annual crops receiving nitrogen fertilizer (Robertson et al., 2000; McSwiney and Robertson, 2005). Should robust markets develop for carbon offsets, those revenues could supplement income from cellulosic biomass sales. Likewise, perennial cellulosic crop systems tend to require little or no fertilization and tillage, hence generating less nutrient runoff and erosion than annual crop systems. Under policies that pay for environmental services (such as the U.S. Conservation Security Program), perennial cellulosic crop systems could qualify for this additional revenue source as well.

In conclusion, most current perennial, dedicated cellulosic biomass crops are unlikely to displace corn on cropland in the southern Great Lakes region at foreseeable prices for cellulosic biomass. The one exception that potentially could compete with corn is miscanthus if produced using low-cost rhizomes, although more agronomic experience is needed to verify its winter hardiness, potential invasiveness, and pest susceptibility. The potential for profitable production of dedicated cellulosic biomass crops may be greater on non-crop land where opportunity costs to the grower may be lower. Further research is needed into the production possibilities of biofuel crops on lands not currently used for intensive crop farming.

APPENDIX

Appendix 1. Scientific name of species composition of mixed-species crops.

Common name	Scientific name
	Composition of the grass-clover mix
Switchgrass	*Panicum virgatum* L.
Canada wild rye	*Elymus canadensis* L.
Little Bluestem	*Schizachyrium scoparium* (Michx.) Nash
Big bluestem	*Andropogon gerardii* Vitman
Indiangrass	*Sorghastrum nutans* (L.) Nash
Red clover	*Trifolium pratense* L.
	Composition of the prairie mix
Big bluestem	*Andropogon gerardii* Vitman
Canadian anemone	*Anemone canadensis* L.
Butterfly weed	*Asclepias tuberosa* L.
New England aster	*Aster novae-angliae* L.
Wild white indigo	*Baptisia leucantha* Torr. & A. Gray
Showy tick trefoil	*Desmodium canadense* (L.) DC.
Canada wild rye	*Elymus canadensis* L.
Junegrass	*Koeleria cristata* Pers.
Roundhead Lespedeza	*Lespedeza capitata* Michx.
Wild bergamot	*Monarda fistulosa* L.
Switchgrass	*Panicum virgatum* L.
Prairie coneflower	*Ratibida columnifera* (Nutt.) Wooton & Standl.
Black-eyed susan	*Rudbeckia hirta* L.
Little bluestem	*Schizachyrium scoparium* (Michx.) Nash
Cup plant	*Silphium perfoliatum* L.
Stiff goldenrod	*Solidago rigida* L.
Showy goldenrod	*Solidago speciosa* Nutt.
Indiangrass	*Sorghastrum nutans* (L.) Nash

Appendix 2. Chemical names of pesticides referenced in budgets.

Common name	Commercial name	Chemical name
mesotrione	Lexar	2-(2-Nitro-4-mesylbenzoyl) cyclohexane-1, 3-dione
glyphosate	Round-up	N-(phosphonomethyl) glycine
pendimethalin	Prowl	N- (1- ethyl propyl)- 3,4 dimethyl-1,2,6 dinitro benzenamine
2,4-D	Trillion	2,4-dichlorophenoxy acetic acid
atrazine		2-chloro-4-ethylamine-6-isopropylamino-S-triazine
dicamba	Clarity	3,6-dichloro-2-methoxybenzoic acid
aminopyralid	Milestone	4-Amino-3,6-dichloropyridine-2-carboxylic acid
S-metolachlor	Dual Magnum	N-Methoxymethyl-2,6-diethylanilide chloroacetate
clopyralid	Transline	3,6-dichloro-2-pyridinecarboxylic acid
imazapic	Journey	5-methyl-2-(4-methyl-5-oxo-4-propan-2-yl-1H-imidazol-2-yl)pyridine-3-carboxylic acid

Appendix 3. Great Lakes Bioenergy Research Center crop systems.

System intensity and perenniality	Crop rotation	Description
Annual/high input	continuous corn	no-till Bt-RR corn grown without rotation to other crops.
	corn-soybean-canola	a no-till rotation of Bt-RR corn, then RR soybean, then RR canola.
Nonnative perennial/low input	switchgrass	'Cave-in-Rock', monoculture
	miscanthus	×*giganteus*, monoculture
	grass mix + clover†	tall prairie grass mix of switchgrass, big bluestem, little bluestem and Indiangrass, with clover
	poplar	Poplar hybrid from *P. nigra* with *P. maximimowiczii* (MN), monoculture
Native perennial systems/low Input	prairie†	Mix of native grasses and forbes (18+ native species)
	old field	Early succession of native plants on land previously planted to row crops left fallow

† See Appendix 1 for a full list of species.

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