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Bringing Better Biomass Feedstocks to Market: An Analysis of the Breakeven Costs of Production

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EXECUTIVE SUMMARY

There is growing interest in bioenergy—energy made from various forms of biomass—as a renewable alternative to fossil fuels for heat, power, and as liquid forms of fuel for transportation. Biomass energy comes from plants, which capture energy from the sun as they grow and draw on limited resources such as land, water, and soil nutrients. It can be obtained from several sources, including crop residues, dedicated energy crops, perennial grasses, and short rotation trees, such as poplar and willow.

Biomass production places demands on land with consequences for farm income, food and feed production, and has ecosystem impacts on land. A meaningful displacement of fossil fuels will require significant production of biomass that is economically, environmentally, and socially sustainable.

To be economically sustainable, biomass must provide an income that covers at least the landowner's production costs; for energy crops and woody feedstocks, these include not only the cost of growing the crops themselves, but also foregone income from alternative uses of the land.

The potential to grow biomass crops on land that is idle, marginal, or not productive for food and feed crops makes these crops an attractive bioenergy feedstock. Energy crops have the potential to provide significant environmental benefits in the form of soil carbon sequestration, reduction in sediment run-off, soil quality improvement, and wildlife habitat. In addition, higher yielding energy crops require less diversion of land from food and feed production or the provision of environmental services. Nevertheless, the environmental implications of biomass production depend on the feedstocks chosen, the types of land on which they are grown, and farm management practices.

The focus of this study is to assess the profitability of different biomass feedstock production systems under various agronomic and economic scenarios to determine what, if any, market incentives are needed to reward growers for producing biomass. Policymakers seeking to promote low-carbon and broadly sustainable bioenergy will be able to use this information in crafting performance-based policies to establish economically viable biomass cropping systems and encourage good conservation practices. It is important to note that this is an economic analysis. This paper does not make claims about the ecological viability of the different pathways examined. The environmental performance of any biomass cropping system will ultimately depend on which biomass crop is grown, in what quantities, on which land, and with which management practices, as well as the efficiency with which it is converted into bioenergy.

We selected three U.S. states—Michigan, Illinois, and Oklahoma—that differ in climate, and therefore also differ in yields and suitability for various crops. The relative profitability of the biomass feedstocks considered varies by region, as do the trade-offs farmers are likely to face as they switch from conventional crops to biomass production. Our analysis estimates the amount of government subsidies that may be required to induce production of particular feedstocks if market prices, based solely on the energy content of different feedstocks, are insufficient to make production economically viable.

This report presents crop budgets and comparative breakeven price analysis for eight potential biomass production systems in Illinois, Michigan, and Oklahoma, and highlights key factors that drive their potential profitability. We determined the breakeven price of biomass feedstocks at the farm-gate on marginal land and on land under the most profitable cropping system in each state: rotation corn with no-till in Michigan and Oklahoma, and corn-soybean rotation with conventional tillage in Illinois. All yields referenced in this report are at the farm-gate after accounting for storage losses, unless otherwise stipulated. We included five biomass sources—corn stover, miscanthus, switchgrass, native prairie grasses, and poplar.


Miscanthus

© edgeplot


Mixed prairie grasses

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The amount of corn stover that can be sustainably harvested depends on the tillage and rotation practices used to grow the corn, and has implications for production cost. While we have not assessed the ecological impacts of taking different levels of corn stover off fields, corn stover harvested from continuous corn planting was compared to corn-soybean rotations, and corn grown using conventional tillage versus no tillage.

For perennial grasses and poplar, the production cost includes the opportunity cost of the land since landowners will allocate land to these crops only if the financial return is at least equal to existing returns. Landowners have a choice of growing perennial grasses on prime cropland or marginal land that may be under pasture or fallow but could be brought back into crop production if it were profitable. According to the National Agricultural Statistics Service categories of idle land and cropland pasture, there are 1.01 million acres of marginal land available in Illinois, 0.81 million in Michigan, and 3.67 million in Oklahoma.[1]

Research is ongoing on energy crop productivity on marginal, low quality land. If yields are found to be similar to those from average cropland, it will be economically viable for farmers to first use marginal land because it has a lower opportunity cost. Lack of availability of marginal land that is easily accessible, unfragmented, and not subject to environmental regulations preventing farming (i.e. under the Conservation Reserve Program) could require cultivation of energy crops on land currently under conventional crops.[2] As a result, this analysis takes into account the costs and profitability of energy crops on both marginal and average cropland.

Feedstock yields vary across regions due to different climatic conditions, soil moisture, and soil quality. Only one variety of miscanthus (Miscanthus giganteus) is currently being evaluated, but there are several varieties of switchgrass, mixed prairie grasses, and poplar currently being grown. The variety best suited for a particular location depends on geographic characteristics—soil, climate, and its resistance to insects, disease, frost, and extreme weather.

The breakeven production costs of biomass feedstocks vary according to the feedstock, region, and scenario, depending on the ease of establishing and harvesting them. The farm-gate costs of biomass feedstocks vary dramatically, from \$35/megagram (Mg) for miscanthus grown on marginal land in Oklahoma to $389/Mg in hybrid poplar grown on cropland (also in Oklahoma). In general, corn stover is cheaper than most dedicated energy crops (on cropland) with a rotation corn system; production costs range from $51/Mg under a rotation corn system with no till in Michigan to $114/Mg with a rotation corn system with conventional till in Oklahoma. We also found no significant difference in the costs of stover production with a no-till rotation corn system between the three study states.

With a monoculture corn system, however, the costs of stover collection increased substantially. In Oklahoma, in particular, the cost of stover collection under a monoculture corn system is dominated by the opportunity cost of land, with a share of land cost of 47 to 60 percent of the total. This suggests farmers in these states do not have an economic incentive to convert from rotation corn to monoculture corn simply for greater stover collection, unless the corn stover prices or subsidies for biomass provision are high enough to compensate for the conversion.

Among the three perennial grass production systems examined, we find that miscanthus has the lowest production costs, ranging from $35 to $87 per metric ton of dry matter (Mg DM) when planted on marginal land, and $43 to $103/Mg DM when planted on cropland. In contrast, biomass production costs on the two different land types range between $46 and $100/Mg DM, and $73 and $135/Mg DM, respectively, for switchgrass, and between $69 and $109/Mg DM, and $99 and $177/Mg DM for mixed prairie grasses. Thus, energy crop production is more likely to be viable first on marginal land in these states and will be viable on cropland only if the biomass price is sufficiently high- and low-cost marginal land is unavailable. At a biomass price of $50/Mg DM, it would be profitable to produce miscanthus on marginal land in Illinois and Oklahoma, switchgrass on marginal land in Oklahoma, and even miscanthus on cropland in Oklahoma if the low-cost scenario prevails.

We analyzed the sensitivity of the breakeven prices of biomass feedstocks to various factors and found that when they are produced on cropland, breakeven prices are most sensitive to corn and soybean price changes. When planted on marginal land, breakeven prices are most sensitive to changes in biomass yields and harvest costs. Moreover, biomass feedstocks with longer lifetimes are more price-sensitive to changes in discount rate.

Our estimates of breakeven costs are the minimum price farmers need to be paid to switch from a corn-soybean rotation to an energy crop on both marginal and average cropland. How much higher this price is than the market price of biomass indicates how large a subsidy would be needed per MT to induce production of a particular feedstock in different regions. The amount depends on the relevant costs of production, yields, and crop prices.

If the production of energy crops is desired on cropland for environmental reasons—for example, as a mechanism to reduce soil erosion and nitrogen leaching, and to increase biodiversity—considerable subsidies would be required. In particular, at a biomass price of $50/MT, the subsidies required to induce production of a high yielding perennial like miscanthus, would range from $12 to $19/MT if the costs of production are low and $23 to $52/MT if they are high. At 66 gallons of ethanol per MT of biomass, this implies subsidies of between $0.18 and $0.77 per gallon of ethanol. At 99 gallons of ethanol per MT of biomass, this implies between $0.12 and $0.52 per gallon in subsidies.

Mixed prairie grasses have attracted attention due to their low-input high-diversity (LIHD) attributes. Subsidies of $19 to $34/MT would be required to motivate landowners to grow mixed grasses even on marginal land if their production costs are low. These would be even higher if production costs turn out to be high and/or policy makers seek to induce their production on cropland.

DATA AND ANALYSIS

BIOMASS YIELDS

Corn stover yields under different rotation and tillage are shown in table 1. The yield of corn stover varies from less than 1 MT/hectare (ha) in Oklahoma under rotation corn and no-till to 3.4 MT/ha in Illinois under monoculture and no-till.

In the absence of long-term observed yields for miscanthus and limited data for switchgrass, we used the MiscanMod crop productivity model to simulate their potential yields. The model estimates yields of miscanthus and Cave-in-Rock switchgrass using Geographic Information System data on climate, soil moisture, solar radiation, and growing degree days as described in Jain et al.[3] Cave-in-Rock switchgrass is an upland variety that originated in Southern Illinois and is cold-tolerant and well-suited for the upper Midwest but has relatively low yields. Lowland varieties of switchgrass, like Alamo, are most suited for the southern United States and have higher yields.[4]

The estimate of harvested yields for mixed prairie grass systems in Illinois is based on the DayCent model, while the estimates for Michigan and Oklahoma are from various other studies.[5] Due to lack of sufficient field experimental data on hybrid poplar yields, the state-specific poplar yield estimates are from a Predictive Ecosystem Analyzer model, which shows that annual yield maximizing rotations for poplar are ten (Illinois), eight (Michigan), and six (Oklahoma) years.[6] Table 5 shows the assumptions made about the yields of biomass feedstocks included in the study. For energy crops, these yields are different for low-cost and high-cost scenarios because of differences in harvest losses and the time taken to establish the grasses.

Recent research indicates that actual yields in a region are typically smaller than the yield potential, because achieving the yield potential requires almost perfect management and soil conditions that may be possible only under experimental conditions.[7] The average yields of row crops like wheat and rice in rainfed conditions were commonly 50 percent or lower than yield potential. In the absence of data on actual yields obtained by farmers growing energy crops, we examined the sensitivity of cost estimates to having 25 percent lower yields of switchgrass, miscanthus, mixed prairie grasses, and hybrid poplar compared to the maximum potential yields projected by crop simulation models using data from experimental plots.

For more on the biomass feedstocks examined, yields, as well as harvesting and storage requirements, see Appendix A.

Table 1: Delivered Crop Yield

Yield	Unit	Illinois		Michigan		Oklahoma	
		Low-cost	High-cost	Low-cost	High-cost	Low-cost	High-cost
Corn	bushel/acre	156.24		122.97		84.24	
Soybean	bushel/acre	43.92		35.7		27.02	
Stover (RC, CT)	Mg DM/ha/yr	1.16		0.92		0.63	
Stover (RC, NT)	Mg DM/ha/yr	1.94		1.53		1.05	
Stover (MC, CT)	Mg DM/ha/yr	2.05		1.61		1.10	
Stover (MC, NT)	Mg DM/ha/yr	3.41		2.69		1.84	
Switchgrass	Mg DM/ha/yr	10.74	9.61	7.53	6.74	9.70	8.68
Miscanthus	Mg DM/ha/yr	25.16	18.46	15.45	11.33	29.54	21.68
Prairie grass	Mg DM/ha/yr	7.02	6.28	7.13	6.38	5.89	5.27
Poplar	Mg DM/ha/yr	9.74	8.63	9.40	8.72	3.15	1.57

RC = Rotation corn; MC = Monoculture corn; CT = Conventional tillage; NT = No tillage.

Method for Determining Breakeven Prices

This study estimates the breakeven prices of different biomass production systems using the following steps:

1. Construct costs of production for each crop system for each year over the life of the crop;
2. Discount these to obtain the present value of these costs;
3. Determine the annual value of the residual return to cropland if used for its most profitable alternative use (continuous corn or rotation corn) at given prices for corn and soybeans. Add this value of land to the discounted net present value of production costs to obtain discounted total costs of production;
4. Determine the time path of biomass yields and its discounted level using the same discount rate as in step 2;
5. Divide the discounted total costs by the discounted level of yield to obtain the breakeven cost of producing biomass with a particular feedstock in terms of $ per dry metric ton.

Table 2 lists the biomass production systems examined in this study. For more information on methodology, data, and agronomic assumptions, see Appendix B.

Table 2: Biofuel Production System

System	Description
I. Rotation corn with CT	A corn-soybean rotation with 30% stover removal rate
II. Rotation corn with NT	A corn-soybean rotation with 50% stover removal rate
III. Monoculture corn with CT	A corn-corn rotation with 30% stover removal rate
IV. Monoculture corn with NT	A corn-corn rotation with 50% stover removal rate
V. Switchgrass	Switchgrass production on cropland/marginal land
VI. Miscanthus	Miscanthus production on cropland/marginal land
VII. Native prairie grasses	Native prairie grasses on cropland/marginal land
VIII. Wood biomass	Hybrid poplar production

CT: conventional tillage; NT: no tillage.

Mixed prairie grasses

COSTS OF PRODUCTION

The farm-gate production cost of biomass includes: (i) the cost of inputs, such as chemicals, fertilizers and seeds; (ii) the cost of field operations, such as planting and harvesting; and (iii) costs of storage. The costs of production for each county are based on 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. For fertilizer application rates, input prices, and assumptions for machinery costs of biomass production and harvest see Appendix C.

Preharvest and harvest costs related to switchgrass, miscanthus, and mixed grasses are from crop budgets compiled by corresponding state extension services; costs related poplar harvest are from James et al.[8] There is considerable uncertainty about the cost of miscanthus rhizomes since they are not yet commercially available for large scale planting. Developers and producers expect miscanthus plugs to cost between $0.30 and $0.80 per plug as they begin commercial sales in 2010, and close to $0.25 per plug by 2011. Costs are expected to be lower for rhizomes than plugs and decrease as production increases. Cost of propagating rhizomes at the University of Illinois is estimated to be $0.10 per rhizome. Therefore, we assume a rhizome cost of $0.25 and a planting rate of 10,000 rhizomes/ha for all three states following Jain et al.[9] Since site-specific information on the price of cuttings for planting poplar was not available, we assumed the cost to be $0.22 per cutting and 2,717 cuttings/ha for all three states based on the same research.[10] The costs of producing corn stover includes the cost of fertilizer to replace the loss of nutrients and soil organic matter due to removal of residue from the soil.

The estimated opportunity cost of cropland is based on the most profitable use of that land. We found that, among the crop choices examined, a corn-soybean rotation with conventional tillage is the most profitable land use in Illinois, with a total revenue above operating costs of $771/ha, while a corn-soybean rotation with no till is the most profitable land use in Michigan and Oklahoma, with a total revenue above operating costs of $458/ha and $409/ha, respectively. These are estimated using state-specific five-year (2003 to 2007) historical average corn and soybean yields per acre as well as state-specific three-year average (2006 to 2008) corn and soybean prices from U.S. Department of Agriculture/National Agricultural Statistics Services.[11]

Illinois has the highest opportunity costs of land since its corn and soybean yields and prices are high, but the production costs are relatively low. On the other hand, Oklahoma has the lowest opportunity cost of land under a corn-soybean rotation due to its low corn and soybean yields and relatively high production costs for these crops. Since a rotation corn system is more profitable than a monoculture corn system in the study states, an opportunity cost of land is also considered for the collection of corn stover for a monoculture corn system. The opportunity cost of land in this case is the foregone profits with rotation corn if the production of corn stover leads the farmer to switch to monoculture corn, measured as the difference in net profits between these two production systems. There is also an opportunity cost of land for switching tillage practices with rotation corn, from conventional till to no-till in Illinois, and from no-till to conventional till in Michigan and Oklahoma. For marginal land costs for energy crops we used the average Conservation Reserve Program (CRP) payments for general CRP sign-ups in the state in 2007 as a measure of the alternative income from that land.[12]

RESULTS

Of the three perennial grass production systems examined, miscanthus has the lowest production costs, ranging from $35 to $87/MT DM when planted on marginal land, and $43 to $103/MT DM when planted on cropland. In contrast, the costs of biomass production under the two types of land range between $46 and $100/MT DM and $73 to $135/MT DM, respectively, for switchgrass, and $69 to $109/MT DM and $99 to $177/MT DM for mixed prairie grasses. Thus, production of energy crops is more likely to occur first on marginal land in these states and will be viable on cropland only if the biomass price is sufficiently high and low-cost marginal land is unavailable.

Oklahoma has the lowest costs of switchgrass and miscanthus production regardless of the type of land used because of its higher switchgrass and miscanthus yields and lower opportunity costs of land. Michigan has the highest costs of switchgrass and miscanthus production due to its low yields for these two crops, though it has lower opportunity costs of land than Illinois. Costs of mixed prairie grass production in most cases are lowest in Michigan because it has the highest grass yields. In addition, the costs of production for perennial grasses for the low- and high-cost scenarios differ by about $17 to $38/MT, suggesting that agronomic decisions about input application rates and crop attributes such as length and ease of establishment and timing of harvest have a substantial impact on the costs of biomass grass production. In addition to its advantage in mixed prairie grass production compared with Oklahoma

Switchgrass seeds

or Illinois, Michigan also has the lowest production costs for hybrid poplar at $88/MT DM to $95/MT DM when planted on marginal land and $106/MT DM to $115/MT DM when planted on cropland. Costs of poplar production in Illinois are slightly higher than in Michigan because of its higher marginal and crop land costs. Oklahoma has the highest costs of poplar because poplar yields are much lower, only about one third of those in Illinois and Michigan.

For biomass production on cropland the breakeven costs of producing corn stover are lower than those of dedicated energy crops (except miscanthus in Oklahoma in the low-cost scenario); the breakeven cost of corn stover ranges between $51/MT DM and $60/MT DM under a rotation corn system with no till in the three states. Costs of corn stover are higher with rotation corn with conventional tillage in all three states because of the lower residue harvest rate. However, breakeven costs of corn stover are much higher with a monoculture corn system, even with no-till, and even more so with conventional tillage. This is due to the opportunity cost of land in the former case and compounded with lower corn stover yields in the latter case. This suggests that farmers in these states are unlikely to have an economic incentive to convert from rotation corn to monoculture corn simply for greater stover collection.

The drivers of biomass production costs vary across crop species but not across states. For corn stover, harvesting accounts for about 80 percent or more of the total operating costs of production excluding the opportunity cost of land, with the rest being the cost of fertilizer needed to replace nutrient loss. When collected from a monoculture corn system and after taking into account the opportunity cost of land, corn stover becomes much more costly, with land costs accounting for 18 to 34 percent of the total cost in Illinois, 44 to 56 percent in Michigan, and 47 to 60 percent in Oklahoma. By contrast, when collected from a rotation corn system, total costs are much lower, and land costs for alternative tillage account for 12 percent of the total cost in Illinois for no till, 6 percent in Michigan for conventional till, and 44 percent in Oklahoma for conventional till. For switchgrass, of the total operating costs excluding the opportunity cost of land, the largest expense is also harvesting, accounting for more than half of the total operating cost, except in the high-cost scenario in Michigan where harvesting costs are only 42 percent. Fertilizer costs are the second highest cost in switchgrass production, accounting for 24 to 38 percent of the total operating costs across states. The cost of land for switchgrass is only about 11 to 31 percent of the total production cost when it is planted on marginal land. However, the share of land cost rises to 35 to 59 percent when switchgrass is planted on cropland.

Harvesting expenses are also the largest cost of miscanthus production, with about 60 percent in total operating costs excluding the cost of land in Illinois and Oklahoma and 41 to 48 percent in Michigan. Miscanthus establishment costs in the three states range from 26 to 38 percent of total operating costs, and are the second largest cost component. Fertilizer costs account for about 8 to 14 percent and are consistently the third largest component. The share of land costs in total cost of miscanthus production varies significantly, ranging from 6 to 8 percent for marginal land and 21 to 27 percent for cropland in Oklahoma to 14 to 18 percent for marginal land and 27 to 40 percent for cropland in Illinois and Michigan.

For low input mixed prairie grasses, the primary expense in total operating costs—excluding the cost of land—is harvesting, accounting for 57 to 63 percent of the total for the study states. Seed costs are consistently the second largest operating cost, and make up 25 to 30 percent of the total. Chemical costs and pre-harvest machinery costs are nearly equal at around 4 to 6 percent in Illinois and Michigan. In Oklahoma, however, pre-harvest machinery costs are 7 to 9 percent of the total, much higher than chemical costs at 2 percent (see table 8 for a summary of machinery cost assumptions). The share of land costs for low input prairies depends substantially on the type of land used. When mixed prairie grasses are planted on marginal land, land costs account for 16 to 20 percent in Oklahoma, 25 to 27 percent in Michigan, and 29 to 34 percent in Illinois. However, when cropland is used, the share of land costs can be 42 to 51 percent in Michigan and Oklahoma, and 57 to 62 percent in Illinois.

For hybrid poplar, in Illinois and Michigan, the dominant component is also harvesting, making up 77 to 85 percent of the total, followed by preharvest machinery costs and seed costs at 6 to 12 percent each. In Oklahoma, harvesting is still the largest cost component, but only makes up 34 to 57 percent. Preharvest machinery costs and chemical costs are the second and third largest components in total operating costs in Oklahoma, but they are significantly higher than in Illinois and Michigan, ranging from 22 to 34 percent for preharvest costs and 19 to 27 percent for chemical costs. In Oklahoma, the share of land costs is just more than 20 percent when poplars are planted on marginal land and 51 to 56 percent when planted on cropland. In Illinois and Michigan, the share of land costs is relatively low when poplar is planted on marginal land, at 17 percent in Michigan and 23 percent in Illinois. Even when cropland is used for poplar production, the costs of land still account for about 32 percent of the total costs in Michigan, and around 49 percent in Illinois.

We also examined the sensitivity of the farm-gate breakeven prices of biofuel feedstocks including the opportunity cost of land to changes in the prices of corn, soybean, seed, and fertilizer, crop and biomass yield, harvest costs, preharvest machinery expenses, and discount rate. The breakeven prices of biofuel feedstocks planted on cropland are also affected by the value placed on corn stover when estimating the opportunity cost of land. The sensitivity of breakeven prices to stover values is ignored in this study since, as shown in Jain et al., the effect is very modest on average, ranging between 3 and 7 percent across grass species and the Midwestern states.[13] Complete results of the sensitivity analysis can be found in Appendix D.

CONCLUSION

We found that the breakeven costs of production of various biomass feedstocks differ widely across feedstocks, regions, and scenarios depending on the ease of establishing and harvesting them. The farm-gate costs of biomass feedstocks vary dramatically from $35/MT for miscanthus in the low-cost scenario on marginal land in Oklahoma to $389/MT in hybrid poplar in the high-cost scenario on cropland, also in Oklahoma. In general, corn stover is less costly than most dedicated energy crops (on cropland) under a rotation corn system, with production costs ranging from $51/MT under a rotation corn system with no till in Michigan to $114/MT under a rotation corn system with conventional till in Oklahoma. We also found no significant difference in costs of stover production in the rotation corn system with a no-till practice across the three study states. However, under a monoculture corn system, the costs of stover collection increase substantially, and in Oklahoma, in particular, the cost of stover collection with monoculture corn system is dominated by the opportunity cost of land, which makes up 47 to 60 percent of the total. This suggests that farmers in these states do not have an economic incentive to convert their production system from rotation corn to monoculture corn simply for greater stover collection unless the price of corn stover or subsidies for biomass provision are high enough to compensate for the opportunity cost of the conversion.

The production of corn stover was restricted to sustainable levels to preserve soil quality and water quality by preventing run-off. If there is interest in preventing farmers from collecting excessive residues, they will need to be compensated for the foregone income from corn stover. This analysis shows their potential income from stover collection and the compensation they will need for reducing the level of stover harvested. Sensitivity analysis can be used to determine the payments that would be needed to prevent harvest levels from being even higher than levels considered here.

We also analyzed the sensitivity of the breakeven prices of biomass feedstocks to various parameter changes and found that when biomass feedstocks are produced on cropland, breakeven prices are most sensitive to corn and soybean prices changes. When planted on marginal land, breakeven prices are most sensitive to changes in biomass yields and harvest costs. Moreover, biomass feedstocks with longer lifetimes are more price sensitive to changes in discount rate.

The breakeven costs estimated, together with information about the market price of biomass, can be used to determine the extent to which farmers would need to be compensated through subsidies to produce biomass from various sources on marginal and average cropland. The subsidy needed will depend on the relevant costs of production, yields, and crop prices.

As shown in figures 1 and 2, the lowest cost biomass production would occur in Oklahoma, where the breakeven cost is $35/MT DM with miscanthus. At a biomass price of $50/MT DM, it would be profitable to produce miscanthus on marginal land in Illinois and Oklahoma, switchgrass on marginal land in Oklahoma, and even miscanthus on cropland in Oklahoma if the low cost scenario prevails. If the production of other energy crops is desired for environmental reasons or if the costs of production of miscanthus and switchgrass turn out to be high, the subsidy required for production can be calculated as the difference between the breakeven price and the market price of biomass. If the market price of biomass happens to be high, say, $60/MT DM, it would also be profitable to produce miscanthus in Michigan and switchgrass in Illinois on marginal land in the low-cost scenario, and harvest corn stover in all three states from rotation corn with no-till practice without any subsidies.

Figure1: Breakeven Cost Including Marginal Land Rent at Farmgate ($/Mg DM)

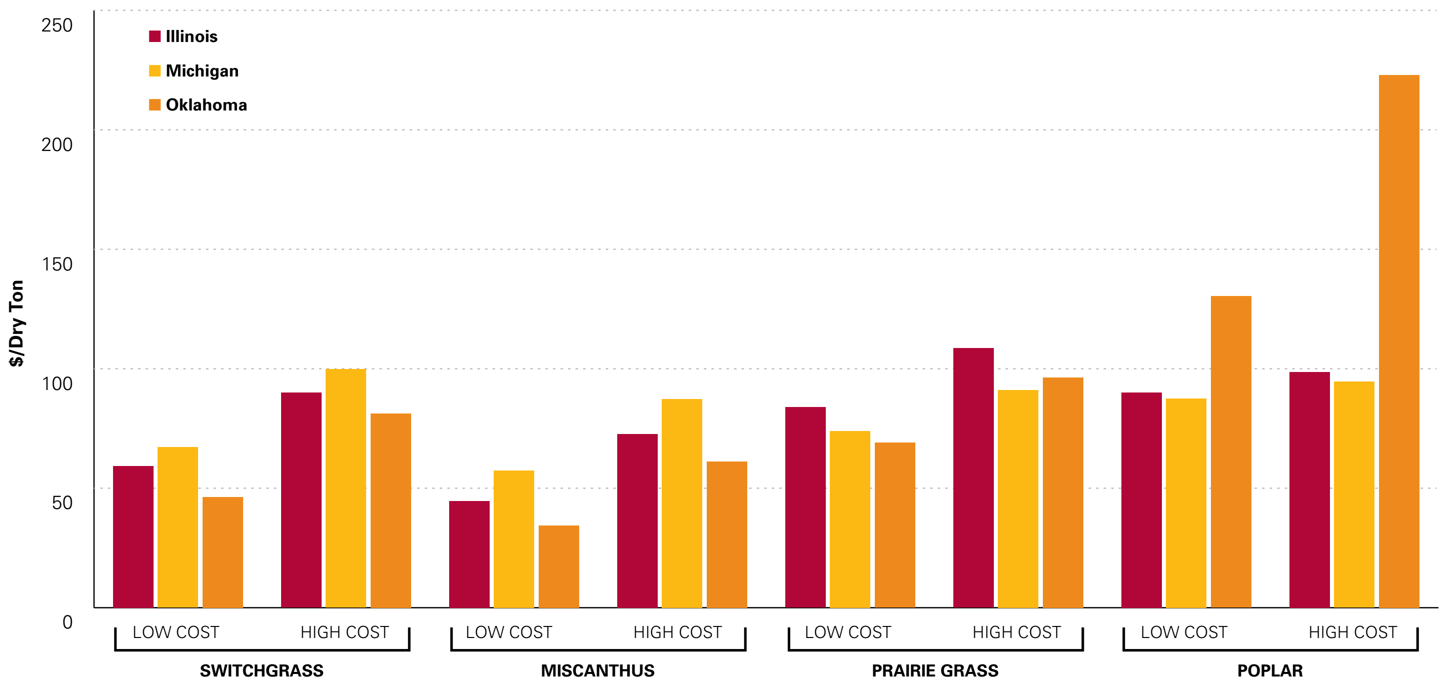
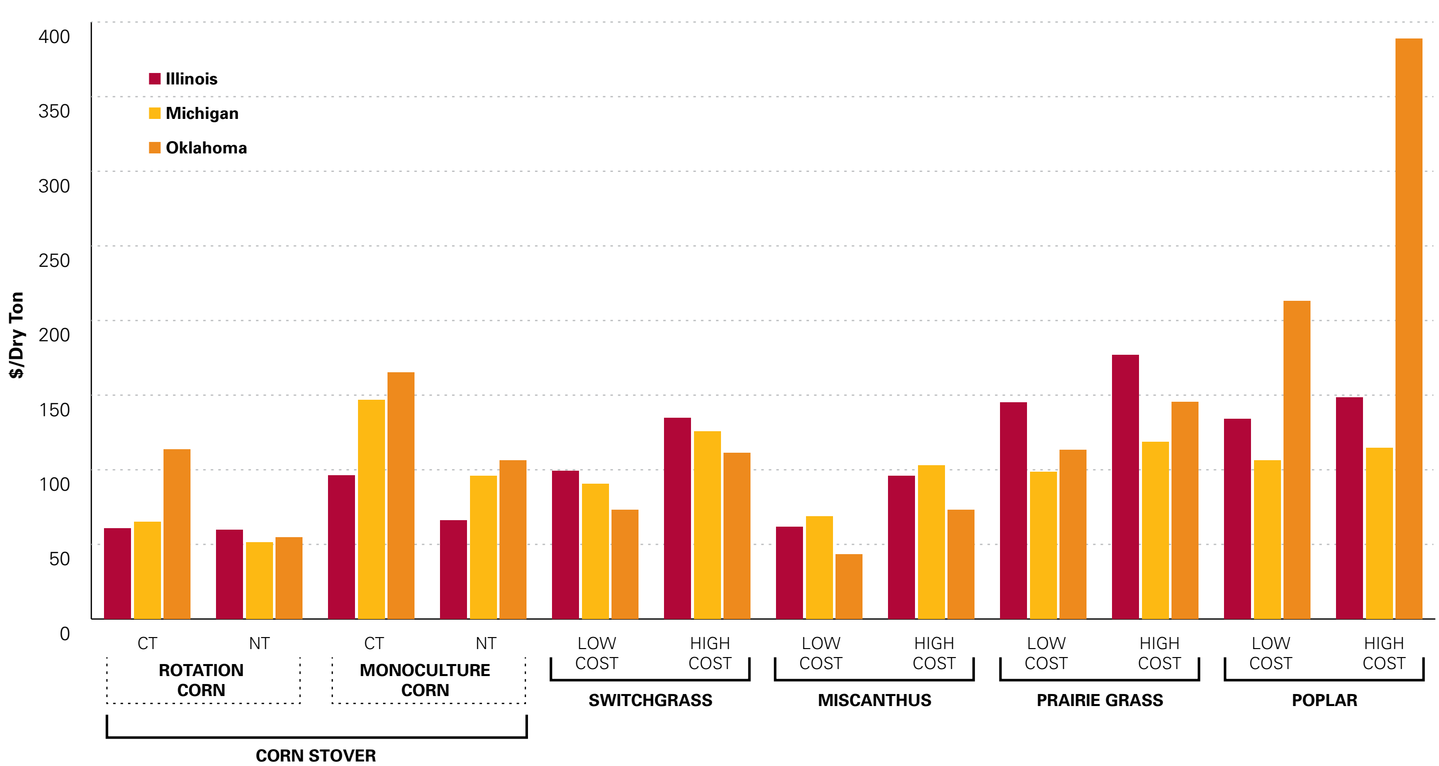


Figure 2: Breakeven Cost Including Cropland Rent at Farmgate ($/Mg DM)



CT = conventional tillage NT = no till

If the production of energy crops is desired on cropland as a mechanism to reduce soil erosion and nitrogen leaching and increase biodiversity, considerable subsidies would be required. In particular, at a biomass price of $50/MT, the subsidies required to induce production of a high yielding perennial like miscanthus, would range from $12 to $19/MT if the costs of production are low, and $23 to $52/MT if they are high. Mixed prairie grasses have attracted attention due to their LIHD attributes. Considerably high subsidies ($19/MT to 34/MT) would be required to motivate landowners to grow mixed grasses even on marginal land if their production costs are low. These would be even higher if production costs turn out to be high and/or policy makers seek to induce their production on cropland.

For example, in the low-cost scenario, the subsidy needed to trigger production of mixed prairie grasses as bioenergy feedstocks on cropland (if the market price of biomass is $50/MT) is $95/MT in Illinois, $49/MT in Michigan, and $63/MT in Oklahoma. Also in the low-cost scenario, the subsidy needed for poplar production on cropland is $84/MT in Illinois, $56/ MT in Michigan, and $163/MT in Oklahoma.

The production of perennials involves lags between planting and harvest, upfront investment in establishment of these crops, and risks and uncertainty about returns over the life of the perennial. The subsidies estimated here are based on a comparison of the breakeven cost of producing a bioenergy crop with the market price of biomass, and ignore farmers' cash flow constraints and concerns about the riskiness of the investment. To the extent that these are significant barriers to investment in perennial crops, per unit output based subsidies may need to include a risk premium and be larger than those estimated in this study. They may also need to be supplemented by subsidies that share the establishment costs and reduce the upfront investment needed in perennials by a landowner.

Endnotes

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APPENDIX A: HERBACEOUS FEEDSTOCKS, YIELDS, HARVESTING, AND STORAGE REQUIREMENTS

HERBACEOUS FEEDSTOCKS

Corn stover. Corn stover yields are closely related to corn grain yields. There is a consistent grain-to-residue ratio of 1:1 for the amount of crop grain dry matter to crop residue dry matter (with 15 percentmoisture).[1] Because biomass returned to the soil is valuable for building soil organic matter and protecting against wind and water erosion, a fraction of the biomass produced is usually left on-field. Recommended stover removal rates depend on soil characteristics, climate, tillage, and other factors that determine the loss of soil organic matter and run-off. Assumed rates of removal range from 38 to 70 percent. One study estimated that 50 percent of the residue can be removed from fields with no-till or conservation tillage, and 30 percent can be removed with till or conventional tillage.[2]

Using these removal rates and 2007 crop yields for corn in the study states, under a monoculture corn system with no till, the average delivered yield for corn stover is the highest in Illinois at 3.41 metric tons of dry matter per hectare (MT DM/ha), followed by Michigan at 2.69 MT DM/ha, and Oklahoma at 1.84 MT DM/ha. For conventional tillage, the rates are 2.05 MT DM/ha for Illinois, 1.61 MT DM/ha for Michigan, and 1.10 MT DM/ha for Oklahoma. The removal of corn stover from the soil has to be supplemented with additional fertilizer application to replace lost nutrients and soil organic matter. Higher rates of stover removal result in higher nutrient application costs, and also increase the likely loss of soil organic matter. Some studies indicate that the harvest of even 25 percent of corn stover could reduce soil organic carbon by 3 MT DM/ha to 8 MT DM/ha in the top 30 cm of soil within the first few years.[3]

Miscanthus. A perennial rhizomatous grass, miscanthus, has the potential for high yields, low input requirements, and several environmental benefits. This variety is a sterile, triploid clone of the species, with a life span of 15 to 20 years. It is a cross between two different miscanthus species, *sinensis and sacchariflorus*, and has three sets of chromosomes instead of the normal two, which makes it sterile. It has been grown in the European Union on a large scale for more than 20 years with no evidence of becoming invasive.

Miscanthus is highly efficient at converting solar radiation to biomass and using nutrients and water, and has good pest and disease resistance. It is planted using rhizomes, and field trials indicate that miscanthus has the potential for relatively high yields in the rainfed regions of the United States. It has a life-time of 14 to 18 years; the first two years are the establishment phase. Miscanthus biomass accumulation normally achieves maximum potential between August and October, following which the plant senesces. Studies in Europe have shown that miscanthus does not respond to annual N fertilization.[4] Translocation of inputs prior to senescence of the above ground tissues reduces overall nutrient use, ash content, and moisture content while improving the suitability of the biomass as a fuel for combustion. Similarly, field trials have not found a strong miscanthus response to applications of potassium, phosphorus, or calcium. However, harvest is expected to remove some nutrients from the crop ecosystem and the long-run nutrient requirements to maintain soil fertility are unknown. Research also suggests that miscanthus could host N-fixing bacteria, which enable it to meet its annual N requirement.[5] Some studies, however, include applications of nitrogen, potassium, phosphorus, and lime to replenish soil reserves, especially on soils with lower fertility.

Simulations using a crop productivity model, MiscanMod, show that the biomass yield of miscanthus is high in the Atlantic states and low in the western states due to insufficient soil moisture.[6] Because of climate differences, Southern states generally have higher yields compared to northern states. The average delivered yields and standard deviation (SD) of miscanthus are the highest in Oklahoma at 29.54 ± 5.59 MT DM/ha, followed by Illinois at 25.16 ± 3.88 MT DM/ha, and Michigan at 15.45 ± 4.46 MT DM/ha.

Switchgrass. This grass grows primarily in the summer months; like miscanthus, it is relatively highly efficient at converting solar radiation to biomass and using nutrients and water; it also has good pest and disease resistance. It is planted using seeds, has a stand life of 10 years or more, and production during the first year or two could be only a fraction of the production achieved in the remaining years. Yields vary considerably according to variety. Cave-in-Rock switchgrass is an upland variety that originated in southern Illinois and is cold-tolerant and well-suited to the upper Midwest. Lowland varieties, like Alamo, are best suited to the southern United States, and typically yield about 50 percent more than the upland variety. Analysis of data from field trials across the United States shows that frequency distributions of yield for the upland and lowland varieties were unimodal, with mean (±SD) biomass yields of 8.7 ± 4.2 and 12.9 ± 5.9 MT DM/ha for the two varieties, respectively. Yields for single harvest in plot trials in Oklahoma range from 8.65 ± 1.57 MT DM/ha to 12.34 ± 1.68 MT DM/ha, depending on nitrogen applications, while yields with commercial scale production range between 3.4 MT DM/ha in Iowa and 7 MT DM/ha in the upper plain states. Other models showed simulated yields of 11.2 MT DM/ha, and onefound yields ranged between 6 MT DM/ha and 17 MT DM/ha in Michigan.[7]

Field studies show that switchgrass has half the nitrogen uptake of miscanthus, and that N-fixing bacteria do not contribute substantially to the annual N requirements of the plant.[8] Unlike miscanthus, switchgrass yields respond to nitrogen applications, but nitrogen requirements vary depending on site-specific conditions. However, trials conducted across the United States have not found a positive response to phosphorus, potassium, and calcium applications.

Switchgrass yields may be about half those of miscanthus in most locations. The MiscanMod model-simulated average delivered yields and SDs in Illinois, Michigan, and Oklahoma are 10.74 ± 1.23 MT DM/ha, 7.53 ± 0.58 MT DM/ha, and 9.70 ± 1.53 MT DM/ha, respectively; these are within the range reported in the literature.

Mixed Prairie Grasses. Mixed prairie systems may be planted to increase biodiversity and improve soil structure, and there are hundreds of species of grasses native to U.S. prairies. Mixed prairie grasses typically consist of various species with different plant types such as C4 grass, forb, and legume. Commonly planted prairie grass species in the study regions include:

- Bermuda grass, a long-lived warm season perennial that spreads by rhizome and seed
- Flaccid grass, which is an upright, tall, weak, bunch type perennial rhizomatous subtropical, warm-season forage grass
- Weeping love grass, a warm-season bunchgrass characterized by quick germination, an active growth period in the summer, high drought tolerance, production of thick mass of vegetative soil cover, and a deep penetrating root system
- Big bluestem, which is a perennial warm-season grass dominant in Midwestern tallgrass prairies
- Indian grass, which is a native, warm-season grass that can endure a wide range of weather extremes and is easily established from seed
- Showy tick trefoil, which is a tall, native, perennial, warm-season legume used as a small component in a seeding mixture for prairie restoration

YIELDS

A field experiment in Minnesota showed that plots with 16 grassland species (low-input, high- diversity LIHD) achieved 238 percent more bioenergy (measured as biomass multiplied by energy release upon combustion) per hectare than monoculture switchgrass on highly degraded soil with no fertilization.[9] Adler et al. found that biomass yield decreased with greater plant species richness, and the composition of the resulting biomass also led to a reduction in biofuel yield per unit biomass.[10] The inclusion of tall, native C4 prairie grasses that are highly competitive and efficient users of inputs and legumes for nitrogen fixation are critical for biomass productivity with low input applications.[11]

Prairie grass yields also vary significantly according to location, species, fertilizer application, and number of harvests per year. According to a University of Illinois database of reported yields, harvested yields of specific prairie grasses in the United States ranged from about 1.5 MT DM/ha for cool-season grass and legume pastures in southwest Michigan to 19.2 MT DM/ha for Indian grass with a nitrogen application rate of 220 kg N/ha in Iowa.[12] However, there is a paucity of field studies on yields of mixed prairie grass systems. Tilman, et al. found that plant species composition and diversity have an important effect on the yield of low-input prairie grass mixtures, with LIHD achieving yields as high as 3.7 MT/ha/yr on degraded and 6.0 MT/ha/yr on fertile soils in Minnesota.[13] On the other hand, Adler, et al.[14] found that high diversity prairie systems may lead to decreased biomass yield based on their field studies at multiple sites in the northeast United States; however, the authors provide no specific yield estimates for prairie mixes with different numbers of plant species.

The delivered yield of mixed prairie grasses in Illinois using the DayCent model (used by the Department of Agriculture and Environmental Protection Agency to create a national inventory of N_2O emissions from U.S. agricultural soils) is 7.02 (3.95 to 10.24) MT/ha/yr in Illinois, while the delivered yield of mixed prairie grasses is 7.53 MT/ha/yr in Michigan, and that of native prairie grasses 4.1 MT/ha/yr.[15] These studies assume no nitrogen application. There is no information available on yields of mixed grasses in Oklahoma. For individual species, Aravindhashan et al.[16] reported that harvested yield with a single harvest and minimum nitrogen application was 4.95 MT/ha/yr ± 1.32 MT/ha/yr for bermuda grass, 8.4 MT/ha/yr ± 1.28 MT/ha/yr for flaccid grass, and 5.98 MT/ha/yr ± 0.9 MT/ha/yr for love grass in Oklahoma. Averaging these individual grass yield estimates,and accounting for storage losses, the delivered yield of mixed prairie grasses in Oklahoma is derived to be 5.89 Mg/ha/yr. See table 1 for full results.

Table 1: Delivered crop yield							
Yield	Unit	Illinois		Michigan		Oklahoma	
		Low-cost	High-cost	Low-cost	High-cost	Low-cost	High-cost
Corn	bushel/acre	156.24		122.97		84.24	
Soybean	bushel/acre	43.92		35.7		27.02	
Stover (RC, CT)	Mg DM/ha/yr	1.16		0.92		0.63	
Stover (RC, NT)	Mg DM/ha/yr	1.94		1.53		1.05	
Stover (MC, CT)	Mg DM/ha/yr	2.05		1.61		1.10	
Stover (MC, NT)	Mg DM/ha/yr	3.41		2.69		1.84	
Switchgrass	Mg DM/ha/yr	10.74	9.61	7.53	6.74	9.70	8.68
Miscanthus	Mg DM/ha/yr	25.16	18.46	15.45	11.33	29.54	21.68
Prairie grass	Mg DM/ha/yr	7.02	6.28	7.13	6.38	5.89	5.27
Poplar	Mg DM/ha/yr	9.74	8.63	9.40	8.72	3.15	1.57

RC = Rotation corn; MC = Monoculture corn; CT = Conventional tillage; NT = No tillage.

HARVESTING AND STORAGE

Farm activities after establishment of an energy crop include mowing, raking, baling, and storage. A single annual harvest results in lower costs than two harvests a year for perennial grasses, including switchgrass and miscanthus.[17] Delaying the harvest of switchgrass and miscanthus until after senescence reduces the need for nutrient application in the subsequent year, reduces drying time, and improves biomass quality. However, waiting to harvest until after senescence also decreases harvestable yield by 20 to 40 percent for miscanthus and 15 to 20 percent for switchgrass compared to peak levels in September to October.[18] The yield and profitability gains with a single harvest versus two harvests may differ for other prairie grasses; some, such as bermuda grass, have high after-harvest growth and fast recovery after a harvest in July at all levels. Flacid grass and love grass yields with two harvests are higher than with a single harvest, but only with high levels of nitrogen application. The economics of harvesting more than once a year for mixed prairie systems are yet to be determined.

Perennial grasses can be harvested using conventional hay harvesting equipment, although more specialized equipment is being developed. A short (four-month) harvest window requires considerable investment in harvest equipment.

One approach for reducing harvesting costs is to extend the harvesting window, which spreads the fixed costs of the harvest machines over more hectares and reduces storage time for harvested material. To maintain productivity, additional fertilizer applications are needed for fields harvested prior to senescence, and biomass yields are lower for fields harvested later.[19] The harvesting window could also be extended by having a mix of different feedstocks, assuming a biorefinery can process a variety of feedstocks. Mapemba et al. considered the possibility of an extended harvest system from June through February, with wheat straw harvested in June and July, corn stover in September and October, and perennial grasses from July through the following spring.[20] They found it possible to allocate harvest equipment so that capital investment in harvest machines was reduced by 50 percent. However, results were based on assumptions about harvest days available, which depend on the weather, the condition of the soil (e.g., sufficiently dry soil to hold the weight of the harvest equipment), and the moisture content of the grass. A reduction in harvest days due to weather could limit flexibility for scheduling harvest equipment optimally and result in substantially higher harvesting costs.

Biomass can be stored after harvest in several ways. In on-farm open air storage systems, biomass is unprotected on the ground, on crushed rock, or covered by a reusable tarp. On-farm covered storage options include a pole frame structure with open sides on crushed rock or an enclosed structure on crushed rock. The loss in biomass is highest when it is left unprotected and lowest in an enclosed structure. Losses depend on the number of days the biomass is stored and need to be weighed against the costs of installation, land, labor, and materials, as well as the biomass quality required by the biorefinery. A centralized covered storage facility could be shared by many farms, but would result in biomass handling and transportation costs to move the biomass from the farm to the facility. The optimal storage choice depends on the volume of biomass and the length of time it has to be stored, the price of biomass, the quality of biomass required, and regional weather conditions.[21]

WOODY BIOMASS

Hybrid Poplar. Short rotation woody crops, in particular hybrid poplar and willow, are also being considered for biomass production. Hybrid poplar and willow are planted using cuttings, or scions, and have 6- to 10-year rotations. The majority of poplars planted are either unrooted hardwood cuttings or bareroot stock, with planting time in May to early June in the northern United States. Weed control in the early years is essential for poplar growth and survival, and can be achieved by hand-weeding, cultivation, mowing, cover crops, using herbicides, and mulching, depending upon the landowner's resources and philosophy. Poplars planted in large areas can suffer from insect problems; these can be controlled by diversifying the species planted, using insecticides, and practicing integrated pest management. Possible animal browsing may require investment in fencing.

Poplars require a high level of nutrients to maintain maximum productivity; if nutrients or water are limited, poplar growth is significantly decreased. The formulation and quantity of fertilizer, the timing of fertilization, and the number of applications are all important for maximizing nutrient take-up by poplars and minimizing nutrient run off. Fertilizers can be applied at any time during the rotation, and once the poplars are established, soil analyses and foliar analysis are the most economical and effective way to diagnose nutrient deficiencies. Poplars sprout readily from a stump or root collar when cut; this re-sprouting is known as coppicing. Coppicing, which should be done in the dormant season, is an inexpensive way to re-establish a poplar stand without replanting. Though landowners may choose to replant improved varieties rather than coppice, coppicing can be productive and often provides higher yields than the original stand in the first five years after harvest.

Poplar stands should be harvested when their annual growth increment begins to decline. There are several options for harvesting, which vary greatly in cost and energy use and range from low-tech labor-intensive methods to sophisticated high-tech harvesting machines and chippers. In the northern states, poplars should be harvested in the winter to minimize soil compaction and maximize resprouting. Winter is also a better time for harvest because foliage is left on site to recycle essential nutrients and organic matter. The choice of a harvest system depends upon the planting area, tree size, and landowner objectives. For relatively small areas, a labor-intensive system or a small tractor can be used, while large areas may require a highly mechanized approach. For bioenergy there are mobile whole tree chippers under development.

Post-harvest, a farmer can kill the stumps of the former planting with herbicide and replant with new improved poplar clonal stock. Stumps can be removed by a bulldozer or left as is if the site is replanted within the old rows. Another post-harvest option is to maintain the subsequent stand as a coppice stand, which may be suitable when poplar is grown for bioenergy. Each stump will have multiple stems, and a coppice stand will be more productive than the old stand. Biomass yields in Minnesota ranged from 5.8 MT/ha/yr to 10.1 MT/ha/yr, and currently operational plantings in Minnesota yield more than 9.0 MT/ha/yr. A goal of 15 MT/ha/yr has been set by geneticists for new poplar clones in the future. Other studies report delivered yields of poplar of 7.3 MT/ha/yr and 13.4 MT/ha/yr in the United States.[22] One study found that poplar variety NM6 yielded 8.3 MT/ha/yr in the Upper Peninsula of Michigan over 10 years.[23]

Based on the maximal annual yields and the rotation to achieve the maximal yields projected by Wang et al., the delivered yields and SDs of hybrid poplar are 9.74 ± 1.12 Mg/ha/yr with a 10-year rotation in Illinois, 9.4 ± 0.69 MT/ha/yr with an 8-year rotation in Michigan, and 3.15 ± 1.58 MT/ha/yr with a 6-year rotation in Oklahoma.[24]

APPENDIX B: METHOD FOR DETERMINING BREAK-EVEN PRICES

More specifically, as described in Jain et al. we calculated 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 percent. We similarly calculated 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. Note that Y_t is yield after losses during harvesting and storage in year t and the annualized yields after losses during harvesting and storage as yield at farm-gate. The breakeven farm-gate price P_B ($ per ton of dry matter) 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 equal to the present value of costs of producing the crop over its life as follows:

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

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

where T is the life of the crop, C_t is the cost of the bioenergy crop per hectare in period t, and d is the discount rate. C_t includes the cost of producing the crop at time t (C_{pt}) and opportunity cost of land (C_{Lt}), both measured in $ per hectare.

We estimated C_{Lt} as follows: $C_{Lt} = (P_{ct}*Q_{ct} - C_{ct} + P_{st}*Q_{st} - C_{st})/2$ where P_{ct}, Q_{ct} and C_{ct} are the price ($ per metric ton), yield (metric tons of dry matter per hectrare) and production cost of corn ($ per hectare), respectively while P_{st}, Q_{st} and C_{st} are the corresponding values for soybeans at time t. For marginal land that is currently idle, we used the average soil rental rate for land enrolled in the Conservation Reserve Program (CRP) in the given state as a proxy for the opportunity cost of that land.

DATA AND ASSUMPTIONS

We developed state-specific enterprise budgets of the costs of the eight biomass feedstock production systems (see table 2) over their lifetime for Illinois, Michigan, and Oklahoma. Specifically, we estimated rotation and tillage-specific costs of production in 2007 prices for corn, soybeans, corn stover, switchgrass, miscanthus, native perennial grass mix, and hybrid poplar for each state.

Table 2: Biofuel Production System

System	Description
I. Rotation corn with CT	A corn-soybean rotation with 30% stover removal rate
II. Rotation corn with NT	A corn-soybean rotation with 50% stover removal rate
III. Monoculture corn with CT	A corn-corn rotation with 30% stover removal rate
IV. Monoculture corn with NT	A corn-corn rotation with 50% stover removal rate
V. Switchgrass	Switchgrass production on cropland/marginal land
VI. Miscanthus	Miscanthus production on cropland/marginal land
VII. Native prairie grasses	Native prairie grasses on cropland/marginal land
VIII. Wood biomass	Hybrid poplar production

CT: conventional tillage; NT: no tillage.

AGRONOMIC ASSUMPTIONS

Corn stover yields are estimated based on a grain-to-residue ratio of 1:1 and a moisture content of 15 percent in grains.[25] We also assumed that corn yield in a monoculture corn system is 88 percent of the yield level achieved in a rotation corn system. The application rates of N, P, and K to replace the loss of nutrients and soil organic matter due to the removal of each dry metric ton of stover are assumed to be 3.5, 0.8, and 7.6 kg, respectively.[26] Similar to Malcolm, we assumed that 50 percent of stover can be removed from fields if no tillage is practiced and 30 percent can be removed if conventional till is used.[27] The delivered corn stover yield is also subject to a 7 percent storage loss, as is the case for biomass feedstocks.

In estimating the costs of miscanthus and switchgrass we relied on agronomic assumptions about fertilizer, seed, and pesticide application rates described in Jain et al.[28] As shown in table 3, both high-cost and low-cost scenarios were included to allow flexibility in input requirements for these variables. The low-cost scenario includes a low fertilizer application rate, low replanting probability, high second-year yield, and low harvest loss, while the high-cost scenario represents the opposite. In both scenarios, we assumed a lifespan of 10 years for switchgrass and 15 years for miscanthus as suggested in numerous studies.[29]

Table 3: Agronomic assumptions for switchgrass and miscanthus production

	Switchgrass	Miscanthus
Establishment year		
Planting density (rhizome m-2)	-	1
Seeding rate (kg per ha)	6.5 LC to 11 HC	-
Planting time	February to March	March to April
Nitrogen (kg per ha)	0	30 LC to 60 HC
Phosphorus (kg per ha)	33.7	7
Potassium (kg per ha)	44.9	100
Lime (Mg per ha)	0 LS to 6.7 HC	2.3 LC to 4.5 HC
Atrazine (Herbicide) (L per ha)	3.5	3.5
2,4-D (Herbicide) (L per ha)	1.8	1.8
Post-establishment years		
Replanting rate in year 2 (%)	15 LC to 50 HC	15 LC to 50 HC
Nitrogen (kg per ha)	56 LC to 140 HC	25 LC to 50 HC
Phosphorus (kg per ha)	0.42 LC to 0.97 HC*	7
Potassium (kg per ha)	9.47 LC to 11.40 HCa	100
Atrazine (Herbicide) (L per ha)	0 LC to 3.5 HC	0
2,4-D (Herbicide) (L per ha)	1.8	0
Percent of peak biomass yield:		
Year 1 (%)	100 LC to 30 HC	0
Year 2 (%)	100 LC to 67 HC	50 LC to 40 HC
Year 3 and after (%)	100	100
Yield loss at harvest (%)	20	20 LC to 40 HC
Harvest timing	After first frost	December or early Spring
Moisture at harvest (%)	15	15
Life of crop (years)	10	15

LC = low-cost scenario; HC = high-cost scenario.
[a]Application rate is measured in kg Per Mg DM of biomass removed.

Similarly, based on James et al. and Haque et al., we developed state-specific low- and high-cost scenarios for prairie grass mixes with different agronomic assumptions about the reseeding rate and harvestable yield in the first two years (see table 4).[30] For hybrid poplar, state-specific agronomic assumptions in the low-cost scenario are based on James et al, featuring low-input, no replanting, and low maintenance between planting and harvest. High-cost scenario assumptions are based on Lazarus, featuring low input for plant establishment but a 20 percent replanting rate and higher N fertilizer application and weed mowing for maintenance (see table 5).[31] A stand of poplar is assumed to last for two rotations and harvestable biomass yields for each of the two rotations are assumed to be the same. Assumptions about the lifetime of the poplar are described in table 4 and differ across states.

Table 4: Agronomic assumptions for prairie production

	Low-cost scenario	High-cost scenario
Species	Native prairie mix	Native prairie mix
Seeding rate (kg or bushel per ha)	9 kg	9 kg
Planting time	February-March	February-March
Nitrogen (kg per ha)	0	0
Phosphorus (kg per ha)	0	0
Potassium (kg per ha)	0	0
Lime (Mg per ha)	0	0
Atrazine (Herbicide) (L per ha)[a]	3.5	3.5
2,4-D (Herbicide) (L per ha)	1.8	1.8
Post-establishment years		
Reseeding rate in year 2 (%)	15	50
Nitrogen (kg per ha)	0	0
Phosphorus (kg per ha)	0	0
Potassium (kg per ha)	0	0
Atrazine (Herbicide) (L per ha)	3.5	3.5
2,4-D (Herbicide) (L per ha)	1.8	1.8
Percent of peak biomass yield:		
Year 1 (%)	85	30
Year 2 (%)	100	67
Year 3 and after (%)	100	100
Yield loss at harvest (%)	20	20
Harvest timing	October	October
Moisture at harvest (%)	15	15
Life of crop (years)	10	10

[a]Atrazine is used in Illinois and Michigan only.

Table 5: Agronomic assumptions for hybrid poplar production		
	Low-cost scenario	**High-cost scenario**
Establishment year		
Seeding rate (cuttings per ha)	2717	2717
Planting time	March to April	March to April
Nitrogen (kg per ha)	0	0
Phosphorus (kg per ha)	0	0
Potassium (kg per ha)	0	0
Lime (Mg per ha)	0	0
Atrazine (Herbicide) (L per ha)[a]	3.5	3.5
2,4-D (Herbicide) (L per ha)	1.8	1.8
Post-establishment years		
Replanting rate in year 2 (%)	0	20
Nitrogen (kg per ha)[b]	0	25
Phosphorus (kg per ha)	0	0
Potassium (kg per ha)	0	0
Atrazine (Herbicide) (L per ha)[c]	3.5	3.5
2,4-D (Herbicide) (L per ha)[d]	1.8	1.8
Harvest in year[e]	6 to 20	6 to 20
Peak Biomass yield (%)	100	One standard deviation lower
Yield loss at harvest (%)	15	15
Harvest timing	October-November	October to November
Number of rotation	2	2
Stump removal in year[f]	12 to 20	12-20
Stump removal timing	November-December	November-December
Moisture at harvest (%)	50	50
Overall stand life (years)[g]	12 to 20	12 to 20

[a]Atrazine is used in Illinois and Michigan only.
[b]Nitrogen is applied in years 4,6,8,14,16 and 18 in Illinois, years 4,6,12 and14 in Michigan, and years 4 and 10 in Oklahoma.
[c]Atrazine is used in years 2, 11 and 12 in Illinois and years 2, 9 and 11 in Michigan.
[d]2,4-D is used in years 2, 11 and 12 in Illinois, years 2, 9 and 11 in Michigan, and years 2, 7 and 8 in Oklahoma.
[e]Poplar is harvested in years 10 and 20 in Illinois, years 8 and 16 in Michigan, and years 6 and 12 in Oklahoma.
[f]Poplar stump is removed in year 20 in Illinois, year 16 in Michigan, and year 12 in Oklahoma.
[g]Overall stand life is 20, 16 and 12 years in Illinois, Michigan and Oklahoma, respectively.

APPENDIX C: FERTILIZER APPLICATION RATES AND INPUT PRICES

Fertilizer application rates in table 6 and input prices in table 7 are from the crop budgets compiled for each state by state extension services with tillage or inflation adjustments.[32] Seed prices for switchgrass and mixed prairie grasses in Michigan are from James et al., and we assumed that seed prices for the two perennial systems are the same in Illinois and Oklahoma.[33]

Table 6: Fertilizer applications for corn and soybeans with stover removal

Crop	State	N (kg/ha)	P (kg/ha)	K (kg/ha)
Rotation corn with CT	Illinois	196	79	68
	Michigan	136	75	210
	Oklahoma	105	24	10
Rotation corn with NT	Illinois	198	72	79
	Michigan	144	62	148
	Oklahoma	109	24	17
Monoculture corn with CT	Illinois	204	70	60
	Michigan	161	61	183
	Oklahoma	93	21	9
Monoculture corn with NT	Illinois	205	63	69
	Michigan	169	51	129
	Oklahoma	96	22	15
Soybean with CT	Illinois	0	42	141
	Michigan	0	40	160
	Oklahoma	0	0	0
Soybean with NT	Illinois	0	54	138
	Michigan	0	38	222
	Oklahoma	0	0	0

Table 7: Crop and input prices				
Prices	**Unit**	**Illinois**	**Michigan**	**Oklahoma**
Corn	$/bushel	3.72	3.77	3.9
Soybean	$/bushel	9.09	8.59	8.48
Nitrogen	$/lb	0.349	0.49	0.35
Phosphorous	$/lb	0.303	0.29	0.5
Potassium	$/lb	0.273	0.25	0.22
Lime	$/ton	20	23	20
CRP payment	$/acre	80.35	57.98	32.67
Seed prices				
Switchgrass	$/lb PLS	11.09	11.09	11.09
Miscanthus	$/rhizome	0.25	0.25	0.25
Mixed grasses	$/lb PLS	36.31	36.31	36.31
Poplar	$/cut	0.22	0.22	0.22

$=U.S. dollars lb=pound

1. Corn and soybean prices are 2006-2008 averages and obtained from NASS.[a]
2. Fertilizer prices are obtained from crop budgets compiled by corresponding state extension services.
3. CRP payments are payment for general sign-ups in 2007 and obtained from the USDA Farm Service Agency.[b]
4. Miscanthus rhizome prices are obtained from Jain et al. and seed/cutting prices for switchgrass, mixed prairie grasses and poplar are obtained from James et al.[c]

[a]National Agricultural Statistics Service. *U.S. & All States County Data - Crops*. http://www.nass.usda.gov/Data_and_Statistics/index.asp. 2009. Accessed October 13, 2011.
[b]Graham RL, Nelson R, Sheehan J, Perlack RD, Wright LL. Current and potential U.S. corn stover supplies." *Agronomy Journal* 2007;99:1-11.
[c]James LK, Swinton S, Thelen KD. Profitability analysis of cellulosic energy crops compared with corn. Agronomy Journal 2010;102(2): 675-687; Jain AK, Khanna M, Erickson M, Huang H. An integrated bio-geochemical and economic analysis of bioenergy crops in the Midwestern United States. *Global Change Biology BioEnergy* 2010; 2(5):217-234.

Table 8: Assumptions for machinery costs of biomass production and harvest	Illinois	Michigan	Oklahoma
Preharvest Machinery repair, fuel and hire			
Chisel/Moldboard plowing ($ per ha)	33.11	33.66	30.89
Harrowing ($ per ha)	13.90	26.37	21.62
Seeder (switchgrass or prairie grass) ($ per ha)	24.71	21.38	24.71
Potato planter (miscanthus) ($ per ha)	77.26	70.19	77.26
Poplar planting ($ per ha)	614.21	614.21	614.21
Fertilizer spreader ($ per ha)	7.91	8.91	9.27
Spraying chemicals (atrazin and 2-4 D) ($ per ha)	12.73	13.30	9.88
Harvesting expenses			
Mowing/conditioning ($ per ha)	35.09	32.07	20.39
Raking ($ per ha)	11.12	14.25	7.78
Baling ($ Per Mg)	16.74	11.78	17.63
Staging and loading ($ Per Mg)	6.38	6.38	6.38
Storage ($ Per Mg)	3.22	3.22	3.22
Feller-buncher (poplar) ($ Per Mg)	14.06	14.06	14.06
Chipping/grounding (poplar) ($ Per Mg)	6.49	6.49	6.49
Stump removal (poplar) ($/Mg of biomass harvested)	14.64	14.64	14.64
Preharvest Machinery repair, fuel and hire			
Chisel/Moldboard plowing ($ per ha)	33.11	33.66	30.89
Harrowing ($ per ha)	13.90	26.37	21.62
Seeder (switchgrass or prairie grass) ($ per ha)	24.71	21.38	24.71
Potato planter (miscanthus) ($ per ha)	77.26	70.19	77.26
Poplar planting ($ per ha)	614.21	614.21	614.21
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Raking ($ per ha)	11.12	14.25	7.78
Baling ($ Per Mg)	16.74	11.78	17.63
Staging and loading ($ Per Mg)	6.38	6.38	6.38
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Feller-buncher (poplar) ($ Per Mg)	14.06	14.06	14.06
Chipping/grounding (poplar) ($ Per Mg)	6.49	6.49	6.49
Stump removal (poplar) ($/Mg of biomass harvested)	14.64	14.64	14.64

APPENDIX D: SENSITIVITY ANALYSIS

We examined the sensitivity of the farm-gate breakeven prices of biofuel feedstocks including the opportunity cost of land to changes in the prices of corn, soybean, seed, and fertilizer, crop and biomass yield, harvest costs, preharvest machinery expenses, and discount rate. The breakeven prices of biofuel feedstocks planted on cropland are also affected by the value placed on corn stover when estimating the opportunity cost of land. The sensitivity of breakeven prices to stover values is ignored in this study since, as shown in Jain et al., the effect is very modest on average, ranging between 3 and 7 percent across grass species and the Midwestern states. Table 10 summarizes the sensitivity of the breakeven prices of corn stover, and tables 11 and 12 report the sensitivity of breakeven prices of perennial biomass feedstocks with the inclusion of marginal land rent and the opportunity cost of cropland. In all three tables, sensitivity is reported as a percentage change relative to the benchmark estimates in table 9.[34]

Table 9: Breakeven cost of biomass feedstock production under benchmark case

Cost of biomass feedstock production	State	Corn stover[a]				Switchgrass	
		Rotation corn		Monoculture corn			
		CT	NT	CT	NT	Low-cost	High-cost
Breakeven cost including marginal land rent at farm-gate[a]	Illinois	Not Applicable				59.31	89.97
	Michigan					67.16	99.80
	Oklahoma					46.38	81.29
Breakeven cost including crop land rent at farm-gate	Illinois	60.71	59.81	96.34	66.03	99.35	134.69
	Michigan	65.12	51.33	146.93	95.78	90.43	125.80
	Oklahoma	113.71	54.76	165.19	106.26	73.20	111.24
Cost of biomass feedstock production	**State**	**Miscanthus**		**Prairie grass mix**		**Switchgrass**	
		Low-cost	**High-cost**	**Low-cost**	**High-cost**	**Low-cost**	**High-cost**
Breakeven cost including marginal land rent at farm-gate	Illinois	44.70	72.62	83.89	108.59	90.06	98.63
	Michigan	57.35	87.40	73.95	91.11	87.57	94.55
	Oklahoma	34.48	61.16	69.04	96.26	130.34	223
Breakeven cost including crop land rent at farm-gate	Illinois	61.79	95.89	145.15	177.01	134.16	148.46
	Michigan	68.70	102.86	98.54	118.57	106.20	114.65
	Oklahoma	43.28	73.15	113.22	145.61	213.00	389

CT = Conventional tillage; NT = No tillage.
[a]For corn stover, the costs of production in this case do not include opportunity cost of land.

Table 10 shows that the breakeven price of corn stover collected from a rotation corn system is most sensitive to changes in harvest costs. A 25 percent increase in harvest costs increases the breakeven price of stover by 12 to 21 percent since harvest costs are always the dominant component in the cost of stover collection in this rotation system. For stover collected from a monoculture corn system, because of the influence of the opportunity cost of land, the increase in the breakeven price of stover with a 25 percent increase in harvest costs is 9 to 17 percent, only slightly higher than changes to a 25 percent increase in crop yields and fertilizer prices. With a 25 percent increase in crop yields, the breakeven price of stover decreases by 5 to 13 percent when collected from a rotation corn system, and 5 to 13 percent when collected from a monoculture corn system. A 25 percent increase in fertilizer prices increases breakeven prices by 2 to 11 percent and 7 to 15 percent for stover collected from the two systems, respectively. A 25 percent increase in corn and soybean prices decreases the breakeven price of stover by 3 to 7 percent across all three states, suggesting that the opportunity cost of land for stover collected from the monoculture corn system decreases as crop prices rise.

Table 10: Percentage change in breakeven cost of corn stover relative to the benchmark

Scenarios	State	Corn stover			
		Rotation corn		Monoculture corn	
		CT	NT	CT	NT
25% Increase in corn-soybean price	Illinois		0.0%	-6.7%	-5.8%
	Michigan	0.0%		-6.0%	-5.5%
	Oklahoma	0.0%		-3.5%	-3.2%
25% Increase in crop yield	Illinois	-6.5%	-6.8%	-11.5%	-8.4%
	Michigan	-4.5%	-5.9%	-5.4%	-5.3%
	Oklahoma	-12.7%	-4.9%	-13.4%	-10.7%
25% Increase in fertilizer price	Illinois	4.1%	3.7%	12.6%	11.6%
	Michigan	11.1%	5.4%	15.0%	12.6%
	Oklahoma	2.0%	4.2%	6.9%	7.3%
25% Increase in harvest cost	Illinois	20.9%	17.9%	13.9%	16.9%
	Michigan	19.4%	19.6%	9.2%	11.1%
	Oklahoma	12.0%	20.8%	8.7%	11.1%

CT = Conventional tillage; NT = No tillage.

We did not include a sensitivity analysis for the impact of a change in the prices of corn and soybeans in table 11 since the opportunity cost of marginal land is fixed at the level of the CRP payments. Over time, however, CRP payments could change with sustained increases in crop prices and raise the opportunity costs of using land for energy crops.

Table 11 shows that breakeven prices of biomass feedstocks on marginal land are also generally insensitive to seed or fertilizer prices changes: when seed or fertilizer prices increase by 25 percent, the increase in breakeven prices of biomass feedstocks is less than 10 percent, with miscanthus in the high-cost scenario being most sensitive to seed price changes (a 6 to 9 percent increase in breakeven price across states), and switchgrass in the high-cost scenario most sensitive to fertilizer prices changes (6 to 8 percent). Breakeven prices of biomass feedstocks are generally most sensitive to crop/biomass yield and harvest cost changes. A 25 percent increase in biomass yields can reduce the breakeven prices by 9 to 14 percent for perennial grasses and 6 to 25 percent for poplar, while a 25 percent increase in harvest costs will lead breakeven prices to increase by 7 to 15 percent for perennial grasses and 7 to 17 percent for poplar.

It should be noted that input requirements are assumed to be essentially unchanged with changes in yield. As shown in tables 2 through 4, we assume seed/rhizome requirements and fertilizer and herbicide applications are determined on a per hectare basis (except for some nutrient application rates for switchgrass) instead of on a per MT basis. This is due to a lack of empirical evidence to support nutrient application rates that are related to biomass yield and may result in an over-estimate of the extent to which an increase in yield reduces breakeven costs.

Table 11 also shows feedstock prices are not sensitive to pre-harvest cost changes since the share of pre-harvest costs in total operating costs is relatively low for the feedstocks examined. In addition, changing the discount rate from 4 to 8 percent leads to a relatively smaller increase in the breakeven prices of switchgrass and mixed prairie grasses (1 to 6 percent), but the impact on miscanthus and poplar breakeven prices can be significantly larger, ranging between 8 and 17 percent because of their longer lifespan.

Table 11: Percentage change in breakeven cost (including marginal land rent) relative to the benchmark									
Scenarios	State	Switchgrass		Miscanthus		Prairie grass		Poplar	
		LC	HC	LC	HC	LC	HC	LC	HC
25% Increase in biomass yield	Illinois							-6.8%	-8.7%
	Michigan							-6.3%	-7.8%
	Oklahoma				-8.7%				
25% increase in seed price	Illinois	0.9%	1.5%	5.9%	6.4%	4.4%	5.0%	1.3%	1.6%
	Michigan	1.1%	1.9%	7.5%	8.6%	5.0%	5.8%	1.6%	1.9%
	Oklahoma	1.3%	1.8%	6.5%	6.5%	6.4%	6.7%	4.0%	5.6%
25% increase in fertilizer price	Illinois	4.4%	5.9%	2.1%	2.2%	0.0%	0.0%	0.0%	0.2%
	Michigan	5.2%	8.0%	2.8%	3.2%	0.0%	0.0%	0.0%	0.2%
	Oklahoma	5.5%	6.7%	2.1%	2.0%	0.0%	0.0%	0.0%	0.2%
25% increase in harvest cost	Illinois	6.9%	10.2%	7.7%	11.5%	6.5%	11.2%	16.5%	15.5%
	Michigan	6.8%	8.2%	6.5%	8.8%	7.3%	11.1%	17.1%	16.2%
	Oklahoma	8.1%	11.9%	9.4%	14.5%	7.2%	11.2%	11.5%	7.1%
25% increase in preharvest cost	Illinois	0.7%	0.7%	0.3%	0.5%	0.9%	0.8%	1.4%	1.8%
	Michigan	1.0%	0.9%	0.7%	0.7%	1.1%	1.0%	1.8%	2.2%
	Oklahoma	1.1%	0.8%	0.6%	0.3%	1.7%	1.4%	4.4%	6.2%
Change in discount rate from 4% to 8%	Illinois	0.9%	2.2%	8.5%	9.0%	3.3%	4.5%	9.6%	11.7%
	Michigan	1.1%	2.8%	10.6%	12.1%	3.6%	5.1%	7.6%	9.1%
		1.2%	2.4%	8.8%	8.6%	4.6%	5.5%	12.2%	17.1%

LC = low-cost scenario; HC = high-cost scenario.

Table 12 shows that when biomass feedstocks are produced on cropland, breakeven prices are most sensitive to corn and soybean price changes. A 25 percent increase in the price of corn and soybeans causes breakeven prices to increase by 11 to 35 percent for perennial grasses and poplar, with switchgrass and mixed prairie grasses in the low-cost scenario being the most impacted species with a breakeven price change around 30 percent on average.

An increase in biomass yields results in a substantial reduction in breakeven prices for all biomass feedstocks. The percentage reduction is larger when energy crops are planted on cropland compared to on marginal land. The implications of a reduction in yields of these feedstocks relative to the benchmark case are simply the inverse of the impact estimated in table 12. If switchgrass yields turn out to be 25 percent lower than in the benchmark case, costs would increase by 12 to 15 percent. On the other hand, the costs of mixed prairie grasses would increase 14 to 17 percent and of miscanthus 11 to 15 percent. The increase in costs would be much higher in the low-cost scenario than in the high-cost scenario where yields are relatively lower and thus the effects of a 25 percent increase is relatively smaller.

Table 12 also shows that the sensitivity of breakeven prices to other parameter changes is similar to the case when biomass is produced on marginal land, with breakeven prices most sensitive to changes in harvesting costs relative to other operating costs and the breakeven price of feedstocks with longer lifespans more sensitive to the increase in discount rate.

Table 12: Percentage change in breakeven cost (including cropland rent) relative to benchmark									
Scenarios	State	Switchgrass		Miscanthus		Prairie grass		Poplar	
		LC	HC	LC	HC	LC	HC	LC	HC
25% Increase in corn-soybean price	Illinois	28.4%	23.4%	19.5%	17.1%	29.7%	27.2%	23.2%	23.6%
	Michigan	35.0%	28.1%	22.4%	20.4%	33.9%	31.5%	23.8%	23.8%
	Oklahoma	24.3%	17.8%	13.5%	10.9%	25.8%	22.4%	25.7%	28.2%
25% Increase in biomass yield	Illinois	-15.0%	-13.8%	-14.0%	-13.1%	-16.8%	-15.3%	-11.1%	-13.2%
	Michigan	-14.6%	-14.5%	-14.5%	-14.7%	-15.3%	-14.3%	-8.7%	-10.2%
	Oklahoma	-13.9%	-11.8%	-12.0%	-10.6%	-16.2%	-14.0%	-14.4%	-28.3%
25% increase in seed price	Illinois	0.5%	1.0%	4.3%	4.8%	2.6%	3.0%	0.9%	1.1%
	Michigan	0.8%	1.5%	6.2%	7.3%	3.7%	4.5%	1.3%	1.6%
	Oklahoma	0.8%	1.3%	5.2%	5.4%	3.9%	4.4%	2.4%	3.2%
25% increase in fertilizer price	Illinois	-0.9%	1.0%	-0.9%	-0.5%	-3.7%	-3.4%	-2.9%	-2.8%
	Michigan	-2.4%	1.3%	-1.7%	-0.9%	-6.1%	-5.6%	-4.3%	-4.1%
	Oklahoma	1.6%	3.5%	0.6%	0.8%	-2.0%	-1.7%	-2.0%	-2.0%
25% increase in harvest cost	Illinois	4.1%	6.8%	5.6%	8.7%	3.7%	6.9%	11.1%	10.3%
	Michigan	5.0%	6.5%	5.4%	7.4%	5.5%	8.6%	14.1%	13.3%
	Oklahoma	5.1%	8.7%	7.5%	12.2%	4.4%	7.4%	7.1%	4.1%
25% increase in preharvest cost	Illinois	0.4%	0.5%	0.2%	0.4%	0.5%	0.5%	1.0%	1.2%
	Michigan	0.8%	0.7%	0.5%	0.6%	0.8%	0.8%	1.5%	1.8%
	Oklahoma	0.7%	0.6%	0.5%	0.2%	1.1%	0.9%	2.7%	3.5%
Change in discount rate from 4% to 8%	Illinois	0.7%	2.2%	7.2%	7.9%	2.0%	3.6%	13.2%	14.7%
	Michigan	0.9%	2.7%	9.5%	10.9%	2.8%	4.4%	9.0%	10.2%
		0.9%	2.3%	7.8%	7.9%	3.0%	4.3%	11.6%	14.3%

LC = low-cost scenario; HC = high-cost scenario.

Endnotes

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