Chapter 8
Economics of Alternative Feedstocks

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Biofuels are increasingly being viewed as the center piece in any strategy for energy independence, stable energy prices, and climate change mitigation in the US A key constraint to our ability to expand biofuel production is likely to be the limited amount of agricultural land available to produce crops and biomass to meet our needs for food and feed while also achieving the ambitious goals of replacing 30% of 2004 gasoline demand by renewable fuels by 2030[23]. High energy prices in recent years have already contributed to an expansion of ethanol production in the US. This increase in ethanol production will place large demands on the feedstock, corn, currently being used for ethanol production in the US.

Since the supply of corn for ethanol is relatively small compared to the U.S. demand for gasoline, other domestic sources of renewable energy, such as biomass feedstocks, must be developed if the country is to significantly reduce its dependence on oil. Two major sources of feedstock for cellulosic ethanol are: crop residues, such as corn stover, and perennial grasses. Two perennial grasses, Switchgrass (*Panicum virgatum*) and Miscanthus (*Miscanthus x giganteus*), have been identified in particular as among the best choices for low input bioenergy production in the US (Heaton et al., 2004; Lewandowski et al., 2003). Miscanthus is a perennial rhizomatous grass found in East Asia, while switchgrass is a native prairie grass. Hereafter, we refer to the biomass feedstocks (corn stover, switchgrass and miscanthus) used for ethanol production as bioenergy crops. We use ethanol and biofuels interchangeably to refer to fuel derived from any of the feedstocks examined here including corn grain.

Field research on switchgrass has been conducted in the U.S. since 1992 with yields averaging between 5 to 9 of dry short tons per acre (t dm per acre) annually (McLaughlin and Kszos, 2005). The average yield of Cave-in-Rock, an upland variety that performs best in the northern central plains in the US, was found to be 4.2 t dm per acre, while its best yield was 5.6 t dm per acre, in trials in Iowa in 1998 and 1999 (Brummer et al., 2000). The sterile hybrid genotype *Miscanthus x giganteus* has been studied extensively through field trials in several European countries and its yields have been found to range between 1.8 to 19.6 t dm per acre per year (Lewandowski et al., 2003). Research on miscanthus in the US was initiated only in 2002 following the establishment of field trials of miscanthus and switchgrass at three University of Illinois Agricultural Research and Education Centers (Heaton et al., 2006). Both crops have a tolerance for cool temperatures of the Midwest and can be grown on a broad range of land types using conventional farming practices. Crop productivity models as well as field trials indicate that miscanthus can have relatively high yields in the Midwest, more than twice those of switchgrass and higher than miscanthus yields observed in Europe (Heaton et al., 2004; Lewandowski et al., 2003). Field trials at three locations in northern, central and southern Illinois in 2005-2006, showed peak yields in October averaged 12.7 t dm per acre, 18.9 t dm per

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[23] http://genomicsgtl.energy.gov/biofuels/

acre and 20.5 t dm per acre, respectively. The average switchgrass yield across the three locations was 4.98 t dm per acre (Heaton et al., 2006).

To engender a viable bio-based energy system, bioenergy crops must compete successfully both as crops and as fuels. Owners of cropland will produce these crops only if they can receive an economic return that is at least equivalent to returns from the most profitable conventional crops, which are corn and soybeans in Illinois. The foregone returns from these conventional crops therefore impose an opportunity cost of using land for producing bioenergy crops. As the market price of conventional crops increases, possibly due to increased demand for corn-ethanol, this opportunity cost of land and therefore the cost of production of bioenergy crops is expected to increase.

To be viable substitutes for fossil fuels, biofuels should be economically competitive and environmentally friendly. Biofuels offer the potential for various environmental benefits relative to the gasoline that they displace. Existing studies of the life cycle greenhouse gas emissions associated with ethanol from different feedstocks show that they are lower than the life cycle emissions from gasoline; but how low they are depends on the choice of feedstock. Estimates of the potential for corn-grain ethanol to reduce greenhouse gas emissions differ widely across studies and range from +25% to -35% (see Farrell et al., 2006). Hill et al (2006) estimate this potential reduction to be 12%. On the other hand, cellulosic ethanol from switchgrass is expected to reduce emissions by 88% relative to gasoline (Farrell et al., 2006). Moreover, bioenergy crops have the potential to sequester more carbon in the soil than row crops grown using conservation tillage (Post and Kwon, 2000; Tolbert et al., 2002; Hansen et al., 2004). In contrast, the use of corn stover for biofuel production removes a significant portion of crop residues from the field and decreases nutrients and soil organic matter, requiring applications of replacement fertilizer which contribute to carbon emissions (Kim and Dale, 2005) and increase eutrophication and acidification of soils (Powers, 2005).

This chapter examines the costs of producing biofuels from alternative feedstocks and the implications of valuing the CO_2 mitigation benefits of these feedstocks relative to gasoline for their competitiveness relative to each other and to gasoline. The carbon mitigation potential of biofuels from alternative feedstocks differ due to differences in the amount of carbon they sequester in the soil, in the amount of carbon emissions generated during the process of producing the feedstocks and in the amount of energy needed to convert the feedstock into fuel. We use life-cycle analysis to estimate this potential and analyze the implications of valuing this mitigation at alternative prices of CO_2 emissions for the net costs of producing biofuels.

The next section describes and estimates the costs of producing the three alternative biomass feedstocks and corn grain. This is followed by (i) a discussion of costs of producing biofuels, including the non-feedstock costs and co-product credit using alternative feedstocks, 9(ii) quantification of the life cycle carbon emissions associated with alternative feedstocks, and (iii) a comparison of the competitiveness of biofuels from alternative feedstocks relative to each other and to gasoline after including both their market-based costs of production at various levels of crop prices and CO_2 mitigation benefits valued at various carbon prices.

Feedstock Costs

To obtain the costs of feedstocks for fuel production, we first describe the costs of producing the three different bioenergy feedstocks being examined here, corn stover, switchgrass and miscanthus. In the case of corn- grain ethanol, we use the market price of corn as a measure of the cost of the feedstock. Yield of corn, grown using a corn-soybean rotation with conventional tillage is assumed to be 145 bushels/acre. The total amount of corn stover (residue) produced with the corn is estimated by assuming a ratio of 1:1 of residue to grain (as in Sheehan et al., 2004). To maximize residue collection while protecting soil from erosion, we assume that large scale demand for corn stover for biofuel production will induce a shift from corn-soybean rotation to continuous corn rotation with no-till. The yield of corn in a continuous corn rotation is assumed to be 130 bushels/acre (12% lower) than the yield under a corn-soybean rotation. To maintain soil erosion losses within USDA's tolerable soil-loss limits, Sheehan et al. (2004) estimate that 70% of the residue can be removed if corn is produced using no-till continuous corn rotation and 40% can be removed if it is produced using conventional till. These assumptions imply a delivered stover yield of 2.02 t dm per acre after accounting for 7% loss of yield during storage and 15% moisture at harvest.

To determine the yield per acre of miscanthus we simulated yields in Illinois using a crop productivity model MISCANMOD at a 2x2 km grid level. The simulated yields follow a similar pattern to those found in the observed yields described above; yields per acre increase as one moves from northern to southern Illinois. Simulated peak yields in October were 13.7 t dm per acre, 15.8 t dm per acre and 17.8 t dm per acre at the three locations mentioned above in northern, central and southern Illinois where field trials were conducted by the University of Illinois. The simulated average peak yield at the three locations was 15.7 t m per acre while the actual average peak yield was estimated to be 17.4 t dm per acre. The simulated average yield for Illinois across all 2x2 grids was 15.95 t dm per acre. This implies an annualized delivered yield of 8.90 t dm per acre of miscanthus in Illinois (after accounting for 33% loss of peak yields by harvest time, 7% yield loss during storage and a 4% discount rate). Peak switchgrass yield is assumed to be 4.2 t dm per acre based on yields obtained in field trials in Iowa and Illinois (see Khanna et al., 2006). This implies a delivered yield of 2.58 t dm per per acre.

The costs of producing corn stover, switchgrass and miscanthus depend on (i) the costs of inputs, such as chemicals, fertilizers and seeds, (ii) the costs of equipment, including hire, repair and maintenance, depreciation, and investment costs for land preparation (for planting Switchgrass and Miscanthus) and harvest operations and (iii) the costs of storage and transportation, and (iv) the opportunity costs of land. The per acre land rent, overhead (such as farm insurance and utilities), building repair and depreciation, and farmer's labor are not included in the costs of bioenergy crops or row crops. In the case of Miscanthus and Switchgrass, the opportunity cost is measured as the difference between the per acre revenues from a corn-soybean rotation and its costs of production (sum of items (i), (ii) and (iii) above). This difference represents the profits foregone by a landowner and, therefore, the opportunity costs of using land, labor and farm buildings to produce a bio-energy crop. In the case of corn stover, the opportunity cost includes the foregone profits from a corn-soybean rotation net of profits earned with a no-till continuous corn rotation.

In estimating the costs of producing Miscanthus and Switchgrass, which are perennials, we recognize that costs in the first year differ from those in subsequent years because they include costs of land preparation and planting to establish the crop. In the second year, we assume a 25% probability of reseeding/replanting for Switchgrass to replace plants that do not survive the first winter. Based on field experience with Miscanthus in Illinois, there is no need for replanting Miscanthus rhizomes (Heaton et al. 2006). Moreover, 67% of the maximum yield of Switchgrass and 50% of the maximum yield of Miscanthus can be harvested in the second year (Heaton et al 2004; McLaughlin and Kszos, 2005). From the third year onwards, yields remain constant through the remaining life of the crop, which is assumed to be 10 years for Switchgrass and 20 years for Miscanthus.[24] Since costs of production and revenues from selling the yield are incurred at different points in time over the life of the crop, we compare cost estimates across the two bio-energy crops and the annual row crops by estimating the discounted value of costs using a discount rate of 4%. The break-even cost of production of a bio-energy crop is then determined as the price in current dollars needed to offset all the costs of production (including opportunity cost) incurred over the lifetime of the crop discounted to current prices taking into account successive yields and revenues that are also discounted to current prices. It does not include any profits for the landowner. In estimating the costs of producing bio-energy crops, we assume that a farmer or a group of co-operating farmers produces the crop using their own machinery, tractors and harvesting equipment. Assumptions about fertilizer, seed and pesticide application rates for switchgrass and miscanthus, as well as costs of inputs in 2003 prices are described in Khanna et al. (2006).

Harvesting of switchgrass and miscanthus involves mowing, swathing and baling and can be performed by conventional grass harvesters and balers. We assume a single harvest of switchgrass in the early winter after the first frost and in December for miscanthus so that translocation of nitrogen and other nutrients out of the foliage into the roots reduces overall nutrient use and ash content while improving the suitability of these grasses as a fuel for combustion. This does, however, reduce switchgrass and miscanthus yields by 20% and 33% of dry matter, respectively, as compared to peak yields in mid- September and is assumed to reduce the moisture content to 15% and 20% respectively which allows baling to immediately follow a mower/conditioner. The annualized costs of mowing/conditioning and swathing are \$15 per acre for miscanthus and \$14 per acre for switchgrass. Costs of baling and staging depend on yield and annualized costs are estimated to be \$28 per t dm for miscanthus and \$26 per t dm for switchgrass. Costs of storage and transportation to an ethanol plant 25 miles away are described in Khanna et al. (2006). A summary of these costs is provided in Table 1.

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[24] The oldest continuous plot of Switchgrass is 13 years old and has shown no evidence of a loss in yield capacity over time [6]. }. Switchgrass typically attains only 33 percent and 67 percent of its maximum production capacity during the first and second year respectively, before reaching its full capacity during the third year after planting. There is no experimental evidence that yields decline with the age of the stand when managed for biomass production [6, 18]. The oldest trial of Miscanthus was 18 years old in 2003 in Denmark [4].

Table 1: Annualized Cost of Production for Perennials and Row Crops

	Source of Bomass Feedstock			Corn-Com Rotation with Conservation Till	Corn-Soybean Rotation with Conventional Till	
Cost Items ($/Acre)	Switchgrass	Miscanthus	Corn stover	Corn	Corn	Soybean
Fertilizer	23.23	16.36	9.27	59.18	53.61	24.09
Chemicals	1.68	0.51	-	54.53	31.00	36.00
Seed	6.35	9.59	-	36.00	36.00	19.20
Interest on operating inputs	2.19	1.85	0.65	6.93	5.63	3.70
Storage/drying/crop insurance	9.68	35.48	-	24.00	24.00	11.00
Machinery cost	90.02	272.60	64.15	65.76	82.00	70.00
Transportation cost	18.49	63.81	13.11	-	-	-
Annual operating cost	151.63	400.19	87.18	246.40	232.24	163.99
Annualized yield	2.58 (short ton/ acre)	8.90 (short ton/ acre)	2.02 (short ton/ acre)	130 (bu/acre)	145 (bu/acre)	50 (bu/acre)
Low Opportunity Cost of Land	78.01	78.01	57.91			
High Opportunity Cost of Land	230.64	230.64	22.03			
Breakeven Delivered Cost with Low Opportunity Cost of Land ($/short ton DM)	89.01	53.73	71.83	-	-	-
High Opportunity Cost of Land ($/short ton DM)	148.17	70.88	54.06			

Low opportunity cost of land is measured with soybean price $5.1/bu and com price $2.05/bu; High opportunity cost of land is measured with corn price of $3.50/bu and soybean price of $7/bu. All other costs are measured in 2003 prices.

In estimating the input costs of producing corn stover we only consider the additional costs imposed, over and above the costs of producing corn, due to the removal of stover from the field. We assume that removal of stover from the field leads to a loss of nutrients and soil organic matter and that lost nutrients need to be replaced by fertilizer applications above and beyond the amount of fertilizer normally applied for corn grain production. The costs of replacement fertilizer are obtained by assuming that removal rates of N, P and K are 9, 1.6 and 15.21 lbs per dry ton of stover removed respectively (i.e., N:P:K::19.5, 3.47, 32.93 lbs per acre) as estimated by Sheehan et al. (2004) for Iowa. We also assume that corn stover collection will involve a second pass through the field using commercial equipment after the farmer has harvested corn grain. The costs of mowing, raking, baling and staging are determined in a similar manner to that in the case of perennial crops as described in Khanna et al. (2006). These amounts to $16.4 per acre for mowing and raking and $24 per short ton for baling and staging. The latter estimate is close to the estimated $26 per short ton for baling and staging corn stover obtained by Aden et al. (2002).

As shown in Table 1, miscanthus is less fertilizer intensive than Switchgrass but has higher costs of planting; switchgrass is planted using seeds, while miscanthus is planted using rhizomes. On the other hand, machinery costs per acre of land which include both pre-harvest machinery, used for planting and soil preparation, and equipment for harvesting and baling are about three times higher for miscanthus than switchgrass primarily due to the need to bale a larger volume of biomass per acre from miscanthus. The opportunity cost of land (estimated to be the foregone profits from a corn soybean rotation) increases as the price of corn and soybean increase, assuming other input costs remain unchanged. An increase in the price of corn and soybeans from $2.05 per bushel and $5.10 per bushel to $3.50 per bushel and $7 per bushel, respectively, would raise the opportunity cost of land that switches to switchgrass or miscanthus from $78 per acre to $231 per acre. This in turn raises the cost of switchgrass from $89 per dry ton to $148 per dry ton and that of miscanthus from $54 per dry ton to $71 per dry ton.

The opportunity cost of land for producing corn stover is estimated to be the difference in profits with a corn-soybean rotation and those with a no-till continuous corn production. The latter results in a 15 bushel loss in average corn yield, higher fertilizer and chemical use but lower machinery costs compared to those with corn-soybean rotation. As the price of corn and soybeans increases, this opportunity cost of land increases only marginally and may even decrease because the higher price of corn offsets the loss in profits due to the foregone soybean crop even at higher soybean prices. The cost of producing corn stover is $72 per t dm with the lower corn and soybean prices and $54 with the higher corn and soybean prices assumed above.

Costs of Producing Biofuels

The cellulosic conversion technology is still in early stages of development, expensive and limited to pilot facilities; there is no commercial cellulose-to-ethanol facilities currently in operation in the US (Schnepf, 2006). As discussed in (Chapter 3) conversion of cellulose to ethanol can be done using acid hydrolysis, enzymatic hydrolysis or thermochemical processes. The US Department of Energy suggests that enzymatic hydrolysis, which processes cellulose into sugar using cellulase enzymes, offers the greatest potential for cost reductions.[25] A recent study conducted jointly by the U.S. Department of Agriculture (USDA), the U.S. Department of Energy and the National Renewable Energy Laboratory (NREL) examined the costs of producing cellulosic ethanol from corn stover assuming an nth generation plant at the same level

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[25] http://www1.eere.energy.gov/biomass/other_hydrolysis.html

of maturity as a corn-ethanol plant (that is, assuming no first of a kind costs) (Wallace et al., 2005). This study analyzed the process that uses co-current dilute acid prehydrolysis of the cellulosic biomass with enzymatic saccharification of the remaining cellulose and co-fermentation of the resulting glucose and xylose to ethanol. The process involves feedstock handling and storage, product purification, wastewater treatment, lignin combustion, product storage and utility costs. Based on pilot demonstrations of this process conducted by NREL fuel ethanol yield from an nth-generation stand alone ethanol plant is estimated at 79.2 gallons per dry short ton of biomass. Lynd et al. (2005) assume a yield of 89.7 gallons per dry short ton of feedstock in the near term (an nth generation plant with a start-up date of 2010) using dilute acid pretreatment, saccharification and fermentation and 103.7 gallons per dry short ton using an advanced technology (at a level of maturity comparable to a petroleum refinery) that uses liquid hot water pretreatment and consolidated bioprocessing.

The corn-grain to ethanol production process is assumed to be a dry mill production process involving grinding of corn, liquefaction of starch, saccharification of the starch to fermentable sugars and fermentation to convert the sugars to ethanol and carbon dioxide. The fermented mash is distilled, dehydrated and denatured to produce ethanol and distillers grains and solubles (DDGS). Following Eidman (Chapter 3) the ethanol yield from corn grain is assumed to be 2.75 gallons per bushel of corn which implies a yield of 98 gallons of ethanol per short ton.

Table 2 shows the amount of ethanol per acre of feedstock; the differences in ethanol yield across feedstocks are largely due to differences in their yield per acre. Miscanthus can produce almost twice as much ethanol as corn per unit of land and more than three times as much as corn stover and switchgrass. Miscanthus can produce 27% more ethanol per acre of land than combined ethanol production from corn grain and corn stover.

Table 2. Quantity of Ethanol per Acre of Land

Corn	398.75
Corn Stover*	159.88
Switchgrass*	204.66
Miscanthus*	706.41

*assuming a yield of 79.2 gallons per short ton of feedstock

The feedstock costs of biofuel are estimated by dividing the per acre cost of producing each feedstock in Table 1 by the gallons per acre obtained with that feedstock in Table 2. These are reported in column 1 in Table 3. These costs are very similar for corn stover and miscanthus which are about two-thirds of the feedstock costs with corn or switchgrass.

The cost of producing cellulosic ethanol is estimated for a 25 million gallon capacity plant. Wallace et al. (2005) estimate that such a plant would require a capital investment of $121 million and operating costs of $12.3 million for chemical, enzymes, other raw materials and labor. Assuming a life of 10 years for the equipment, 330 days of operation a year, non-feedstock cost in 2003 prices is estimated to be $1.38 per gallon. A co-product credit for electricity generated as a by-product of ethanol production is estimated to be equivalent to $0.11 per gallon of ethanol. These costs vary across studies depending on assumptions about the size of the plant, ethanol yield per ton of feedstock and the specific production process modeled. Lynd et al. (2005) estimate the non feedstock cost (not including co-product credit) to be $0.73 per gallon in the near term and $0.14 per gallon in the advanced case.

Table 3: Cost of Production of Biofuels from Alternative Feedstocks

Feedstock sources	Feedstock cost ($/gal)	Opportunity Cost of Land for Producing Feedstock ($/gal)	Non-Feedstock Cost ($/gal)	Co-Product Credit ($/gal)	Total cost ($/ gal)
Corn (with low energy cost and corn price $2.05/bu)	0.75	-	0.58	0.27	1.05
Corn (with high energy cost and corn price $3.50/bu)	1.27	-	0.73	0.43	1.57
Corn Stover (with corn price $2.05/bu)	0.59	0.36	1.38	0.11	2.22
Corn Stover (with corn price $3.50/bu)	0.59	0.14	1.38	0.11	2.00
Switchgrass (with corn price $2.05/bu)	0.74	0.38	1.38	0.11	2.39
Switchgrass (with corn price $3.50/bu)	0.74	1.13	1.38	0.11	3.14
Miscanthus (with corn price $2.05/bu)	0.57	0.11	1.38	0.11	1.95
Miscanthus (with corn price $3.50/bu)	0.57	0.33	1.38	0.11	2.16

Soybean price is assumed to be $5.1/bu when corn price is $2/05/bu and it is assumed to be $7/bu when corn price is $3.50/bu.

The costs of conversion of corn-grain to ethanol are based on Tiffany and Eidman (2005) and are estimated for a 40 million gallon capacity plant that has an investment cost of $1.50 per gallon of nameplate capacity. The per-gallon cost of processing corn-grain to ethanol is estimated to be $0.58 /gallon in 2003 prices. More recently Eidman (Chapter 3) estimates that investment costs per gallon for a 50 million gallon plant have risen to $2.25 per gallon. Fuel costs account for more than half of the total cost of ethanol production and have risen the most in recent years. Energy costs have risen from $0.21 per gallon in 2003 to $0.36 per gallon and account for most of the increase in the cost of producing ethanol to $0.73 per gallon. The co-products produced are 18 pounds of DDGS per bushel and 18 pounds of liquid CO_2 collected per bushel of corn ground and processed. It is assumed that the CO_2 is sold as a liquid at $6 per ton and that the DDGS is sold at a price of $80 per ton. These are valued at $0.27 per gallon of ethanol in 2003 prices but $0.35 per gallon in 2007 with a higher DDGS price of $103.57 per bushel. The price of DDGS is assumed to be equal the price of corn when corn price is \$2.05 per bushel (that is \$0.037 per pound) and expected to increase 90% as much as the increase in the price of corn (as in Eidman, Chapter 3).

As shown in Table 3, the non-feedstock cost per gallon of cellulosic ethanol is currently estimated to be more than twice that of corn-grain ethanol while the co-product credit for the former is less than half that of the latter. Even with the higher energy costs, the cost of producing cellulosic ethanol is not expected to increase much because lignin-rich process residues are expected to provide all the required process energy and extra electricity for export as well. Thus there is little need to purchase process energy externally, unlike in the case of the corn-ethanol conversion case. The opportunity cost of land in Table 3 is estimated assuming a corn price of \$2.05 and soybean price of \$5.1 per bushel. Increase in the price of corn and soybean to \$3.50 per bushel and \$7 per bushel respectively would reduce the opportunity costs of land for corn stover to \$0.14 per gallon but increase them for switchgrass and miscanthus to \$1.13 per gallon and \$0.33 per gallon, respectively.

Carbon Emissions from Biofuels with Alternative Feedstocks

The greenhouse gases generated in the process of ethanol production are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Greenhouse gas emissions were aggregated into a CO_2 equivalent emissions (CO_2e) using the 100 year global warming potential factors of 1 for CO_2, 23 for CH_4, and 296 for N_2O (Intergovernmental Panel on Climate Change, 2001).[26] The CO_2e generated by alternative feedstocks can be classified into two broad categories (a) net emissions generated during crop production and (b) emissions generated during the biorefinery stage. Category (a) is net of emissions displaced/increased due to change in land use from the alternative use and carbon sequestered in soil by crop production. Category (b) is net of co-product credit.

Emissions generated during the process of producing a crop include CO_2e emissions based on energy embodied in fertilizer and chemical inputs, energy to transport inputs to the farm, energy embodied in farm machinery and fuel used to operate machinery on the field. Emissions generated during the round trip transportation of feedstock to a refinery located 25 miles are also included. Specific farm inputs considered are nitrogen, phosphorous, potassium, agricultural lime, herbicides, insecticides, and seeds. Direct energy used as fuel on the field is disaggregated into gasoline, diesel, liquefied petroleum gas, and electricity. The input application rates are the same as used to obtain the costs of feedstock production in Table 1. The application rate per acre of each input is multiplied by the CO_2e emissions generated per unit input during its production to compute carbon emissions per acre for the production of each crop.[27] The embodied energy rates and CO_2e emission rates per unit of inputs used in production

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[26] In EBAMM, CO_2e emissions are calculated for each of the material inputs such as fertilizers and chemicals by summing the emissions from primary energy use during the production of each of these inputs. In the case of nitrogen fertilizer the model accounts for CO_2 emissions from energy use and N_2O emissions from denitrification in soil.

[27] We excluded the carbon emissions associated with packaging and seed production because of lack of reliable data.

are based on the Energy and Biofuel Analysis Meta-Model (EBAMM) developed by Farrell et al. (2006). As shown in Table 4, the CO_2e emissions per gallon of ethanol are three times higher with the use of corn or switchgrass as a feedstock as compared to emissions with the use of corn stover or miscanthus. The high rate of emissions from switchgrass is in part due to the high rate of nitrogen application assumed here based on McLaughlin and Kszos (2005) and the relatively low yield per acre assumed here compared to EBAMM (Farrell et al. 2006). However, even with a 50% reduction in the nitrogen fertilizer application rate, the CO_2e emissions per gallon of ethanol from switchgrass would be more than twice the emissions from miscanthus and corn stover.

Table 4: Life Cycle Carbon Emissions

	Production phase KgCO$_2$e/Gallon of Ethanol			Biorefinery phase KgCO$_2$e/Gallon of Ethanol		
Feedstock source	Feedstock	Displacement of alternative land use	Net Sequestration	Processing phase	Co-product credit	Total KgCO$_2$e/Gallon of Ethanol
Corn	3.05		-0.73	4.92	-1.99	5.25
Corn stover	1.09	3.45	0.40	0.26	-0.40	4.81
Switchgrass	3.29	-3.68	-5.06	0.26	-0.40	-5.58
Miscanthus	0.90	-1.07	-0.98	0.26	-0.40	-1.28
Gasoline*						7.15

* Emissions from gasoline are calculated for a gasoline equivalent to a gallon of ethanol.

Emissions per acre from chemical use for miscanthus production are 52% lower than those for switchgrass. This offsets to some extent the higher emissions per acre during transportation of the larger yield of biomass from miscanthus compared to switchgrass to the biorefinery. The CO_2e emissions per acre from miscanthus production and transportation are only 5% lower than those from switchgrass. However, the emissions per gallon from miscanthus feedstock are several times smaller than those with switchgrass, because the former yields more than three times greater volume of ethanol per acre.

In estimating the emissions from miscanthus and switchgrass, we also include the carbon mitigation benefit generated when these perennial crops displace a corn-soybean rotation. Both switchgrass and miscanthus displace the same amount of CO_2e emissions per acre of land by displacing corn and soybeans from that acre of land. In per gallon terms, however, the displacement effect of switchgrass is larger because fewer gallons of ethanol are produced per acre from switchgrass than from miscanthus. Switchgrass and miscanthus reduce carbon emissions relative to corn production by 3.7 and 1.07 KgCO2e/gallon, respectively. On the other hand, corn stover utilization as feedstock is likely to increase emissions rather than displacing them, because the no-till continuous corn rotation is more carbon intensive than the corn-soybean rotation. Use of corn stover for biofuel production is likely to induce a shift from a less carbon intensive corn-soybean rotation to a more carbon intensive continuous corn rotation. Continuous corn production, particularly with no-till, requires more fertilizer and herbicide application and lower corn yields but lower fuel use for machinery operation than corn grown in a corn-soybean rotation with conventional tillage. It also requires less energy intensive equipment (a seed drill and a tandem disk instead of a chisel plow and planter). The production of no-till corn is nevertheless more energy intensive than that of soybeans. The change in land use from a corn-soybean rotation to a continuous corn rotation with no-till is estimated to increase emissions by 3.45 KgCO_2e/gallon.

Soil carbon can be sequestered on cropland using either conservation tillage or by switching to perennial grasses. The amount of carbon that can be sequestered depends on the existing stock of carbon in the soil, quality of the soil, type of production practice and length of time for which that practice is maintained. In the absence of field level measurement values for soil carbon sequestered during production of corn with conservation tillage or perennial grasses, we use an average of the carbon sequestration rates reported in the literature. Annual carbon sequestration rates with conservation tillage are estimated to be in the range of 0.13 – 0.22 short ton per acre (Wander et al 1998; Dick et al. 1998; Robertson et al. 2000; Eve et al.2002). Annual carbon sequestration rates with Switchgrass are reported to lie in the range of 0.31- 0.49 short ton per acre (Gebhart et al.1994; and McLaughlin et al 2002), while those with miscanthus are reported to be in the range of 0.42-0.62 short ton per acre (Beuch et al. 2000; Kahle et al. 2001; and Mathews and Grogan 2001, Hansen et al., 2004). For this study, we take average of the reported range and obtain an annual sequestration rate of 0.18 ton per acre with conservation tillage, 0.40 ton per acre with Switchgrass, and 0.52 ton acre with miscanthus. To allocate the carbon stored by conservation tillage to corn grain and to stover, we assume that it is in the same ratio (1:1) as the yield of grain to stover (Wallace et al. 2005; Sheehan et al. 2004).

Removal of corn stover residue from the soil results in soil carbon loss. Based on Sheehan et al. (2004), we assume a loss of 4.91 short tons of soil carbon per acre of corn stover removed over a 90 year period; this is equivalent to a loss of 0.20 short tons of CO_2 per acre per year. Miscanthus and switchgrass serve as net sinks for carbon by reducing carbon emissions by 5.06 and 0.98 Kg CO_2e/gallon of ethanol respectively as opposed to corn stover which increases emissions by 0.4 Kg CO_2e/gallon of ethanol.

The biorefinery phase includes emissions generated during the conversion process after the feedstock is delivered to the refinery and are estimated to be many times larger with corn grain than with cellulosic feedstocks. These estimates are based on Farrell et al. (2006) and estimated emissions are assumed to be the same for all types of cellulosic feedstocks. The estimates of CO_2e emissions in Table 4 indicate that ethanol from corn-grain emits 73% while cellulosic feedstocks emit 67% of the emissions of a gallon of ethanol equivalent gasoline. If we focus only on the emissions generated during feedstock production and the refining process net of co-product credit then the emissions from corn-grain, corn stover, switchgrass and miscanthus are 84%, 13%, 44% and 11%, respectively, of those from a gallon of ethanol equivalent gasoline. Our estimate of the relative emissions of corn-grain ethanol agrees closely with that in Farrell et al. (2006) (aren't your estimates based on Farrell? and Hill et al. (2006). The estimate of relative emissions for switchgrass-based ethanol is considerably higher than corn stover and miscanthus primarily because we are assuming a higher rate of nitrogen application (based on recommendations of McLaughlin and Kszos, 2005). With the exception of emissions generated during the biorefinery phase, all other categories of emissions are estimated in terms of CO_2e per acre of land and then converted to CO_2e per gallon of biofuel using estimates of the amount of ethanol that can be produced per acre of land from different feedstocks presented in Table 2.

Competitiveness of Biofuels at Various Crop Prices and Carbon Prices

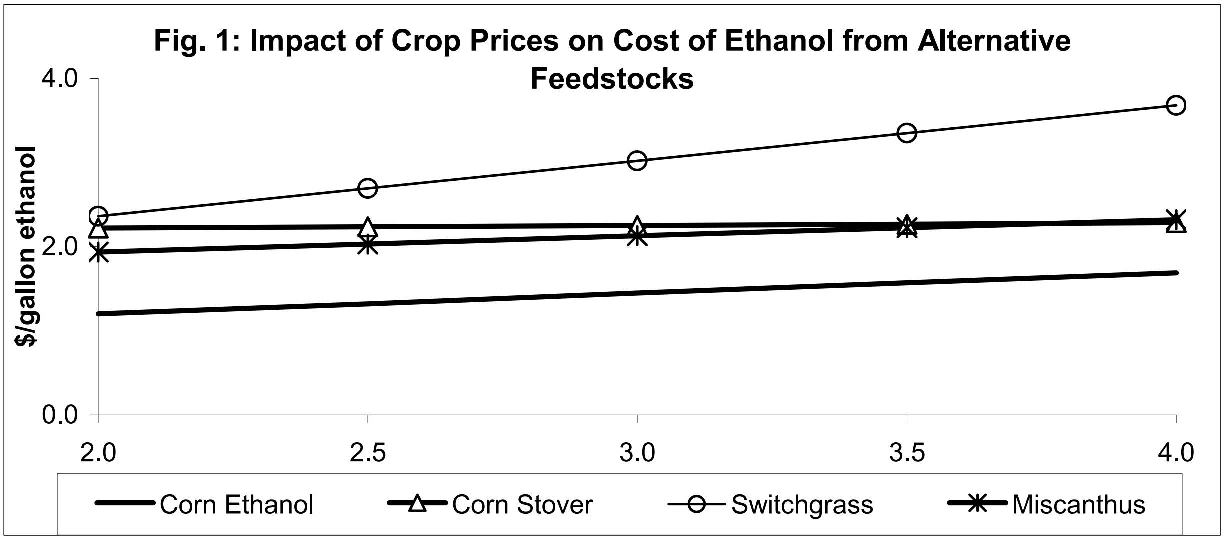
We examine the impact of crop prices on the opportunity cost of production of corn stover, switchgrass and miscanthus reported in Table 1 and therefore on the costs of production of ethanol using various feedstocks. The costs of corn-ethanol production are estimated assuming high energy costs and a non-feedstock cost of $0.73/gallon. We also examine the effects of valuing the carbon reduction per gallon of ethanol that would be achieved by using alternative feedstocks to displace an energy equivalent amount of gasoline; and estimate the net costs of production of ethanol using alternative feedstocks after incorporating this carbon credit per gallon of ethanol.

Results are reported in Table 5. At a price of $2 per bushel of corn and $5 per bushel of soybeans, costs of producing ethanol from corn ($1.2 per gallon) is almost half the cost of producing it from corn stover and switchgrass, which are $2.22 per gallon and $2.36 per gallon, respectively. The gap between the price of ethanol from corn and that from miscanthus is $0.74 per gallon at $2/bu corn price. As the price of carbon increases the gap between the cost of production of ethanol using corn vs. miscanthus decreases. At a price of $50 per metric ton of CO_2, these costs are $1.2 per gallon and $1.94 per gallon of ethanol, respectively. As the price of corn increases to $3.50 per bushel and that of soybeans increases to $7 per bushel, the costs of producing ethanol from corn increases rapidly to $1.57 per gallon while that from miscanthus increases to $2.16 per gallon (due to an increase in the opportunity cost of the land). At a price of $50 per metric ton of CO_2, the gap between the costs of production of ethanol from corn and miscanthus decreases to $0.3 per gallon.

Table 5. Sensitivity of Costs of Production to Crop and Carbon Prices

Crop Prices	**$2/bu Corn; $5/bu Soybean**			**$3/bu Corn; $5/bu Soybean**			**$3.50/bu Corn; $7/bu Soybean**		
Price of CO_2 ($ metric ton CO_2)	**0**	**10**	**50**	**0**	**10**	**50**	**0**	**10**	**50**
Cost of Ethanol ($/gal 100E fuel)									
Corn	1.20	1.18	1.08	1.45	1.42	1.33	1.57	1.55	1.45
Corn Stover	2.22	2.20	2.10	1.86	1.63	1.74	1.99	1.97	1.87
Switchgrass	2.36	2.23	1.72	2.71	1.44	2.08	3.14	3.01	2.50
Miscanthus	1.94	1.85	1.52	2.04	1.20	1.62	2.16	2.08	1.74
Cost of Ethanol ($/gal gasoline equivalent 100E fuel)									
Corn	1.78	1.75	1.60	2.15	2.11	1.97	2.33	2.30	2.15
Corn Stover	3.30	3.26	3.12	2.76	2.41	2.59	2.95	2.92	2.78
Switchgrass	3.50	3.31	2.56	4.03	2.14	3.08	4.65	4.46	3.71
Miscanthus	2.87	2.75	2.25	3.03	1.78	2.40	3.21	3.08	2.58

As crop prices increase, the cost of producing ethanol from switchgrass increases from \$2.36 per gallon to \$3.16 per gallon. Despite a price of \$50 per metric ton of CO_2 and the large carbon mitigation benefits of switchgrass, the cost of production of ethanol from switchgrass is \$2.50 per gallon, the highest among the feedstocks examined here. Valuation of carbon does not lead to much reduction in the net costs of production of corn stover because of its low relative potential to lower carbon emissions. The lower half of Table 5 shows the costs of production of ethanol equivalent to a gallon of gasoline. Since one gallon of ethanol has two-thirds of the heat content of a gallon of gasoline, the costs of production of ethanol equivalent to a gallon of gasoline are about 50% higher than those of a gallon of ethanol. These costs can be directly compared to the price of gasoline to examine the extent to which ethanol from various feedstocks is competitive with gasoline. These costs are not fully comparable to the cost of gasoline at the gas station because the costs of producing ethanol do not include the profits earned by a refinery, costs of transporting the ethanol, blending it and selling it retail. Nevertheless, cost estimates in Table 5 do suggest that at a minimum a gasoline price over \$3 per gallon would be needed to make cellulosic ethanol competitive with gasoline. As shown in Figure 1, as corn and soybean prices increase from initial levels of \$2 per bushel and \$5 per bushel by the same percentages, the costs of production of ethanol from all feedstocks increases, but at different rates. Costs of production of ethanol from corn stover and miscanthus begin to converge and tend to become closer to those from corn ethanol. On the other hand, the costs of producing ethanol from switchgrass diverge further from those using other feedstocks. This is because the higher opportunity costs of land that accompany the higher crop prices coupled with the relatively lower yields of ethanol per acre, lead to a large increase in the cost of production per gallon of ethanol.



Conclusions

This analysis shows that breakeven delivered cost of miscanthus (for an average delivered yield of 8.9 t dm per acre) in Illinois is $54 per t dm, which is 60% of the breakeven delivered cost of Switchgrass with an average delivered yield of 2.58 t dm per acre when the opportunity cost of the land is based on corn and soybean prices of $2.05 per bushel and $5.1 per bushel respectively. As these crop prices increase to $3.50 per bushel and $7 per bushel respectively, the opportunity cost of land more than doubles and the cost of production of miscanthus and switchgrass increases. The cost of production of miscanthus increases slower than that of switchgrass and the ratio of their costs decreases to 44%. Furthermore, the cost of corn stover with a delivered yield of 2.02 t dm per acre is higher than that of Miscanthus but lower than that of Switchgrass. As row crop prices increase by the amounts above, the cost of corn-grain ethanol increases by about 30% while that of ethanol from corn stover decreases slightly (because the opportunity cost of switching from corn-soybean rotation to continuous corn rotation increases only slightly or may even decrease).

In sum, we can conclude that Switchgrass is not likely to be competitive with Miscanthus for biofuel production in Illinois at current prices and yields. Ethanol from Miscanthus is also cost-effective relative to that from corn stover within the range of crop prices considered here, particularly if corn price is low or the price of carbon is high. However, ethanol from Miscanthus is considerably more expensive than that from corn ethanol and is unlikely to be competitive with gasoline at a price lower than about $3 per gallon of gasoline. These findings imply a role for public policy in inducing greater production and use of biofuels. Pricing of carbon emissions or a cap on carbon emissions from gasoline production would create a value for producing biofuels that mitigate those carbon emissions. Unless the carbon price is high enough, such a policy would need to be supplemented by additional subsidies either to ethanol production or to farmers that produce bio-energy crops to enable these crops to compete with row crops and to enable ethanol to compete with gasoline.

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