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Cellulosic Biofuels: Are They Economically Viable and Environmentally Sustainable?

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Biofuels are being extensively promoted for their potential to contribute to energy security, stable energy prices, and climate change mitigation in the United States. A key constraint to our ability to expand biofuel production to significantly reduce dependence on fossil fuels is likely to be the limited amount of agricultural land available to produce food, feed and energy crops. The use of crop residues like corn stover, wood chips and high yielding herbaceous energy crops such as perennial grasses is being explored to mitigate this competition for land and achieve higher quantities of biofuel per acre of land than being achieved by corn–grain based ethanol. Among herbaceous energy crops, miscanthus and switchgrass have been identified as promising crops because they have higher yields than other perennial grasses, provide high nutrient use efficiency and require growing conditions and equipment similar to those for corn, which makes them compatible with conventional crop cultivation (Heaton et. al., 2004). They also have several positive environmental attributes.

To be economically viable, energy crops must compete successfully both as crops and as fuels. Biofuels produced from these energy crops (referred to as cellulosic biofuels) need to compete with fossil fuels and corn–based ethanol. Owners of cropland will produce cellulosic feedstocks only if they can receive an economic return that is equivalent to or preferably higher than the returns from the most profitable conventional crops, particularly if energy crop production is exposed to more price risks. The foregone returns from these conventional crops are the opportunity cost of using cropland for producing energy crops. Geographical variations in the costs of producing these crops and in the opportunity costs of land are likely to make the economic viability of cellulosic biofuels differ across locations.

Energy crops and the cellulosic biofuels produced from them offer the potential for various environmental benefits compared to the row crops they may displace and compared to grain–based ethanol. These include reduced soil erosion and chemical run-off, extended habitat for wildlife, stabilization of soil along streams and wetlands, sequestration of more carbon in the soil than row crops grown using conservation tillage, and lower input requirements for energy, water and agrochemicals per unit of biofuel produced (McLaughlin and Walsh, 1998; Semere and Slater, 2007). These environmental benefits tend to differ across different energy crops, due to differences in their energy input requirements, ability to sequester carbon in the soil, canopy cover and palatability of leaves for insects. There have been some concerns that miscanthus, as an introduced species, might be an invasive plant. However, most varieties used for biofuel production (like *Miscanthus x Giganteus*) are sterile hybrids and do not produce seed. Environmental groups are also concerned that demand for biofuels might lead to the dominance of single species of perennial grasses within a landscape rather than polycultures with mixed prairie grasses, like Indian Grass and Big Bluestem, which would enhance biodiversity.

The potential to mitigate greenhouse gas emissions by using biofuels for transportation is a key benefit, since there are few substitutes for transportation fuel given current vehicle technology. We will examine the costs of producing biofuels from alternative feedstocks (corn stover, switchgrass and miscanthus) using data for Illinois. Life–cycle analysis allows us to estimate the CO_2 mitigation potential of these feedstocks relative to gasoline. We will then discuss the implications of valuing these CO_2 mitigation benefits for the competitiveness of these feedstocks relative to each other and to gasoline.

Costs of Cellulosic Feedstocks

The economic potential of cellulosic feedstocks depends on their yields, input requirements and costs of production and is expected to vary spatially with differences in climatic and soil conditions. Corn (and thus corn stover) require good soil quality while perennial grasses require long growing periods and higher temperatures and can be grown on less fertile lands. Corn stover yields are expected to be in the ratio of 1:1 with corn yields and to range from a low of 2.25 t dm per acre (metric tons of dry matter per acre, with 1kg=0.001 metric ton) in southern Illinois to a high of 4 t dm per acre in northern and central Illinois; of this, the amounts that can be sustainably harvestable vary between 40% and 70% depending on tillage practice (Sheehan et al., 2004). In contrast to this historically observed pattern of corn yields, peak yields of miscanthus (simulated using a crop productivity model), are estimated to be lower in northern Illinois (12 t dm per acre) than in southern Illinois (18 t dm per acre) (Khanna, Dhungana and Clifton-Brown, 2008). The spatial pattern of switchgrass yields is expected to be similar to that of miscanthus, however, switchgrass yields are about a quarter of those of miscanthus based on field experiments conducted in Illinois and Iowa. Yields per acre of these crops influence not only their costs of production per ton but also the volume of biofuels that can be obtained per acre of land and thus the amount of land that would need to be diverted from row crops to meet a given level of biofuel production.

Table 1 presents an estimate of annualized costs of producing switchgrass and miscanthus and the annual costs of collection of corn stover in 2007 prices. These cost estimates are developed for average delivered yield levels for Illinois (for details about agronomic assumptions see Khanna, Dhungana and Clifton-Brown, 2008; Khanna and Dhungana, 2007). Switchgrass is assumed to have a life of 10 years, while miscanthus is assumed to have a life of 20 years.

Fertilizer and chemical input requirements for corn stover and energy crops relative to conventional crops are fairly low. In the case of corn stover, fertilizer applications are needed to replace the nutrients removed with the stover to sustain soil fertility (Sheehan et al., 2004). The largest component of the costs of producing cellulosic feedstocks is the cost of harvesting, baling and storing them, particularly if they are stored in an enclosed building for several months after harvest. Since there is considerable uncertainty about the methods of harvesting and storage of biomass, we consider two alternative scenarios for estimating baling and storage costs. In the high cost scenario, we consider baling costs per acre as linearly related to the yield per acre, while in the low cost scenario, we treat a portion of the baling costs (those related to the equipment, tractor and implements) as fixed and a portion as variable (fuel and labor) that depend on the biomass yield to be baled. The high cost scenario also considers storage of bales in an enclosed building, while the low cost scenarios assumes it is on the field on crushed rock and covered by tarp.

Another large component in the case of energy crops is the opportunity cost of the land, which is tied to the price of row crops such as corn and soybeans. In the case of corn stover, we assume that the use of stover

Table 1. Farmgate Costs of Production of Cellulosic Feedstocks in Illinois

Cost Items ($/Acre)	Switchgrass		Miscanthus		Corn Stover	
Scenario	High	Low	High	Low	High	Low
Fertilizer	66.7	66.7	29.8	29.8	15.3	15.3
Chemicals	7.7	7.7	0.5	0.5	-	-
Seed	7.0	7.0	70.8	70.8	-	-
Interest on operating inputs	5.7	5.7	7.1	7.1	1.1	1.1
Preharvest Machinery	14.1	14.1	11.0	11.0	-	-
Harvesting	86.8	64.0	277.5	151.6	69.5	60.2
Storage	54.2	10.2	199.3	37.6	41.7	7.9
Annualized Total Operating Cost	**242.2**	**175.4**	**595.9**	**308.4**	**127.3**	**84.1**
Annualized deliverable yield (t dm/acre)[a]	2.5	2.3	8.5	8.1	1.9	1.8
Opportunity cost of land ($/ t dm)[b]	179.4	189.0	51.9	54.7	43.9	46.3
Break–even total cost ($/t dm)	**277.8**	**264.2**	**122.0**	**92.9**	**111.3**	**93.1**

[a] Deliverable yield at the farm gate estimated after including losses during harvest and storage. Losses during storage are assumed to be 7% of harvested yield in the low cost scenarios and 2% in the high cost scenario.

[b] Opportunity cost of land is estimated assuming a price of $5 per bushel for corn and $12 per bushel for soybeans and a yield of 145 bushels/acre for corn and 50 bushels/acre for soybeans with a corn–soybean rotation.

for biofuels leads farmers to switch from a more profitable corn–soybean rotation to a corn–corn rotation with a 12% lower yield of corn, imposing an opportunity cost of land. As can be seen in Table 1, the per ton costs of producing switchgrass are more than two times higher than those of miscanthus and corn stover, in large part because of the high opportunity cost of using land given switchgrass yields. The per ton costs of producing miscanthus are similar to those of corn stover in the low cost scenario.

The costs of producing these feedstocks vary considerably spatially due to differences in their yields as well as differences in the costs of land as shown in the case of Illinois in Figure 1. Costs of producing corn stover are relatively lower in parts of northern and central Illinois where corn yields are high while those of miscanthus are relatively low in the southwestern and southern regions of Illinois where its yields are high. Costs of producing switchgrass in Illinois are much higher than those of corn stover and miscanthus (given its present yields). Thus, unlike the present generation of ethanol which is dominated by a single feedstock, corn, the next generation of (cellulosic) biofuels in the United States might be produced from a mix of feedstocks with more corn stover being used in central and northern Illinois and more miscanthus in southern and southwestern Illinois.

Table 2 shows the quantity of ethanol per hectare of land with different feedstocks with current yield of 2.8 gallons of corn ethanol per bushel of corn and projected yield of 87.3 gallons per delivered metric ton dm of cellulosic feedstocks (Wallace, Ibsen, McAloon and Yee, 2005). Costs and yield estimates in Table 2 are under the high cost scenario described above. Miscanthus can produce more than twice as much ethanol as corn can per unit of land and more than three times as much as corn stover or switchgrass. Miscanthus can produce at least 30% more ethanol per acre of land than combined ethanol production from corn grain and corn stover.

Figure 1. Farmgate Costs of Producing Cellulosic Feedstocks in Illinois

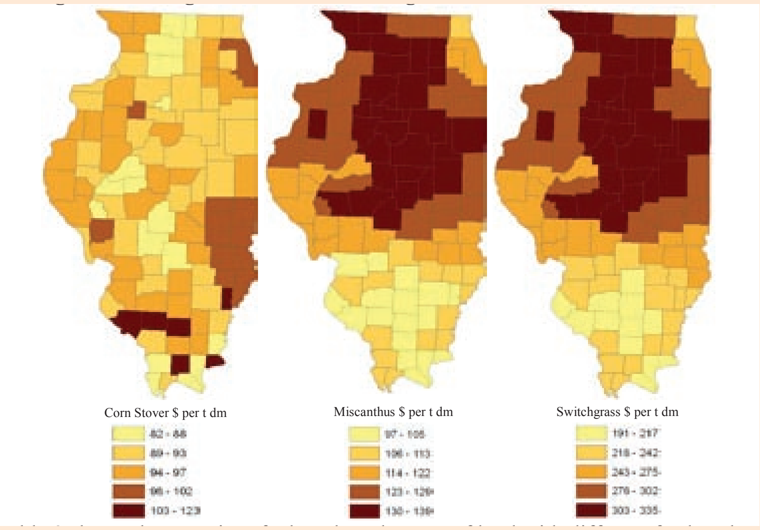

Table 2. Quantity and Costs of Production of Biofuels

	Gallons per Acre	Feedstock Cost	Cost of Conversion	Coproduct Credit	Total[a]
		Dollars per Gallon of Ethanol			
Corn Ethanol	398.75[b]	1.82	0.78[c]	0.48	2.12
Corn Stover	165.04[d]	1.27	1.46	0.12	2.62
Miscanthus	742.45	1.40	1.46	0.12	2.74
Switchgrass	214.74	3.18	1.46	0.12	4.53

[a] Wholesale costs at the refinery including zero return to equity. Feedstock cost for corn ethanol assumes $5/bu corn.

[b] Assuming an average yield of 145 bushels/acre under a corn-soybean rotation; [c] http://farmdoc.uiuc.edu;

[d] Assuming average yield under a corn-corn rotation.

Costs of Producing Cellulosic Biofuels

The per gallon cost of producing biofuel in Table 2 includes farmgate cost of the feedstock (including cost of land), cost of converting the feedstock into fuel, and credit for the value of coproducts produced during the conversion process (for example, dried distillers grains in the case of corn ethanol and electricity in the case of cellulosic biofuels). The technology for producing cellulosic biofuels is not yet commercially available. Projected estimates of these costs for cellulosic biofuels produced in a biorefinery with a 25 million gallon a year capacity are obtained from Wallace, Ibsen, McAloon and Yee (2005) and updated to 2007 prices using the GDP deflator. As can be seen from Table 2, delivered feedstock costs per gallon for corn stover and miscanthus are lower than those for corn. However, even optimistic projections of costs of conversion for cellulosic fuels ($1.46/gallon) are about twice as high as those of corn ethanol ($0.78/gallon) making cellulosic biofuels from corn stover and miscanthus 24% and 29% more expensive than corn ethanol, respectively. Biofuel from switchgrass is more than twice as expensive as corn ethanol making it very unlikely that current varieties of switchgrass will be competitive on cropland in Illinois unless their yields improve dramatically.

The market demand for cellulosic biofuels will depend on their competitiveness relative to corn ethanol and gasoline. The market price of denatured corn–ethanol is increasingly being determined by its energy content (which is about two–thirds of that of gasoline) and the blender's tax credit (Tyner and Taheripour, 2008). The recently enacted Energy Bill and Farm Bill provide several new incentives to encourage production of cellulosic biofuels while lowering the blenders' tax credit for corn ethanol from \$0.51 per gallon to \$ 0.45 per gallon.

Current Policy Incentives for Cellulosic Biofuels

To induce a market demand for cellulosic biofuels, the Energy Independence and Security Act of 2007 has imposed a renewable fuels standard of 36 billion gallons of ethanol by 2022. It mandates 21 billion gallons of advanced biofuels that can reduce life–cycle greenhouse gases by 50% relative to baseline levels. The recent Food, Conservation and Energy Act of 2008 includes more than \$1 billion to provide incentives to farmers to grow cellulosic feedstocks and to biofuel producers to use cellulosic feedstocks. This includes a \$1.01 per gallon tax credit for producers of cellulosic biofuels and cost share payments (up to 75% of establishment costs, plus annual payments to cover the cost of the land during establishment and \$45 per ton to cover costs of harvest, storage and transport). It also provides assistance for cellulosic biorefineries and for research and development, and incentives for using biomass (instead of fossil fuels) to power existing ethanol plants, thus creating a market for biomass feedstocks. Whether these incentive payments will stimulate production of cellulosic biofuels will depend on the price of gasoline, the costs at which it will be commercially viable to convert cellulosic feedstock into fuel and the costs of producing corn–based ethanol.

Policy Incentives to Encourage a Sustainable Mix of Biofuels

From a social efficiency perspective, the case for government intervention in biofuel markets is arguably justified, if biofuels reduce market failures caused by environmental externalities. If market prices of biofuels do not reflect environmental benefits then they are likely to lead to under–production of biofuels. Market based policies that reward environmental services are preferable to arbitrarily set mandates or subsidies. Biofuels not only provide a renewable source of energy but also a range of other environmental benefits. These benefits differ across biofuels from different feedstocks. While some feedstocks such as switchgrass may provide better habitats for wildlife, others such as miscanthus may have greater greenhouse gas mitigation potential. Feedstock derived from native mixed prairie grasses such as Indian grass and Big Bluestem contribute to enhanced biodiversity in the agricultural landscape and other ecological benefits but have much lower yields than even switchgrass. We estimated the average greenhouse gas mitigation potential of alternative biofuels in Illinois relative to gasoline using the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (http://www.transportation.anl.gov/software/GREET/) (Table 3). The estimates below are illustrative based on current knowledge and reasonable assumptions about input application rates, energy requirements and emissions coefficients.

While corn and corn stover reduce greenhouse gas emissions (including soil sequestration) by 37% and 94%, respectively, relative to energy equivalent gasoline, miscanthus and switchgrass can serve as net carbon sinks. These estimates show that corn ethanol produced with the current production technology would not qualify as being an advanced biofuel.

Table 3: Life Cycle Carbon Emissions Kg CO_2 per Gallon of Ethanol

	Feedstock Production	Biorefinery Phase	Coproduct Credit	Displacement due to change of land use[a]	Total Above Ground CO_2 Emissions	Soil Carbon Sequestration[b]	Total CO_2 Emissions Net of Soil Sequestration	Emissions Reduction Compared to Gasoline [c]
Corn	2.42	4.93	-1.99	0.00	5.36	-0.62	4.75	2.79
Corn Stover	1.22	0.28	-0.40	0.45	1.54	-1.09	0.46	7.08
Miscanthus	0.97	0.28	-0.40	-0.88	-0.04	-2.25	-2.29	9.83
Switchgrass	3.78	0.28	-0.40	-2.89	0.76	-6.40	-5.63	13.17

[a] These emissions include those due to direct land use changes from conversion of cropland to energy crops (column 5) but do not include those due to indirect land use changes in other countries due to diversion of U.S. cropland to energy crops.

[b] Of the estimated soil carbon sequestration by corn under conservation till, 50% is allocated to corn ethanol and 50% to stover ethanol.

[c] Emissions from gasoline are 7.54 Kg CO_2e per energy equivalent gallon of ethanol.

While volumetric subsidies and cost–share payments are market–based policies, they do not distinguish among biofuels based on their environmental sustainability and are likely to encourage production of feedstocks that have high yields per acre and low costs of production. They also tend to make fuel cheaper and lower cost of vehicle miles for consumers which tends to increase vehicle miles travelled and can reduce or even negate any greenhouse gas mitigation benefits due to substitution of renewable fuels for gasoline (Khanna, Ando and Taheripour 2008). Subsidies for corn–ethanol have also tended to expand production of corn grain ethanol and contributed to the rise in corn prices (Abbott, Hurt and Tyner, 2008). An alternative approach would be to provide carbon mitigation subsidies, the magnitude of which would depend on the market price of CO_2. Most analysts expect the price of CO_2 to be around $34 per metric ton over the 2008–2012 period in Europe (http://www.euractiv.com/en/climate-change/european-co2-emissions-2007/article-171327). At this price, the carbon mitigation (including sequestration) provided by biofuels relative to gasoline (indicated in Table 3) would imply a subsidy of $0.09, $0.24, $0.33 and $0.45 per gallon ethanol from corn, corn stover, miscanthus and switchgrass, respectively. Other environmental services provided by cellulosic feedstocks could be similarly monetized using appropriate values to correct the market prices of biofuels.

A Final Note

Crop residues can be used for cellulosic biofuel production without creating a food–fuel competition for land. A USDA/USDOE (2005) report estimates that 68 million metric tons of corn stover could be sustainably harvested from existing corn acres in the United States with a potential to produce 7 billion gallons of cellulosic biofuels. This would meet only about a third of the ethanol mandate for advanced biofuels in 2022 in the United States necessitating the development of other feedstocks such as switchgrass and miscanthus that are promising due to their relatively high yields per acre and low input requirements. This article explores the economic viability of these feedstocks using data for Illinois and finds that it is likely to differ across geographic locations. A mix of cellulosic feedstocks is, therefore, likely to be more economically viable than a single feedstock. Current estimates suggest that cellulosic biofuels are likely to be more expensive to produce than grain–based biofuels. However, the advent of new technologies for harvesting, storing, and converting cellulosic sources into biofuels could make them more competitive. Rewarding biofuels based on their environmental services would help to internalize environmental externalities and promote a sustainable mix of feedstocks. Aligning energy policy and climate policy through tax credits that are inversely related to their carbon footprint can provide incentives to produce low carbon cellulosic feedstocks. Policy incentives could also be created to encourage feedstocks that increase biodiversity and enhance ecosystem services.

For More Information

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