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Corn Stover Potential: Recasting the Corn Sweetener Industry*

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Corn stover is by far the largest single available biomass not being used, representing more than one-third of the total waste, including municipal solids. An estimated 200 million dry tonnes (t) remain each year as aboveground residue.

THE CORN STOVER ISSUE

The corn sweetener industry is based on processing corn grain (maize), creating value-added products such as glucose, dextrose, and fructose. Conversion of corn stover to sugars has been stymied for years due to cost. Environmental benefits, wider adaptation of sustainable farming practices and the relentless improvements in biotechnology are expected to overcome the economic hurdle within the next five years and recast the corn sweetener industry. The corn sweetner industry uses about 8% of the corn crop (20 million t) in 1997; the fuel ethanol industry used about 13 million t (515 million bu). These combined demands equal 13% of domestic demand for corn.

Corn stover consists of the stalks, leaves, and cobs remaining aboveground after the corn kernels are harvested. About 1 kg of stover is produced per kg of grain. In 1997 about 200 million dry t of stover was produced. The mass of stover increases with the yield of the corn—expected to increase 1% to 2% annually

More than 90% of the stover is left in the fields. Less than 1% of corn stover is collected for industrial processing. About 5% is baled for animal feed and bedding. Much of the remaining 90+% must be plowed under for planting to proceed on schedule, ensuring the best yield, eliminating weed seeds, insects and disease harbored by the stover, and reducing the threat of alpha-toxins in the corn. Although some residue is required to protect the soil from erosion, some residue can be safely removed.

Improved management of the residue has the potential to be a win-win for the producer, processor, and the environment. Now, up to 75% of the surface material decays to CO_2, a greenhouse gas (Parr and Papendick 1978; Gale and Cambardella 1999). Excessive residue makes no-till farming more difficult and reduces crop yield; cold soil temperature in the spring slows field drying, retards germination, and reduces growing seasons. It also contributes to problems with disease, weeds, pests, and irrigation. As a result of plowing, a carbon deficit can occur in the soil. The plowing activity exposes soil carbon to oxidation, increasing organic carbon loss with the release of CO_2. The plowing activity also releases soil N to the atmosphere by increasing soil oxidation, similar to the oxidation of soil carbon. This can lead to increases in NO_x and N_2O emissions. Plowing residues back into the soil also increases the amount of fertilizer chemicals that need to be applied. Residues raise the soil carbon content relative to the soil N content. If no N is added, the cash crop harvest is adversely affected while the residue decomposes.

Farmers and the corn processing industry—along with the fuel ethanol producers—are in position to benefit from conversion of excess corn stover to fuels and other products. The farmer wins from the stover sales, reduced cultivation costs and possible carbon credits for the greenhouse gas (GHG) offset. The processors grow to meet fuel market needs and create additional products, some new and others previously produced from petroleum. The environment benefits from improved agricultural practices and fewer GHG emissions.

Drivers for achieving this vision include moving to more sustainable agricultural practices, improved biomass conversion technology, worldwide commitment to reduce GHG emissions, and increases in petroleum cost as supply dwindles. Many envision this scenario to occur within the next five years.

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Impediments for Corn to Ethanol Expansion

Present annual ethanol production of 5.7 billion liters (1.5 billion gal) is just 1% of the total fuel transportation market. If corn grain is used to double ethanol production, the following disruptive effects ensue according to studies by the Government Accounting Office (USGAO 1990) and the USDA Economic Research Service (Petrulis et al. 1993): (1) higher corn prices, 9% to 15%; (2) increased livestock costs; (3) reduced corn export market, 5%; and (4) reduced soybean price, 6% to 11%.

Both studies show corn price would increase over baseline projections by $7 to $13/t (19 to 32 cents/bu). The higher corn price causes a 6% to 10% increase in feed cost, leading livestock producers to reduce the amount of corn purchased for animal feed and lower the number of cattle by 3% to 4%. Export markets for corn would also shrink, as higher prices would reduce the foreign demand for American-grown corn 4% to 5%.

Soybean processors and producers would face lower demand for their products because ethanol from corn generates protein-rich feed and corn oil by-products that compete with soybean meal and oil. Soybean prices would drop $13 to $426/t (31 to 66 cents/bu), 6% to 11% from the baseline and production would drop 3% to 5%.

Corn Stover Expansion Potential

Innovative corn stover harvest, collection and transportation practices have reduced the corn cost to $30–$35/dry t delivered in Western Iowa where 20,000 ha (50,000 acres) were collected during the 1997 crop year. Planned improvements in productivity and storage stability are expected to reduce costs to less than $30/dry t.

The sustainable amount removed depends on soil, topography, crops, crop rotation, tillage practice, and environmental constraints. Removing just one-third of the stover and hydrolyzing its 38% cellulose content with improved cellulase enzyme systems (currently being developed) results in 29 million t (64 billion lb) of glucose with a targeted cost of $132/t ($6/cwt) or less, twice the amount of sweeteners shipped in 1997. Low sugar cost can spur further market expansion to replace other petroleum-derived products.

The stover also contains 32% hemicellulose. When converted to pentose sugars that have less food value, their most likely future use is a nutrient for fermentation processes, with the largest being alcohol. Taking 80% of the hemicellulose to alcohol employing any of at least three engineered organisms presently under development produces 14 billion liters (3.6 billion gallons) of ethanol from one-third of the corn stover, again more than twice the 5.7 billion liters (1.5 billion gallons) produced annually. The targeted cost is less than $0.25/liter ($1/gal).

The market potential for sugar to supply the ethanol industry and other sugar-based products can be improved significantly by using excess corn stover. This excess may supply more than 5% of US gasoline needs—an additional 20 to 40 billion liters (5 to10 billion gallons) of ethanol. Farm income can be raised significantly without the production of feed coproducts and their adverse effects on livestock and soybeans.

Some surface residue—a minimum of 30% surface coverage—is required to comply with USDA guidelines for erosion protection. Removing 3 t/ha from 9 t/ha produced in many areas can comfortably attain erosion compliance with conservation tillage. With no-till, the quantity removed could likely be doubled.

Today, the excess corn stover decomposes; its potential to offset fossil fuel feedstock is lost. Other environmental benefits result from increased soil organic matter (SOM) formation that occurs by reducing the need to plow under the excess stover.

The stover offers an inherent cost advantage over corn, other grain or energy crops since the crops carry a production cost. The historical net corn cost is about twice the delivered cost of corn stover. The historical cost between 1980 and 1997 for dry mill corn ethanol plants averaged about $60/dry t (Lewis 1997). Delivered cost of corn stover is $32/dry t. Improvements are projected to lower the cost to less than $25/dry t delivered (Glassner et al. 1998).

Improved conversion of the biomass feedstock to sugar is proceeding rapidly. Application of proven biotechnological tools is projected to reduce fermentation sugar costs to less than 6 cents/lb. An early result is the current construction of two biomass conversion plants by BC International (BCI) and a joint venture between Iogen and Petro-Canada. Both are expected to be operating in 2000 (Wald 1998; Canadian Report 1998).

MARKET PULL

There are three drivers for increased ethanol in the transportation fuel market: (1) energy independence; (2) GHG offset of fossil fuel; and (3) cleaner air from vehicle emissions. The dependence of the US on imported fuel continues to increase. Global production of fossil fuel is likely to peak in the next decade. Questions regarding the security and availability of future supply continue to be raised (Scientific American 1998; Campbell 1998). There is increasing likelihood that interruptions and shortages will occur, along with the price hikes, recessions and political struggle unless actions are taken now.

To offset this scenario, domestic production of transportation fuel from biomass is receiving increased attention. For example, the last Congress extended the fuel ethanol subsidy through 2007. Also, the US Department of Energy has recently embarked on efforts to increase use of biodiesel in urban buses and other transportation sectors and "Bridge to the Corn Ethanol Industry" using the infrastructure in the corn ethanol industry.

The fuel ethanol market needs to grow quickly to meet these needs, according to former CIA Director Jim Woolsley (1998). Fuel ethanol represents just 1% of the transportation fuel market. He urges the industry to increase supply to 10% of the market "quickly" or risk being seen as an insignificant factor in energy markets. The California oxygenate market for ethanol is expected to become available in 1999. How ethanol production can be expanded nearly twofold to meet this new demand is currently an open question. Cleaner air from vehicle emissions has been established for a wide range of ethanol blends (Lynd 1996). Increasing the amount of ethanol in the blend reduces improves the quality of the emissions.

Using biomass to replace fossil fuel reduces GHG. The US has signed the Kyoto agreement to reduce GHG emissions, but that agreement faces an uncertain future in the Senate. Nonetheless, large multi-national corporations are faced with compliance in the EU, Canada, Australia, and other parts of the world. They are working to reduce GHG now and are pressing Congress to pass legislation that would give them valuable credits for early actions (Cushman 1999).

SUPPLIER PUSH

Excessive corn stover may significantly reduce crop yields, providing a push for its partial removal from the surface. If the surface residue is not managed well, the following problems can result: (1) germination is delayed due to low soil temperature in northern corn belt; (2) it contributes to weeds, pests and possibly results in toxins in the corn; (3) more chemicals are required for pest and weed control; and (4) excess restricts water in irrigated fields.

As producers have increased corn yields, disposition of the increasing amounts of stover remaining on the surface has become a greater problem for the producer. For example, 9.4 t/ha corn (150 bu/acre, 15.5% moisture) has approximately 9.4 t/ha aboveground residue, whereas a comparable 2.7 t/ha soybean crop (45 bu/acre) on that same land produces just 4.1 t/ha, has less than half the stover amount.

In the northern corn belt, excess stover on the surface can significantly reduce in crop yields, particularly on poorly drained soils and in cooler-than-normal growing seasons due to lower soil temperature in the spring. Lower soil temperature reduces the rate of seed germination and plant growth. The surface cover acts as insulation, causes higher soil moisture, and retards the soil-warming rate. Lower soil temperature also slows nutrient intake by the crops, increasing crop susceptibility to pests and disease.

Throughout the corn belt excess stover is an excellent harborage for weed seeds, insects, and disease. Crops can be seriously damaged if these issues are not addressed. Since herbicides and pesticides are partially absorbed by the residue, control is more expensive and difficult. Where irrigation is practiced, the excess can restrict water flow in the fields. Uneven stands and lower yields result.

SUPPLIER CHOICES

The producer choices for removing excess stover are usually limited to baling or plowing. Just leaving the corn stover on the surface to decompose is often not an effective solution. The rate of stover decomposition is relatively slow due to its carbon to nitrogen ratio. A C:N ratio of 10:1 is near optimum for rapid microbial action. Soybean stubble, with C:N ratios of 20:1, breaks down more quickly. Corn residue with a C:N ratio of 30:1 up to 70:1 is much slower to decompose (Shomberg et al. 1996).

Limited Bale Market

The bale market is limited to less than 10% of the total, almost exclusively for animal feed and bedding. Its use as feed is sub-marginal (Klopfenstein 1996). Although its fiber content suggests papermaking potential, economics remain a hurdle. Currently, the only industrial market—furfural production—uses less than 81,000 ha (200,000 acres) of the annual 32 million ha (80 million acres) of corn grown.

Tillage Chosen for Removal

Conventional tillage is the choice for most corn growers. In 1998, 61% of the land planted in corn was conventional-till, according to the national crop residue survey conducted annually by the Conservation Technology Information Center, CTIC. The CTIC survey data include crop by area and type of tillage practice: no-till, ridge-till, mulch-till, conventional tillage with 15% to 30% residue and 0% to 15% residue.

Table 1 shows virtually no change in conventional tillage practice in the US for corn over the past 7 years. In contrast, soybean conventional tillage has declined 20%, from 61% to 48%. These values for conventional-till are the sum for the land covered with 0%–15% and 15%–30% residue after tilling as reported on the CTIC web site: www.ctic.purdue.edu.

The motivation for tillage choice is not reported. Climate, crop rotation, soil type, previous crop yield and cultural values are all factors. The CTIC data do confirm the impact of climate. Colder weather in the northern corn belt makes producers in states such as Minnesota 28% more prone to plow under the surface residue in contrast to all farmers (Table 2).

Plowing under has many negatives including: (1) estimated $20/ha ($8/acre) or more to bury the stover; (2) additional N required for the stover; (3) loss of SOM; and (4) long-term adverse impact on soil quality from plowing versus no-till.

Tillage Cost. Using the Iowa farm custom rate survey (ISU Extension 1998), conventional tillage cost is $20 to $37/ha ($8 to $15/acre). Disking or soil finishing adds another $12 to $27/ha ($5 to $11/acre).

Additional Nitrogen Required. Plowing under heavy amounts of corn stover requires about another 10 kg N/t of stover to prevent nutrient deficiency. Crop residue that has a high C:N ratio, such as stover, can limit the availability of nutrients, especially nitrogen, for the succeeding crop as microorganisms that decompose the residue are competing for these nutrients.

Organic Matter Loss. Soil organic matter (mostly sequestered C and N in the soil) is also lost when the soil is disrupted by tillage. The loss of SOM is directly related to the amount of disruption. Moldboard plowing has the highest SOM loss, tandem disc is less, and chisel plow is still smaller. No-till soil organic matter (SOM) loss is mostly from the surface residue.

Table 1. Conventional till area of corn and soybean. Source: CTIC's National Crop Residue Survey.

	Conventional till area (% of total crop)							
Crop	1992	1993	1994	1995	1996	1997	1998	% decline 1992–1998
Corn	61	57	60	59	60	59	61	0
Soybeans	61	53	54	51	51	48	48	20

Table 2. Conventional till area of corn in Minnesota and the US. Source: CTIC's National Crop Residue Survey.

	Conventional till area (% of total corn crop)							
Location	1992	1993	1994	1995	1996	1997	1998	% ave. 1992–1998
Minnesota	75	73	78	80	79	N/A	N/A	77
US	61	57	60	59	60	59	61	60

An initial burst of CO_2 occurs and the loss continues over weeks. Aeration simulates microbial activity, SOM is rapidly consumed. Plowing mixes fresh residues into the soil where conditions for decomposition are more favorable than on surface. More than 40 studies have been made showing this effect on SOM (Janzen et al. 1997; Paustian et al. 1997). Fig. 1 shows the initial tillage induced tillage loss; Fig. 2 shows the loss over 19 days (Reicosky et al. 1993; Reicosky 1997).

Long-Term Tillage Impact. Continued tillage reduces SOM and fertility. Other negative effects include increased erosion, water run-off is often contaminated with chemicals, soil pore size is reduced, soil crusting occurs. The list goes on, and the CTIC web site offers information and other links. www.ctic.purdue.edu.

EXPAND MARKET FOR CORN STOVER

The market for corn stover can be expanded by low-cost collection and storage of stover, along with meeting the conversion target of \$134/t (\$6/cwt) of glucose and less than \$0.25/liter (\$1/gal) ethanol. Collecting stover has many benefits, including: (1) producers bale excess stover to resolve surface residue problems and increase margins; (2) processors have low-cost feedstock for new market opportunities, expanding fuel ethanol, and other fermentation products from sugar; and (3) environmental benefits from GHG offset and cleaner air as a result more no-till, increased SOM, and fossil fuel offset.

Sustainable Collection

If corn stover is baled, removing mainly the stalk portion of the stover and leaving much of the leaf, husk, and cob on the surface, along with the anchored stubble, it is most likely more producers could plant no-till. Properly managed, with adequate residue for erosion compliance, soil tilth and productivity are expected to improve.

The surface residue does have an important role in controlling wind and water erosion, SOM, and soil physical and chemical properties. Factors related to managing its removal include: (1) soil type; (2) topography; (3) crops; (4) crop rotation; (5) environmental constraints; (6) weather history; (7) tillage practice; and (8) value judgments.

Considerable effort has been expended to determine removal effects. As a result of the energy crisis more than 20 years ago, a team of USDA scientists studied residue availability: Woodruff and Siddoway (1965), Bisal and Ferguson (1969), Wischmeier and Smith (1978), Allmaras et al. (1979), Campbell et al. (1979), Gupta et al. (1979), Holt (1979), Larson (1979), Skidmore et al. (1979), and Lindstrom et al. (1979). Generally, they caution that removal should be justified only when the long-term impact on soil productivity is inconsequential. Reduced and no-till emphasis had not yet emerged.

Corn stover removal impact on erosion for reduced tillage, no-till, and conventional till was reported by Lindstrom (1986) for two sites. The experimental results show the excess stover is greater than can be removed with baling equipment. For 9.4 t/ha (150 bu/acre), the stover to be removed, 76% and 82%, is above the normal 70% limit of commercial balers. These site-specific results are summarized below.

The Universal Soil Loss Equation was used to determine the retained surface residue mass, Y, required to control soil loss to a tolerable level, T. The slope was 6% in both cases. The Y for Swan Lake was 2,240 kg/ha. For Madison, Y was 1,680 kg/ha. In both locations, leaving the amount of residue results in less actual soil loss than the tolerance level. Table 3 shows the results.

The effect of residue removal on SOM and sequestered C is less known. The relative contribution of roots and surface residue to SOM is receiving increased attention. Campbell et al. (1997) shows no adverse

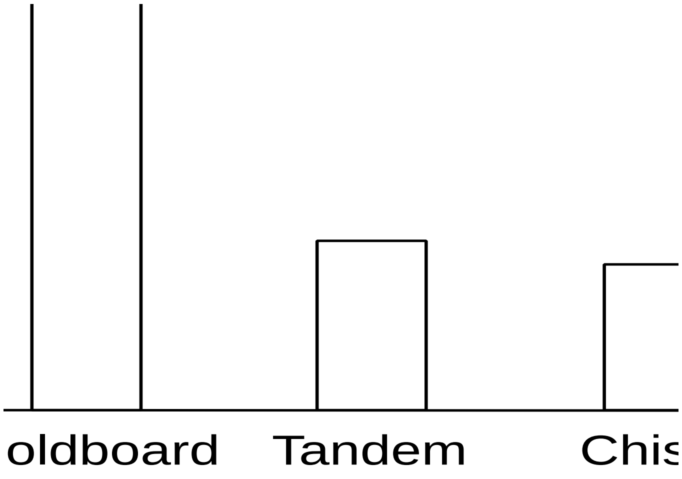

Fig. 1. Tillage induced soil organic matter loss as CO_2, Source: Reicosky (1993).

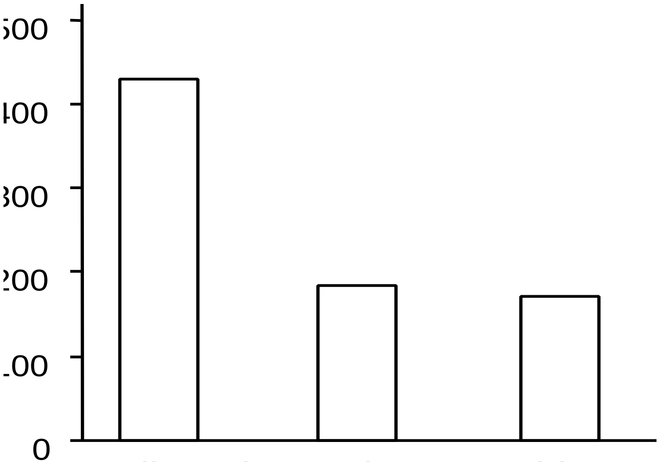

Fig. 2. Tillage induced soil organic material loss as CO_2, Source: Reicosky (1993).

effect on soil C and N since 1990 by removing straw from no-till fields. They address the use of several SOM measurement methods, and indicate the methods vary considerably. A search of the USDA CRIS database indicates much additional research is underway in this area, but not yet published.

Low-Cost Collection

Recent collection of corn stover show delivered cost of $30/dry t or less is achievable (Glassner et al. 1998). An industrial processor contracted with 440 producers for 20,000 ha (50,000 acres) of stover near Harlan, IA last year. Custom operators performed all baling, collecting, and hauling.

Table 4 summarizes corn stover pricing used for the 1997–1998 crop year. The delivered price for the stover was $34.76/dry t if about 8 t/ha (3 tons/acre) were collected. If only 4 t/ha (1.5 tons/acre) were harvested, the price increased to $39.30/dry t. Most producers chose higher collection, Case 2. Producers with sloped land mostly chose Case 1. The two prices were based on perceived quality differences in bale composition. No difference was seen and two-tier pricing was discontinued this year. The baler received $16.06/dry t, regardless of the density. The producer and the hauler shared the remainder based on distance. Table 4 summarizes corn stover pricing used for the 1997–1998 crop year.

The combine left a windrow by shutting off the spreader. No raking was required. Both round and square balers were used. Bale density was about 550 dry kg/bale. Round bales were triple wrapped with plastic net that permitted outside storage.

Table 3. Effect of residue harvest and till practice on soil loss.

Location Tillage	Total[z] residue (kg/ha)	Residue retained & surface cover (kg/ha)		Residue removed (kg/ha)		Soil loss tolerance (kg/ha)	Actual loss (kg/ha)
		(kg/ha)	(%)	(kg/ha)	(%)		
Swan Lake, Minnesota							
Conventional-till	9,430	9,430	9	0	0	11,200	7,100
Reduce-till, 0.5Y	9,430	1,120	16	8,310	88	11,200	11,800
Reduce-till, Y	9,430	2,240	29	7,190	76	11,200	6,500
Reduce-till, 2Y	9,430	4,480	33	3,950	42	11,200	1,600
Madison, South Dakota[y]							
Conventional-till	9,430	9,430	10	0	0	11,200	32,800
No-till, 0.5Y	9,430	840	33	8,590	80	11,200	42,700
No-till, Y	9,430	1,680	46	7,750	82	11,200	10,400
No-till, 2Y	9,430	3,360	56	6,070	64	11,200	5,500

[z] Based on 9,430 kg/ha (150 bu/acre) corn harvest.

[y] Two exceptional rainstorms resulted in high erosion at Madison, SD.

Table 4. Corn stover pricing summary (1997–1998).

	Corn stover payments ($/dry t)			
	Hauling radius			
Revenue	0–25 km	26–49 km	50–80 km	81–164 km
Producer				
4 dry t/ha (Case 1)	16.50	13.56	10.63	7.70
>5.5 dry t/ha (Case 2)	12.00	9.05	6.12	3.19
Baler	16.06	16.06	16.06	16.06
Hauler	6.71	9.65	12.58	15.51
Total, Case 1	39.30	39.30	39.30	39.30
Total, Case 2	34.76	34.76	34.76	34.76

Table 5. Projected sugar cost based on improved conversion technology.

Process improvement	Technology availability date	Total sugar costs ($/MT)	($/cwt)
Current industrial cellulase expression with mesophilic fermentation system	1998	154	(7.00)
3× specific activity improvement, thermophilic expression system	2003	117	(5.30)
10× specific activity improvement, increased sugar fermentation	2008	106	(4.80)
Higher carbohydrate feedstock infrastructure to support larger plants	2013	84	(3.80)

High-speed tractors were used with "load and go" wagons. One operator could load 17 round bales, about 12 to 14 t, in less than 20 min. Safe tractor-wagon speeds, up to 70 km/hr, permitted economic transport over a 50-km radius. Less than 10 min was required to weigh, sample and unload at the processing location.

Cost reduction to $25/dry t or less is projected from improved baling productivity, transportation efficiency and regulatory changes that include the custom operators in the same category as producers for transporting the stover to the processor. This activity furthers infrastructure development for biomass collection. It also improves the base for accelerating entry of energy crop production.

Corn Stover Conversion

The corn stover is primarily composed of cellulose, hemicellulose, and lignin. The cellulose and hemicellulose are hydrolyzed to hexose and pentose sugars using thermochemical and enzymatic unit operations. Lignin has high value and is used as a fuel for steam and electrical production used in biomass conversion process. Removing just one-third of the stover and hydrolyzing its 38% cellulose content with improved cellulase enzyme systems currently being developed results in 29 million t (64 billion lb.) of glucose with a targeted cost of $132 t ($6/cwt) or less, twice the 58 million t of sweeteners (32 billion lb.) shipped by the corn refiners in 1997.

The stover also contains 32% hemicellulose. When converted to pentose sugars that have less food value, their most likely future use is a nutrient for fermentation processes, with the largest being alcohol. Taking 80% of the hemicellulose to alcohol employing any of at least three genetically engineered organisms (GEOs) presently under development produces 14 billion liters (3.6 billion gallons) of ethanol from one-third of the corn stover, again more than twice the 27 billion liters (1.5 billion gallons) produced annually. The targeted cost is less than $0.25/liter ($1/gal).

Application of proven biotechnological tools is expected to reduce fermentation sugar costs to less than 6 cents/lb. Table 5 summarizes the expectations for process improvement.

BC International is currently starting up a 76 million liter (20 million gallon) per year plant in Jennings, LA for the conversion of hemicellulose using a GEO. BCI will employ one of the three GEO for pentose conversion to ethanol. Also, Iogen and Petro-Canada announced a partnership for construction of a 2 million liter (0.5 million gallon) cellulose and hemicellulose demonstration plant. They will use two other GEO for cellulose conversion to glucose and pentose conversion to ethanol. Both plants are expected to be operating in 2000.

CONCLUSIONS

Corn stover has the potential to produce more than 50 million t of sugar annually, more than doubling the current sweetener industry production. The projected sugar conversion cost can open up new market possibilities by replacing petroleum-derived products. Transportation fuels and other petroleum derived products can be produced from the stover-derived glucose and pentose sugars, reducing the future need for fossil fuels. Realization of this scenario depends of the following: (1) sustainable harvest of corn stover in sufficient quantities; (2) attainment of improved corn stover conversion technology; (3) a worldwide commitment to reduce GHG emissions; and (4) increase in the price of petroleum.

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