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Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol

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Summary

Corn stover is the residue that is left behind after corn grain harvest. We have constructed a life-cycle model that describes collecting corn stover in the state of Iowa, in the Midwest of the United States, for the production and use of a fuel mixture consisting of 85% ethanol/15% gasoline (known as "E85") in a flexible-fuel light-duty vehicle. The model incorporates results from individual models for soil carbon dynamics, soil erosion, agronomics of stover collection and transport, and bioconversion of stover to ethanol.

Limitations in available data forced us to focus on a scenario that assumes all farmers in the state of Iowa switch from their current cropping and tilling practices to continuous production of corn and "no-till" practices. Under these conditions, which maximize the amount of collectible stover, Iowa alone could produce almost 8 billion liters per year of pure stover-derived ethanol (E100) at prices competitive with today's corn-starch-derived fuel ethanol. Soil organic matter, an important indicator of soil health, drops slightly in the early years of stover collection but remains stable over the 90-year time frame studied. Soil erosion is controlled at levels within tolerable soil-loss limits established for each county in Iowa by the U.S. Department of Agriculture.

We find that, for each kilometer fueled by the ethanol portion of E85, the vehicle uses 95% less petroleum compared to a kilometer driven in the same vehicle on gasoline. Total fossil energy use (coal, oil, and natural gas) and greenhouse gas emissions (fossil CO_2, N_2O, and CH_4) on a life-cycle basis are 102% and 113% lower, respectively. Air quality impacts are mixed, with emissions of CO, NO*x*, and SO*x* increasing, whereas hydrocarbon ozone precursors are reduced.

This model can serve as a platform for future discussion and analysis of possible scenarios for the sustainable production of transportation fuels from corn stover and other agricultural residues.

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Looking at Ethanol within the Framework of Sustainable Development

The oil crises of the 1970s sparked an interest in the United States in the development of domestic and renewable energy resources that could reduce the country's voracious appetite for nonrenewable and foreign energy supplies. In the meantime, other environmental and economic concerns have broadened the debate over energy to include issues such as climate change, air quality, water quality, and sound stewardship of the land. Overlying all of these questions is the constant pressure for economic development that "lifts all boats." This often awkward and conflicting collection of social concerns is captured in the growing public debate about the possibility of, and pathways toward, what E. O. Wilson appropriately refers to as the "ethic" of sustainable development (Wilson 1998).

This study uses life-cycle assessment (LCA) as a tool to understand some of the key energy, environmental, and economic aspects of ethanol made from stover, the agricultural residue that is left in the field after harvesting corn grain. The results of this study, as with the results of any life-cycle assessment, can do no more than identify key technical questions and trade-offs. Because sustainability is fundamentally an ethical issue, the technical context presented here is not adequate to fully assess the sustainability of ethanol or any other fuel choices. The results presented here are meant to seed serious public dialogue about this fuel's "sustainability," rather than provide the answer to a question that cannot be answered without public input and debate.

Agreeing on the Scope of the Study

In the spirit of dialogue, life-cycle assessment standards call for involvement of stakeholders early in the process of setting the scope of the work (ISO 1997, 1998). To that end, in May of 2000, we invited a group of farmers, environmentalists, automakers, grain processors, and government researchers to come together and discuss their concerns about using corn stover to make fuel ethanol and to help us establish the scope for this study.

The Indicators of Sustainability

Stakeholders established a list of indicators that they felt should be used to measure the relative sustainability of switching from gasoline to stover-derived ethanol to fuel our cars. These are summarized in table 1. We have been able to quantify many of these indicators. Some have been addressed in very narrow terms or in very qualitative terms. The biggest omission in the study is the lack of data on water quality effects (eutrophication), which we hope to address in future studies. In this article, we highlight our findings regarding energy, economic, global climate change, air quality, and soil health impacts.

The System Boundaries

Stakeholders established the system shown in figure 1. The stages of the life cycle for bioethanol include (1) production and collection of stover on the farm, (2) transport of the stover from the farm to a processing facility that produces ethanol and electricity, (3) distribution of ethanol to retail fueling stations, and (4) use of the ethanol in the form of E85 (85% ethanol/15% gasoline on a volume basis) in a flexible-fuel light-duty passenger car. Because we want to understand the impact of switching from gasoline to ethanol, we also include all of the life-cycle stages for gasoline, from extraction of crude oil in the ground (both domestically and around the world) to the use of gasoline in the same flexible-fuel vehicle (FFV) that can operate on any fuel mixture containing 0 to 85% ethanol in gasoline. The total life-cycle flows from gasoline use in this system are treated as avoided flows, meaning that the life-cycle flows associated with driving 1 kilometer (km) on gasoline are subtracted from the life-cycle flows associated with driving 1 km on E85. At the same time, a portion of the life-cycle flows for gasoline production are added to the ethanol life-cycle system to account for the 15% volume per volume (v/v) gasoline content of E85.

Similarly, we account for avoided flows associated with the U.S. Midwest electricity generation that is displaced by electricity exported from the stover-to-ethanol processing facility. (See the section on geographic scope for details on the characterization of Midwest electricity

Table 1 Stakeholder indicators for sustainability

Metric identified by stakeholders	*Specific measures*	*Addressed in this study?*	*Addressed in this article?*
Energy security	• Fossil energy savings (includes coal, petroleum, and natural gas)	Yes	Yes
	• Petroleum savings	Yes	Yes
Climate change	• Carbon dioxide (CO_2)	Yes	Yes
	• Methane (CH_4) as CO_2 equivalents	Yes	Yes
	• N_2O as CO_2 equivalents	Yes	Yes
Air quality	• Hydrocarbon ozone precursors	Yes	Yes
	• Carbon monoxide	Yes	Yes
	• Nitrogen oxides	Yes	Yes
	• Sulfur oxides	Yes	Yes
Acidification	• Equivalent H^+ to the atmosphere	Yes	No
Land use and biodiversity	• Qualitative description of land use changes	Yes	Yes
Soil health	• Soil erosion	Yes	Yes
	• Soil organic matter measured as soil carbon	Yes	Yes
Community impacts	• Economic flows to Iowa farm communities	Yes	No
Solid waste	• Hazardous and nonhazardous solid waste	No	No
Eutrophication	• Biological and chemical oxygen demand	No	No
	• Nutrient leaching to groundwater and surface water	No	No
Air and water toxics	• Not studied	No	No

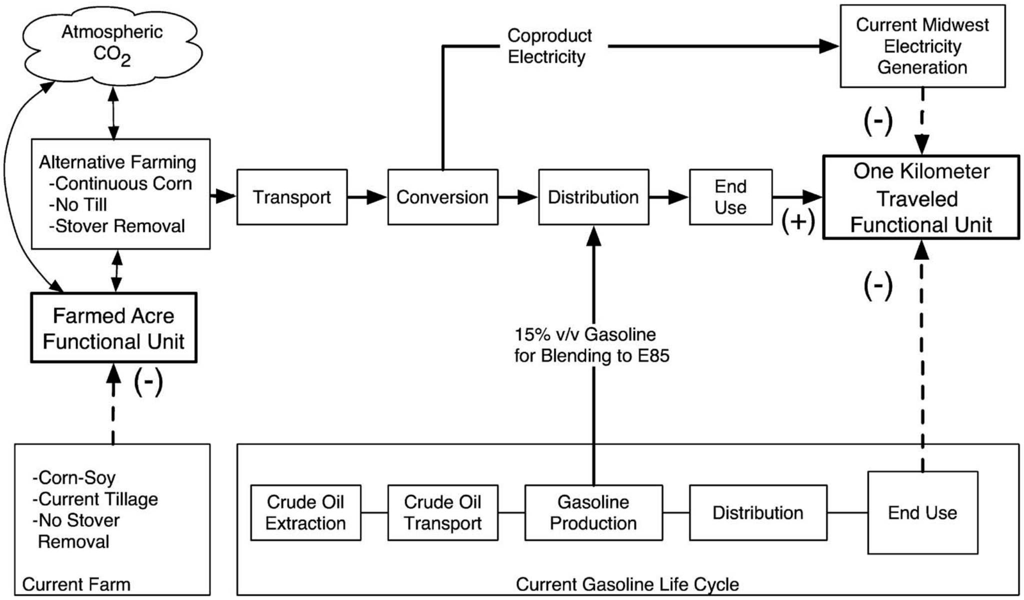


Figure 1 The life-cycle system for driving fueled by ethanol from corn stover.

generation.) At the farm, we assume changes from current farming practices. The net flows from the farm are estimated as the difference in flows associated with the modeled changes in farm practices and flows associated with current farm practices (this is described in more detail later).

The system is actually more complex than shown in figure 1. It includes the indirect life-cycle flows associated with raw materials, chemicals, and fuels used in each life-cycle stage. We exclude construction of equipment, buildings, and other basic elements of infrastructure.

The Functional Basis for Measuring Changes in Sustainability

Standards for life-cycle assessment require that stakeholders identify, at the very start, a functional unit for normalizing all of the changes in life-cycle flows (ISO 1997, 1998). Almost all previous life-cycle studies of ethanol have reported resource and environmental flows associated with 1 km of travel using the fuel (Delucchi 1994a, 1994b; Riley and Tyson 1994; Wang et al. 1997, 1999). Although stakeholders agreed that this was an appropriate basis for looking at stover-derived ethanol, they also suggested that we consider the changes in the sustainability of farming itself. This led to designing the system so that we could report life-cycle flows in our system for farming 1 hectare (ha)[1] of land[2] as well as for traveling 1 km (figure 1).

The Temporal Scope of the Study

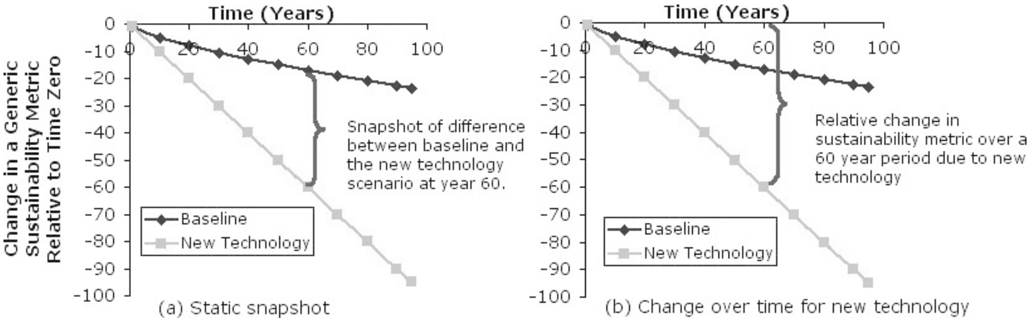
The stakeholders gathered at our goal and scope meeting agreed to look at the possible impacts of a near-future introduction (within the next five to ten years) of new technology for the conversion of corn stover to ethanol. This is an important caveat. No commercial technology for ethanol production from stover exists today. More details on the nature of the projected ethanol facility are provided later in this article. All other aspects of the life-cycle system are based on current practices.

Typically, life-cycle assessments offer a single snapshot in time of the systems being studied. The introduction of soil carbon effects in our study requires a different approach to defining the temporal scope because soil carbon changes occur on a timescale measured in decades. The soil carbon modeling we have done is not only time dependent, but it is specific to the initial conditions of the soil being studied. We looked at the effect of stover-to-ethanol technology relative to a baseline soil condition at time zero when stover collection begins (see panel b of figure 2 for generic, time-dependent soil CO_2 emissions).

Our choice of a time-zero baseline was based on the lack of data available to adequately describe the baseline behavior of soil carbon and soil erosion throughout a 90-year period for the current mix of crop rotations and tilling practices[3] in Iowa. In future studies, we hope to measure relative changes in time-dependent sustainability metrics using the difference between the new technology scenario and the time-dependent baseline (as in panel a of figure 2), rather than using a fixed time-zero baseline.

As figure 2 suggests, the use of a time-zero baseline for CO_2 emissions overestimates the benefits of introducing stover technology when the baseline case for soil emissions includes carbon reductions related to ongoing sequestration in the soil. Conversely, if the baseline case includes net positive emissions of CO_2 from the soil to the atmosphere, our use of a time-zero baseline underestimates the benefits of introducing stover technology. We have done a preliminary analysis of soil carbon trends for 100% adoption of corn-soybean rotations (currently the dominant rotation in Iowa) in conjunction with 100% adoption of moderate tilling practices among current Iowa corn farmers over a 90-year period. This combination of practices is an optimistic representation of current corn-farming practices in Iowa, because we estimate that 60% of corn farmers in Iowa actually practice more aggressive conventional tilling (Brenner et al. 2001), which is known to release CO_2 from the soil (Reicosky et al. 1995, 1999). For 100% adoption of both a corn-soybean rotation and moderate tilling practices, overall levels of carbon in the soil increase slightly over the first 20 years but are relatively constant over most of this time. Although more complete analysis of projected baseline emissions of soil carbon is needed, we conclude that the use of a time-zero baseline has only modest impacts on the overall findings for projected CO_2 benefits.

Using a time-zero baseline also ignores any changes in technology that may occur over the next 90 years. In particular, we are ignoring any future changes in the production of gasoline and its use in a light-duty vehicle. Gasoline and vehicle technology are likely to continue to move



(a) Static snapshot

(b) Change over time for new technology

Figure 2 Two approaches to handling temporal changes in life-cycle assessment metrics (case b was used to model soil carbon effects).

Table 2 Geographic scope of the life-cycle study

Life-cycle stage	*Geographic scope*
Feedstock production	Iowa (county level)
Stover production, collection	Global (foreign and domestic crude oil)
Crude oil production	
Feedstock transport	Iowa (individual plants in Iowa)
Stover transport	Global (foreign and domestic transport)
Crude oil transport	
Feedstock conversion	Iowa (individual plants in Iowa)
Stover to Ethanol	U.S. Midwest
Refinery production of gasoline	
Fuel distribution	U.S. Midwest
Ethanol	U.S. Midwest
Gasoline	
Fuel use	Midwest (urban)

toward lower emissions at the tailpipe (Weiss et al. 2000). We are likely, therefore, to overestimate tailpipe emission benefits (and underestimate penalties) associated with the replacement of gasoline by ethanol made from corn stover. Finally, this approach ignores changes in farm practices and improvements in the production and use of chemicals and fertilizers. We are simply asking if the path of implementing stover-to-ethanol technology improves or worsens the sustainability of driving and/or farming, all other things being equal.

The Geographic Scope of the Study

In the ideal world, we would be able to define the geographic boundaries of the system consistently for all aspects of the system we have modeled. Unfortunately, this is rarely, if ever, possible. Consider the system we have studied (table 2). The geographic scope of farming has been explicitly limited to a county-by-county analysis of the state of Iowa in the central U.S. Given the regional specificity of land use and biomass production, it makes sense that farming should be the most narrowly defined component in the life-cycle system. Likewise, stover transport and conversion are limited to the state of Iowa. The stover-to-ethanol conversion facility produces both fuel and electricity. We assume that the electricity displaced by the stover facilities reflects the mix of electricity produced in the Midwest region of the U.S. National Electricity Reliability Council that includes Iowa. The fuel mix for this region includes 73% from coal, 16% from nuclear, 10% from hydroelectric sources, and the remaining 1% from natural gas and heavy oil (EIA 1996). Production and transport of crude oil must be modeled on an international scale, because more than 50% of the oil consumed in the United States is from foreign sources.

Modeling Tools

A comprehensive life-cycle assessment requires a multidisciplinary approach. This study brings together four highly specialized modeling tools to describe the production of ethanol from corn stover:

1. Soil erosion modeling based on the U.S. Department of Agriculture's (USDA's) revised universal soil-loss equation for rainfall erosion (Wischmeier and Smith 1965; Renard et al. 1996) and the USDA's wind erosion equation (Skidmore et al. 1970, 1979) for wind erosion
2. Soil carbon modeling based on Colorado State University's CENTURY model, which describes the dynamics of soil carbon flows in agri-ecosystems (Parton et al. 1988, 2001; Parton 1994; Paustian et al. 1997b; CSU-NREL 2001)
3. Economic and transportation modeling for collection and transport of stover based on Oak Ridge National Laboratory's geographic information system (GIS) based ORIBAS model (Graham et al. 2000)
4. Process simulation for material and energy balances in the stover-to-ethanol process (Wooley et al. 1999a, 1999b; Aden et al. 2002) using AspenTech's AspenPlus modeling software

The results of all four models are incorporated in a life-cycle model constructed using PriceWaterhouseCoopers' commercial life-cycle modeling tool, TEAM™, and its companion life-cycle database, DEAM™.

Modeling the Farm

Most of the cropland in Iowa is farmed in a multiyear rotation of corn and soybeans (Brenner et al. 2001; NASS 2001; Sheehan et al. 2002). Because of limitations in data available at the start of this study, we model farming in Iowa as though all farmers instantaneously shifted from the dominant corn-soybean rotation to continuous production of corn. Furthermore, we make the assumption that all farmers switch to no-till practices that maximize the rebuilding of soil carbon and the protection of soil from erosion. These two assumptions represent a significant change. At time zero in our model, we assume the following:

- 90% of the corn acres in Iowa experience a two-year rotation of corn and soybean production.
- 58% of Iowa corn farmers practice conventional tillage.
- 26% of farmers practice some form of moderate or mulch tilling.
- 16% of farmers practice no-till cultivation.

These assumptions about baseline practices influence the starting levels and dynamics of carbon in the soil. Thus, our results do not apply to farming as it is currently practiced in Iowa. Despite this limitation, the results offer useful insights about the trade-offs involved in using corn stover to make ethanol.

Allocation of Life-Cycle Flows on the Farm

Allocation methods for systems that generate multiple products and serve multiple functions can be problematic. Allocation in the Iowa corn-farming system is complicated at two levels:

1. Allocation of life-cycle flows between corn grain and corn stover production
2. Comparison of life-cycle flows between the baseline farm that produces corn and soybeans in alternating years and the proposed farm that produces corn only

Figure 3 expands the level of detail for the farming portion of the life-cycle system shown previously in figure 1. The changed farming system requires a shift from corn-soybean rotation to continuous corn production. In addition, the new system includes life-cycle flows for the collection of the corn stover during a second pass through the field after the grain has been harvested. We also assume that nutrients removed with the stover must be replaced with fertilizer additions above and beyond the amount of fertilizer already applied for corn grain production. This new system has two outputs for an acre of

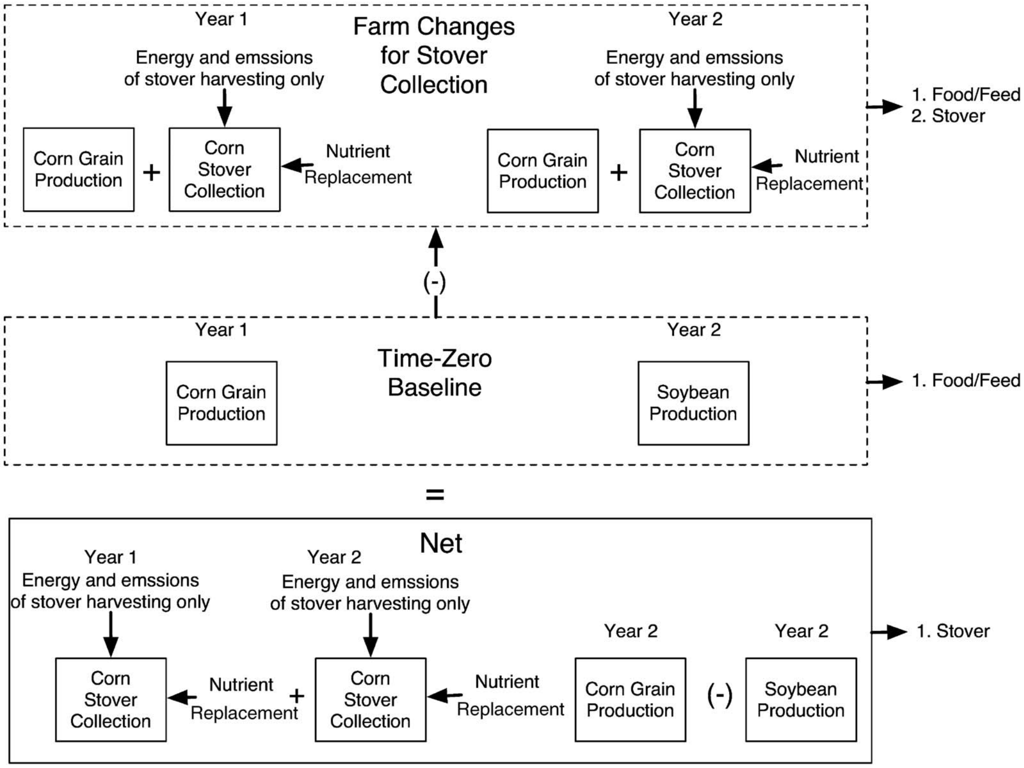


Figure 3 Allocation of life-cycle flows on the farm.

land: grain used in the food and feed market and stover used to make ethanol.

We make the very broad assumption that the functional services delivered by an acre of corn and an acre of soybeans are about the same. This gross simplification leads to a net system in which the life-cycle burdens of stover collection and the incremental burdens of corn versus soybean production in the second year of the two-year rotation are completely allocated against the production of stover (as illustrated in figure 3). This admittedly inelegant solution to the allocation problem is likely to provide a conservative view of the life-cycle impacts of stover-derived ethanol. It represents one extreme alternative to handling the allocation of the incremental corn versus soybean production burdens. At the other extreme, we could set up the system so that all of the grain and soybean production burdens are allocated to the food and feed services and only the direct burdens associated with stover collection are assigned to the stover. Finally, there is the possibility of an intermediate solution in which some fraction of these incremental production burdens are allocated to the food and feed functional service. This last option is probably closer to reality than either of the two extremes. The problem with this approach is that there has to be a basis for allocating between the food/feed products delivered and the stover. This allocation problem deserves further study and analysis.

Finally, we make one more simplifying assumption. We estimate the incremental life-cycle flows of corn versus soybean production as the incremental burdens associated with the nitrogen, phosphorus, and potassium fertilizer applied. In other words, we assume that there are only small differences in the use of farm diesel and other farm chemicals between corn and soybean production.

Constraining Residue Removal Based on Soil Erosion

Residues left behind after the grain is harvested provide surface cover that protects the soil from washing away when it rains and blowing away when it is windy. The more residues that are removed, the more soil erosion that occurs. But soil erosion is also a "fact of life"; it happens with or without the "help" of farmers. So, the question we pose in this study is not whether residue collection can be done without causing soil erosion, but if it can be done with erosion loss that we can tolerate.

Coming to agreement on what is a tolerable level of soil loss is not trivial. The USDA has wrestled with this question for decades (Wischmeier and Smith 1965). In its simplest terms, tolerable soil loss is defined as "the maximum amount of soil loss due to erosion by water or wind that can be allowed without causing adverse effects on soil and water resources" (Miller et al. 1999, p. 7). Commissioners of every soil and water conservation district have set tolerable soil-loss limits for each soil type unit in Iowa.

We use tolerable soil loss as a constraint on the collection of stover, rather than predicting soil erosion resulting from stover collection. In the 1970s, researchers at the USDA developed a methodology for estimating how much residue could be removed and still maintain soil erosion losses within USDA's tolerable soil-loss limits for various regions of the United States (Larson 1979; Lindstrom et al. 1979, 1981; Skidmore et al. 1979). It accounted for climate, soil type, differences in terrain, and the total amount of residue produced, as well as the type of crops planted and the type of tilling practiced. We have adapted this methodology to estimate the maximum amount of residue that can be collected in each of the 99 counties in Iowa for continuous corn production and no-till practices.

The details of our methodology are provided elsewhere (Nelson 2002). The rainfall and wind erosion models allow us to calculate the minimum residue required to be left on the field to keep the erosion within USDA tolerable soil-loss limits. The total amount of residue produced, for corn, is calculated assuming a 1:1 ratio of residue to grain, using average corn yields reported for each county in Iowa from 1995 to 1997. The difference between total residue produced and minimum residue in the field is the maximum amount of collectible residue.

Figure 4 shows the average minimum amount of residue that must be left on Iowa cornfields for a typical tilling operation (mulch till) and for no-till operation, assuming that all farmers are growing corn continuously. Statewide, 24 million metric tons (MMT)[4] of residue must be left in the field for erosion prevention for mulch till practices. This drops by a factor of 2 if farmers adopt no-till practices. For comparison, from 1995 to 1997, Iowa farmers achieved a statewide average yield of 8.23 metric tons (mt) of grain/ha (131 bushels of corn grain/acre)[5] on 4.8 million hectares (11.9 million acres) of land. Yields at the county level ranged from a low of 5.75 mt of grain/ha (91.5 bushels/acre) to a high of 9.36 mt of grain/ha (149 bushels/acre). This corresponds to approximately 40 MMT of residue available across the state of Iowa. Thus, approximately 40% of the residue can be collected under continuous corn production and mulch till, compared with 70% under no-till. Note that the percentage of collectible residue would be lower for a corn-soybean rotation because of the smaller amounts of residue produced by soybean crops.

Predicting Soil Carbon Levels

The choice of Iowa as the geographic scope of the farming system was driven by the availability of an extensive database of historical information on Iowa soils developed by the USDA Natural Resources Conservation Service in conjunction with researchers at Colorado State University (Brenner et al. 2001). This provided approximate soil carbon profiles on each county in Iowa from the mid-1800s to the present.

To model the effect of switching from current practices in Iowa to continuous corn production and no-till practices, we run the CENTURY model for 20 years with just the switch to continuous corn production in conjunction with the current mix of conventional, moderate, and no-till practices. Then, we introduce complete adoption of no-till practices for a 90-year period, along with the option to remove any amount of corn stover from zero up to the maximum removable rate (as constrained by soil erosion). Soil carbon values are reported out by CENTURY at 0, 5, 10, 15, 20, and 90 years after the introduction of no-till and different levels of stover removal. Climate data used in this study represent long-term averages recorded from 1961 to 1991 (Brenner et al. 2001). Because our analysis

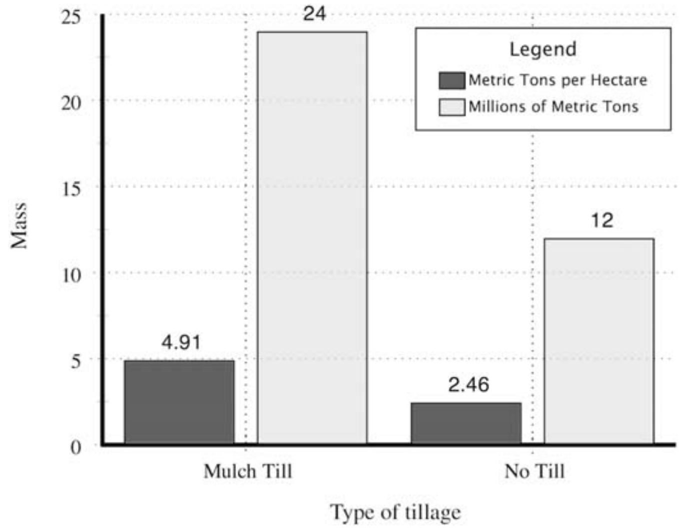


Figure 4 Minimum residue requirements in Iowa cornfields.

was done at the county level, temperature and precipitation values were calculated for each county on an area-weighted basis. All other effects being equal, the soil ecosystem responds to a change in biomass carbon addition rates by asymptotically increasing or decreasing the amount of soil carbon toward a new equilibrium level (Paustian et al. 1997a), depending on whether the rate of biomass carbon addition increases or decreases.

We use a regression model of CENTURY's predicted soil carbon response based on saturation kinetics to fit a continuous response curve to the data points reported out of CENTURY for each county. We do this to simplify the linkage between the CENTURY model and the life-cycle model. In the life-cycle model, each county in Iowa has a corresponding regression equation that describes soil carbon as a function of time and the level of residue collection. An example of the regression curves for Dubuque County is plotted in figure 5 for the case of no stover removal and the case of maximum stover removal, with the actual CENTURY values shown for comparison. These results demonstrate how the switch to continuous corn production leads to a buildup of soil organic matter. This benefit practically disappears when stover is removed at its maximum (erosion-limited) rate.

Another important advantage of generating a regression equation to describe the soil carbon profiles directly in the life-cycle model is that it allows us to estimate the year-to-year flux of carbon to or from the soil. We use a derivative of the soil carbon regression equations to estimate soil carbon flux into the atmosphere (in grams of carbon per hectare per year) as a function of time in each county. Figure 6 shows the soil carbon flux plot for Dubuque County, Iowa, corresponding to the soil carbon profiles shown in figure 5. Details of how we developed these response curves are provided elsewhere (Sheehan et al. 2002). The large negative fluxes associated with the scenario of no-till and continuous corn production without residue collection reflect the fact that the soil is taking up carbon from the atmosphere and storing it as organic matter.

Corn Yield

Implicit in all of the calculations presented thus far are important assumptions regarding yield. These assumptions fall into three categories:

- Forecasting future corn yields under current farm practices
- Predicting the effect of stover removal on yield
- Predicting the effect of corn stover on soil carbon levels

When we estimate total removable stover, we assume constant yields of corn based on the average corn yields reported by the USDA in each county from 1995 to 1997. We know, of course, that this is unlikely to be true. Corn yields in

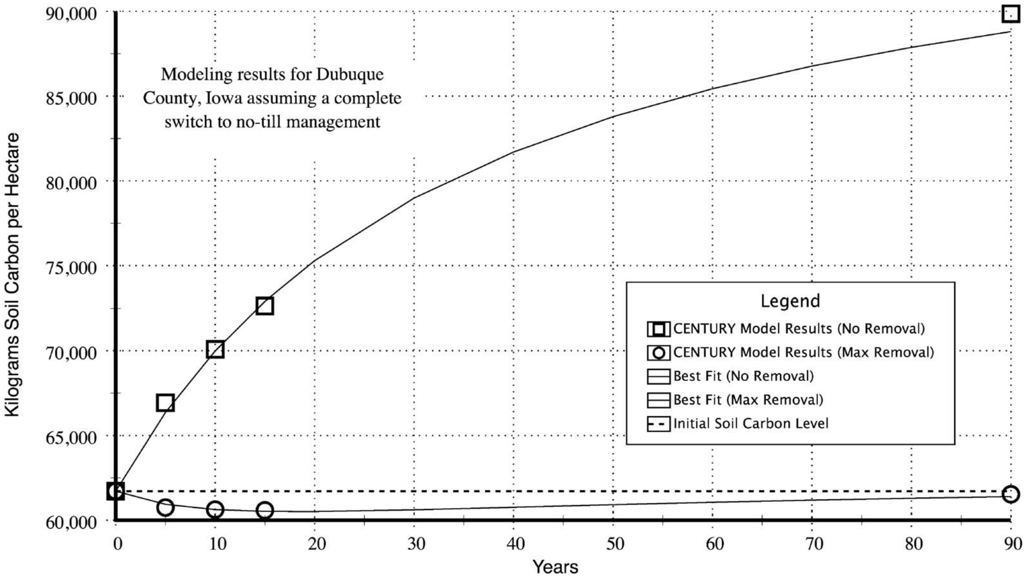


Figure 5 Soil carbon profiles for Dubuque County, Iowa.

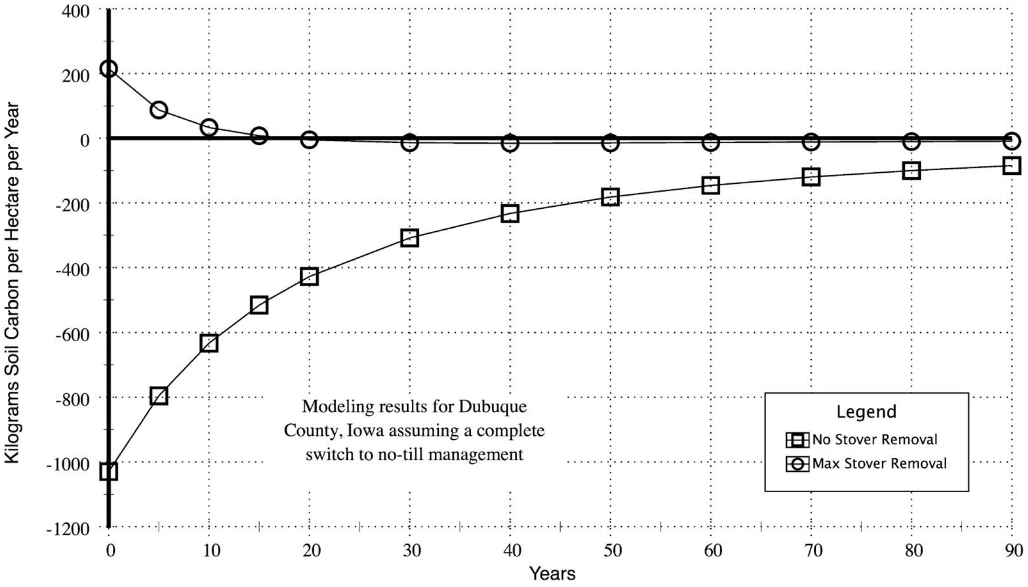


Figure 6 Soil carbon flux for Dubuque County, Iowa.

Iowa continue to climb, based on improvements in breeding and farm practices (NASS 1994, 1998, 2001). Thus, from this perspective, our study may underestimate future supplies of available corn stover. On the other hand, removing stover reduces the total amount of carbon that can be incorporated in the soil. Removing stover could, therefore, adversely impact yields of corn.

In this study, the CENTURY model independently predicts corn yield for given conditions of tilling, crop choices, and stover management in each county. A comparison of the predictions of corn yield from CENTURY with and without stover removal suggests that, under our scenario of maximum stover collection constrained to maintain soil erosion at tolerable levels, stover removal has little effect on yield (Sheehan et al. 2002). For the purposes of this study, average data for 1995–1997 (NASS 2001) were used to predict the total supply of stover in each county, as well as the percent of stover that could be removed in a given county. This percent removal was used in the CENTURY model to predict the effect of maximum stover removal on soil carbon levels. Because the yields predicted by CENTURY do not (and cannot) match the average yield data for specific years, there is an inconsistency between the soil carbon modeling and stover collection modeling. We recognize that further study is needed to understand the interaction of residue management on stover yield.

Modeling Fertilizer Usage Changes

As indicated in figure 3, the net system we model for the farm includes the following components:

- Direct emissions associated with the harvesting and staging of stover in each of two years
- The incremental burdens of replacing the second year of soybean production in the baseline rotation with the production of corn under the modeled continuous corn scenario
- An increase in the amount of nutrient fertilizers added each year above the level currently used for corn production in each county to compensate for the nutrients contained in (and removed with) the collected residue

The nitrogen fertilizer additions for the net system shown in figure 3 can be calculated as

$$\Delta N_{yr1+yr2} = (N_{residue})_{yr1} + (N_{residue})_{yr2} + (N_{corn})_{yr2} - (N_{soy})_{yr2} \quad (1)$$

where $\Delta N_{yr1+yr2}$ is the net change in nitrogen fertilizer addition for years 1 and 2 of corn production with stover removal versus corn-soybean production without stover removal, $(N_{residue})_{yr}n$ is the amount of nitrogen removed with the corn stover in year n, $(N_{corn})_{yr}n$ is the amount of nitrogen fertilizer added for corn production in year n, and $(N_{soy})_{yr2}$ is the amount of nitrogen fertilizer added for corn production in year n.

Simplifying on the basis that nitrogen replacement and fertilizer addition rates in years 1 and 2 are the same, we find that change in net fertilizer use relative to Iowa corn acres already in continuous corn production can be represented as

$$\Delta N = N_{corn} - N_{soy} + 2N_{residue} \quad (2)$$

In our model, we account for the corn acres in Iowa that are already in continuous corn production. We need to correct the equation to reflect the fact that there is no net fertilizer usage change for these acres except for the additional fertilizer added to compensate for nutrients removed with the stover. Finally, we need to normalize the fertilizer impacts on an annual basis, rather than on the two-year cycle shown in figure 3. This leads to a description of net annual nitrogen fertilizer usage in the farm system, as in equation (3),

$$\Delta N = \frac{(1 - x_{cc})}{2} (N_{corn} - N_{soy}) + N_{residue} \quad (3)$$

where x_{cc} is the fraction of corn acres in Iowa already in continuous production of corn.

Similar calculations are done for phosphorus and potassium. We estimate that 10% of the corn acres in Iowa are already in continuous production of corn ($x_{cc} = 0.1$). Values for nitrogen fertilizer use in corn production are based on county-level rates for Iowa as reported in the CENTURY model (Brenner et al. 2001; Sheehan et al. 2002). Potassium and phosphorus application rates are based on usage rates of each fertilizer per bushel of corn harvested in Iowa. Individual county-level values are calculated by combining phosphorus and potassium use per bushel with county average yields for corn. Average statewide values for nitrogen, phosphorus, and potassium fertilizer use for soybean production are based on USDA statistical data (Sheehan et al. 1998). Nitrogen content in the residue is based on a carbon content of 45% and an assumed C:N ratio of 100. Values for P and K content are based on chemical analyses of residue done at the U.S. National Renewable Energy Laboratory. Table 3 summarizes state averages for fertilizer and average nutrient content for corn stover used in this study.

Modeling Soil Nitrogen Emissions

Emissions of nitrous oxide (N_2O) and nitrogen oxides (NOx) from the soil can be significant. We use guidelines from the International Panel on Climate Change (IPCC) to estimate soil nitrogen emissions associated with the switch from the current mix of continuous corn and corn-soybean rotations in Iowa to just continuous corn production (IPCC 1996). As with the estimates of fertilizer burden, we only apportion the incremental nitrogen emissions associated with the new crop management strategy. Equation (4) shows the incremental N_2O calculation. A similar equation is used for NOx emissions.

$$\Delta N_2O = (1 - x_{cc}) \left[\frac{N_2O_{corn} - N_2O_{soy}}{2} \right] \quad (4)$$

where x_{cc} is the fraction corn acres in Iowa already in continuous production of corn, ΔN_2O is the incremental amount of soil N_2O emissions, N_2O_{corn} is the emissions of N_2O for corn production including the effects of fertilizer and residues, and N_2O_{soy} is the emissions of N_2O for soybean production including the effects of fertilizer and residues. Details of how the IPCC methodology is used are available elsewhere (Sheehan et al. 2002).

Modeling Stover Collection

A number of researchers have proposed single-pass systems in which both the corn grain and the stover could be collected simultaneously (Sokhansanj et al. 2002). Allowing farmers to collect stover and grain in a single pass through the field dramatically reduces fuel and labor costs; however, the equipment required to do this does not exist today. In this study, we model corn stover collection based on actual experience collecting stover for energy production during a second pass through the field using available commercial equipment, after the farmer has harvested the corn grain (Richey et al. 1982; Glassner et al. 1998). This is far from an optimal approach to collecting corn stover, but it reflects what we know can be done today and it serves as a conservative starting point for looking at the life-cycle impacts of using ethanol made from corn stover.

We assume that corn stover is collected as large round bales (1.52 m diameter [5 ft] × 1.83 m length [6 ft]) weighing 544 kg each. Costs are estimated using methodologies recommended by the American Agricultural Economics Association (AAEA 2000) and machinery engineering parameters from the American Society of Agricultural Engineers Standards (ASAE 1998). Collection costs include repairs, depreciation, interest, fuel, oil and lube, mesh wrap, housing, insurance, taxes, and labor for each county and are estimated as a function of the dry metric tons per hectare of stover that can be removed. For quantities less than 4.5 dry mt/ha, the combine spreader is turned off and the resulting windrow is baled. For quantities greater than or equal to 4.5 mt/ha, the corn fields are mowed, raked, and baled. Staging costs (i.e., picking up the bales, moving them to the field edge, and stacking) are included in the costs.

As part of the cost estimation, fuel and oil use is also estimated as shown in figure 7. The three segments of the curve labeled as A, B, and C represent three different regression equations. The discontinuity in the curves between B and C reflects changes in equipment and operation assumed for stover collection rates greater than 4.5 mt/ha.

Modeling Transport of Corn Stover

We assume that baled corn stover is delivered to an ethanol conversion facility at a rate of 2,000 dry mt/day on a 17-bale wagon pulled by tractors capable of traveling up to 64 km/hr (40 mi/hr). Bales are loaded from the edge-of-field stack using a tractor equipped with a forklift. We use our county-level information on stover collection cost, quantity, and distribution and farm-level impacts as input to the ORIBAS GIS-based transportation model to site individual 2,000 mt/day ethanol plants across the state of Iowa assuming the continuous corn, no-till scenario (figure 8). The sequence of plants sited in the state is

Table 3 Fertilizer use and nutrient content of corn stover

Nutrient	*Fertilizer application for Iowa corn production*	*Fertilizer application for Iowa soybean production*	*Percent by weight of nutrient in stover (%)*
Nitrogen	144.70 kg N/ha/yr	13.45	0.45
Phosphorus	55.76 kg P/ha/yr	20.18	0.08 (NREL 2001)
Potassium	70.03 kg K/ha/yr	67.25	0.76 (NREL 2001)

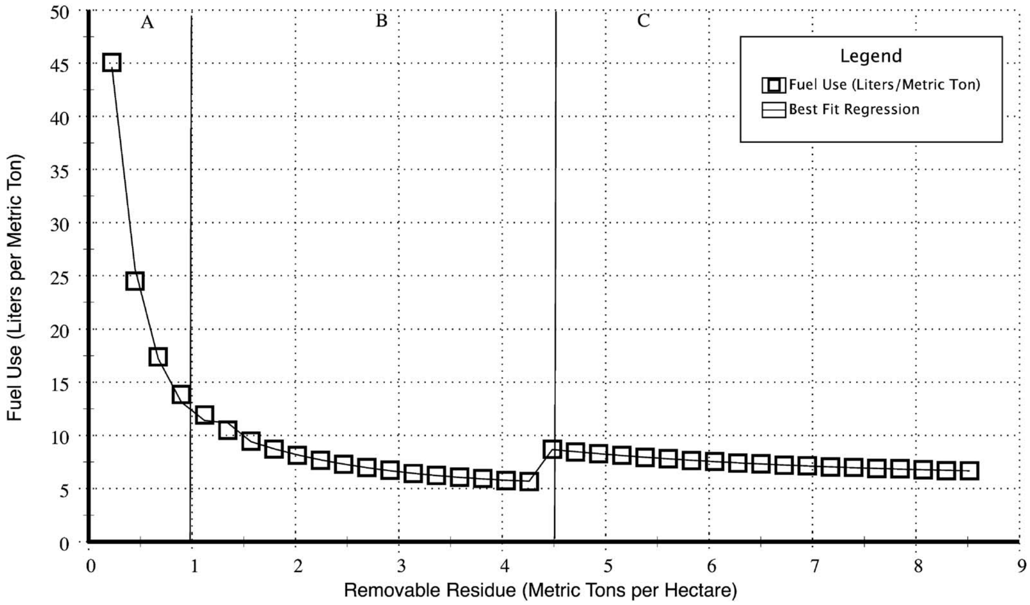


Figure 7 Fuel use as a function of stover collection rate.

based on the location of the lowest cost stover supplies. As each new facility is added, the combined cost of collection and transport increases.

By siting these plants in sequence, we hope to provide a more consistent basis for assessing what overall transportation and collection impacts would look like for a fully developed ethanol industry. We by no means claim that the specific siting reflects exactly how the industry will develop. For example, as the best sites for ethanol conversion facilities and access to the lowest cost feedstock are taken, later facilities are forced to draw their supply from an increasingly wide area across the state. Because our algorithm forces each plant to lock out their own supply, it creates situations where plants can be located next to one another, with the first facility utilizing neighboring supplies but the later facilities being forced to draw supplies from a very large area beyond the immediate supplies. Larger ethanol facilities and/or a statewide trading system might mitigate such imbalanced transportation demands and close proximity of the facilities. Another limitation of this approach is the arbitrary placement of ethanol facilities within state boundaries. This no doubt creates artifacts due to "edge effects" in the placement of the plants near state borders.

Nevertheless, our approach to locating facilities one at a time does provide a consistent way to estimate how marginal cost and life-cycle flow emissions increase as the industry grows. Figure 9 shows how the cost of feedstock increases as each new facility comes on line. We include three types of cost: (1) the direct cost of baling, staging, and transport of stover, (2) an arbitrary farmer profit of $10/dry mt, and (3) an added cost of $7/dry mt of stover associated with fertilizer replacement for nutrients removed with the stover. The first plant has a delivered feedstock cost

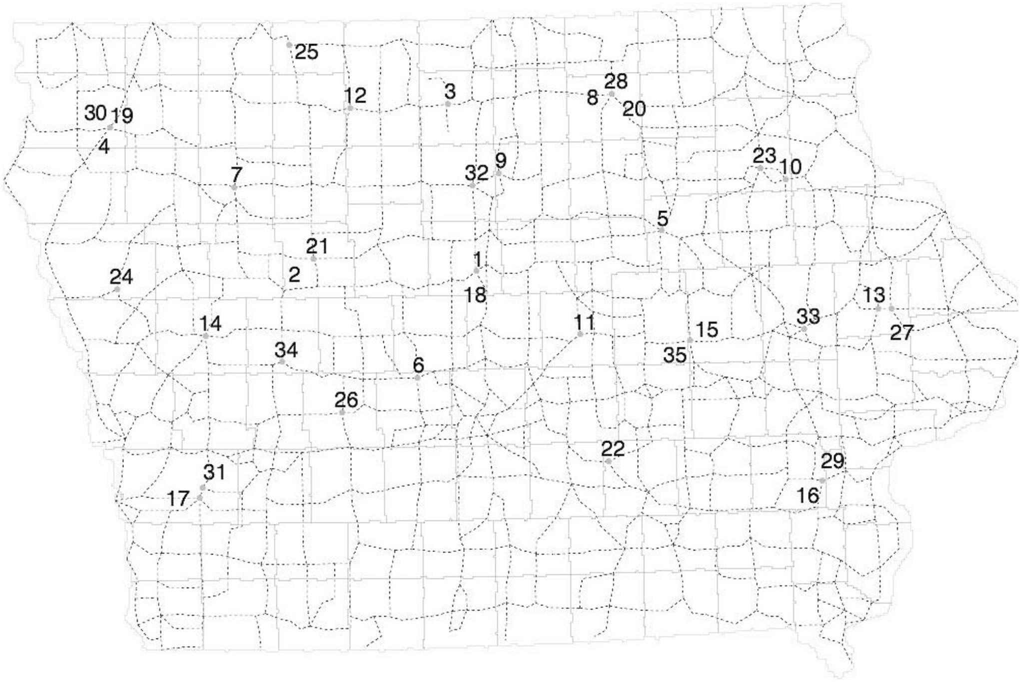


Figure 8 Siting of 2,000 mt/day ethanol plants across Iowa (the numeral "1" indicates the first plant sited, "2" the second, and so on).

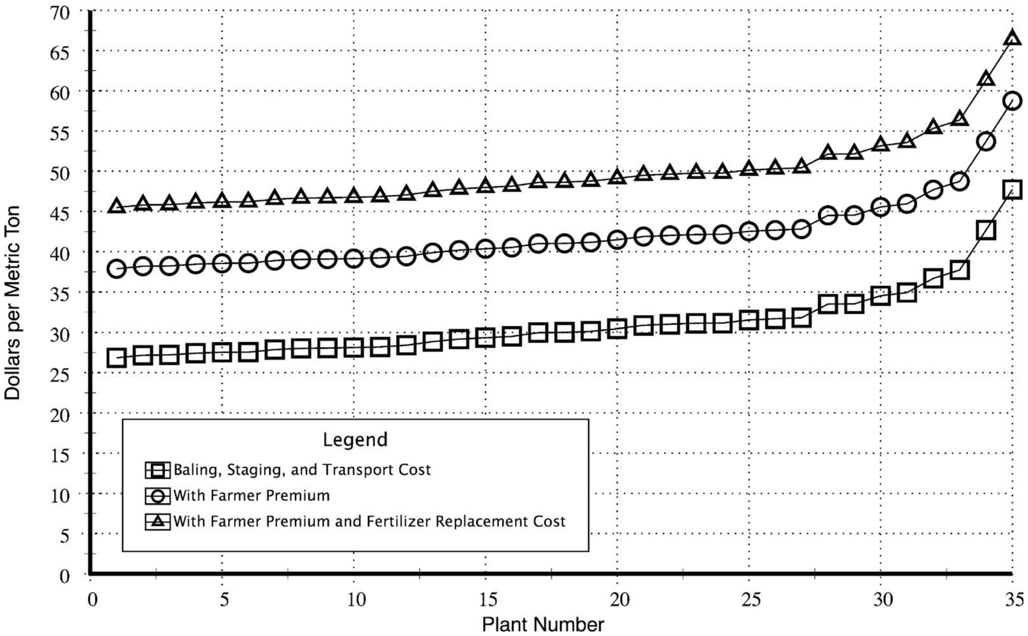


Figure 9 Delivered feedstock costs for each new 2,000 mt/day ethanol facility.

of $46/mt. Delivered feedstock cost rises by only $3/dry mt for the first 25 plants, but then jumps by $20/dry mt for the last ten plants.

Modeling of the Ethanol Conversion Facility

Table 4 summarizes the chemical composition of the corn stover assumed in our process design (Sheehan et al. 2002). Cellulose, the largest component in the feed, is a polymer of glucose sugar molecules. Hemicellulose, the next largest component in the feed, consists of four sugar polymers. Xylan and arabinan are polymers of the five-carbon sugars xylose and arabinose, respectively. Mannan and galactan are polymers of the six-carbon sugars mannose and galactose, respectively. Lignin, the third major component in stover, is a complex polymer of aromatic compounds. The key to converting corn stover to ethanol is the ability to efficiently release and then ferment all of the sugars contained in the hemicellulose and cellulose fractions of the biomass.

The basic steps included in the process are shown in figure 10. Our design includes a baled-stover handling section that provides milled stover to a dilute acid pretreatment step that releases hemicellulosic sugars from the stover. "Conditioning" refers to a step following pretreatment in which some unwanted by-products are removed. In our design, conditioning is accomplished by adding lime to the liquid phase from pretreatment to raise the pH to alkaline conditions. The unwanted by-products are removed as precipitated solids. In addition to releasing the sugars from hemicellulose, pretreatment also increases the vulnerability of cellulose to hydrolysis by enzymes in the next step of the process. In the hydrolysis step, the bulk of the glucose is released from the cellulose polymers into a liquid phase, leaving mostly lignin in the form of a solid. Sugars released from the biomass in the pretreatment and the hydrolysis steps are then fermented to ethanol using genetically engineered organisms capable of converting the full suite of sugars found in the stover. In addition, the process design includes accommodations for ethanol purification, wastewater treatment, lignin combustion for steam and electricity generation, product storage, and other utilities.

Table 4 Assumed composition of corn stover delivered to the plant gate

Component	*Weight fraction*
Cellulose fraction	0.374
Hemicellulose fraction	0.275
Xylan	0.211
Arabinan	0.029
Mannan	0.016
Galactan	0.019
Lignin fraction	0.180
Ash	0.052
Acetate	0.029
Protein	0.031
Extractives	0.047
Other	0.011
Total	1.00

An important caveat for the results presented in this study is that the life-cycle model assumes performance of the conversion facility that has not yet been achieved. Table 5 summarizes design parameters and performance data for the design used in this study and design parameters and performance data for a stover-to-ethanol plant based on the best available experimental results to date (Aden et al. 2002). The model anticipates a 50% improvement in overall ethanol yield from biomass over what has been demonstrated today (340 versus 255 L/dry mt of biomass). We base much of this improvement on the development of a new generation of cellulose-hydrolyzing enzymes that is expected to be the result of an ongoing, targeted research effort sponsored by the U.S. Department of Energy in partnership with two of the leading industrial enzyme companies.

Another important research outcome that contributes to the improved process performance is the development of genetically engineered organisms that are capable of fermenting all of the sugars from hemicellulose, in addition to the glucose that can be fermented today in commercial ethanol facilities. Genetically engineered organisms have already been developed that are capable of fermenting glucose and xylose (Ingram et al. 1987, 1991; Lawford and Rousseau 1992; Zhang et al. 1995). In our model, we project success in expanding the genetic engineering of these fermenting organisms to include the ability

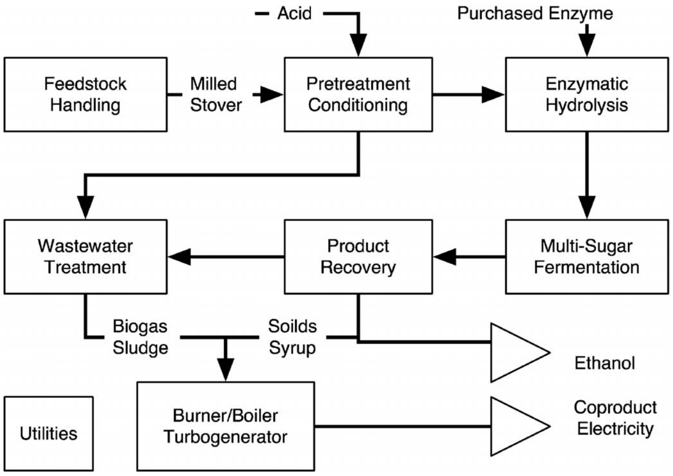


Figure 10 Process flow diagram for the conversion of stover to ethanol and electricity.

to ferment glucose, xylose, arabinose, mannose, and galactose.

Finally, improvements in pretreatment are expected to lead to higher yields of hemicellulosic sugars and improved performance in the enzymatic hydrolysis step. We assume that hemicellulose sugar yields rise from 67.5% to 90%, whereas glucose yields from cellulose rise from 63.5% to 90%.

Table 6 summarizes the carbon balance around the ethanol conversion facility. We are able to account for 99% of the biomass carbon that comes into the stover-to-ethanol biorefinery. The 1% of carbon we are unable to account for is related to uncertainty in the tracking of carbon in the waste treatment section of the plant. Carbon leaves the facility as combustion exhaust (47%), ethanol product (34%), and fermentation-generated CO_2 in the scrubber vent (17%). Thus, approximately one-third of the biomass carbon that comes into the facility leaves as fuel ethanol.

Table 7 summarizes the energy balance around the ethanol conversion facility. To get a sense of how efficiently energy from biomass is utilized, we can calculate the total amount of useful energy from the plant and compare it to the total amount of biomass energy brought in to the plant as corn stover. We define the ratio of energy out to energy in as the primary energy efficiency shown in equation (5).

$$\eta_{\text{primary}} = \frac{\text{Energy}_{\text{ethanol}} + \text{Energy}_{\text{electricity}}}{\text{Energy}_{\text{biomass}}} \tag{5}$$

where η_{primary} is the efficiency of primary energy use, $\text{Energy}_{\text{ethanol}}$ is the embodied energy of the ethanol product measured as the heat of combustion in millions of kilocalories[6] per hour of product flow, $\text{Energy}_{\text{electricity}}$ is the energy value of coproduct electricity measured in millions of kilocalories per hour, and $\text{Energy}_{\text{biomass}}$ is the embodied energy of the biomass measured as the heat of combustion in millions of kilocalories per hour of feedstock into the plant.

Using the values in table 7, we calculate a primary energy efficiency of around 53%. In other words, the projected process performance leads to an ability to utilize just over half of the energy contained in the corn stover.

The life-cycle model also includes a separate facility that uses a fraction of the total stover collected in Iowa to produce the enzymes needed to break down cellulose to glucose. Several bacteria and fungi naturally produce cellulase enzymes, including bacteria in ruminant and termite guts and white rot fungus. The most common organism used to produce cellulase industrially is *Trichoderma reesei*. *T. reesei* is a fibrous fungus that can grow and produce cellulase in aerobic bioreactors. The enzyme production design used in the life-cycle model is based on a 1999 ethanol design study (Wooley et al. 1999a, 1999b) that included eleven 1,000 m^3 (264,000 gal) bioreactors, with eight in operation, one being drained, one being filled, and one being cleaned and sterilized at all times. The carbon source for the bioreactors is detoxified, pretreated corn stover slurry that has been diluted. Table 8

Table 5 Comparison of current and projected performance of the stover-to-ethanol conversion facility

Parameter	*Demonstrated at bench scale or higher*	*Projected design used in life-cycle model*
Overall		
Dry metric tons biomass per day	2,000	2,000
Million liters ethanol per year	179	262
Ethanol yield (liters per dry metric ton biomass)	255	340
Pretreatment and conditioning		
Acid concentration (acid/liquor)	1.16%	1.10%
Solids concentration (w/w)	19.0%	30.0%
Temperature (°C)	179	190
Residence time (min)	6.2	2
Xylan to xylose yield	67.5%	90.0%
Mannan to mannose yield	67.5%	90.0%
Galactan to galactose yield	67.5%	90.0%
Arabinan to arabinose yield	67.5%	90.0%
Type of conditioning	Overliming	Overliming
Hydrolysis		
Enzyme production (in-house or purchased)	Purchased	Purchased
Purchase price ($/L ethanol)	0.17	0.03
Hydrolysis residence time (days)	7 (includes fermentation)	1.5
Temperature (°C)	32	65
Cellulose to glucose yield	63.5%	90.0%
Fermentation		
Fermentation residence time (days)	7 (includes hydrolysis)	1.5
Temperature (°C)	32	41
Chilled water (time necessary)	20%	0
Effective solids level	12.6%	20.0%
Corn steep liquor nutrient loading	0.25%	0.25%
Diammonium phosphate nutrient loading (g/L)	0.33	0.33
Glucose to ethanol yield	95.0%	95.0%
Xylose to ethanol yield	90.2%	85.0%
Arabinose to ethanol yield	0.0%	85.0%
Galactose to ethanol yield	0.0%	85.0%
Mannose to ethanol yield	0.0%	85.0%
Contamination loss	7.0%	3.0%

summarizes the performance parameters and inputs and outputs associated with the enzyme production facility.

Modeling Fuel Distribution and Use

Fuel distribution in the model includes the transport of ethanol by rail from the plant gate to bulk storage terminals over an average distance of 241 km (150 mi). Blended E85 is shipped from the bulk terminal to retail outlets by diesel truck over an average distance of 161 km (100 mi). Fuel performance and emissions assumptions for gasoline and E85, shown in table 9, are based on U.S. Environmental Protection Agency (U.S. EPA) engine certification data for the model year 2000 Ford Taurus Sedan FFV (U.S. EPA 2000, 2002). This vehicle is assumed to be representative of the population of spark-ignition flexible-fuel passenger vehicles in the 2000–2010 time frame.

Table 10 summarizes the specific gravity and energy density properties of pure ethanol and

Table 6 Carbon balance around the stover-to-ethanol conversion facility

Parameter	*Carbon flow (C kmol/hr)*	*Ratio to feedstock carbon content (C kmol basis)*
Carbon inlets		
Stover feedstock	3,144	1.000
Enzymes	25	0.008
Total	3,169	1.008
Carbon outlets		
Combustion exhaust	1,497	0.476
Ethanol product	1,066	0.339
Scrubber vent	532	0.169
Ash	16	0.005
Gypsum	10	0.003
Aerobic vent	3	0.001
Loss to atmosphere	4	0.001
Total	3,129	0.995

Table 7 Energy balance around the stover-to-ethanol conversion facility

Source	*Energy flow (Mkcal/hr)*	*Ratio to feedstock Energy Flow*
Energy inlets		
Stover feedstock	358	1.000
Enzymes	3	0.009
Air	2	0.005
Sulfuric acid	−2	0.005
Well Water	−2	0.006
Other	−1	0.004
Total	358	1.000
Energy outlets		
Ethanol	174	0.487
Cooling tower	79	0.220
Combustion exhaust	54	0.151
Ambient heat and work losses	22	0.060
Byproduct electricity	16	0.045
Loss to atmosphere	1	0.004
Ash	1	0.003
Other	−2	−0.004
Total	346	0.966

Note: Mkcal/hr = millions of kilocalories per hour.

pure gasoline. Combining the fuel economy data with the property data for ethanol and gasoline, we estimate the efficiency of the engine running on E85 and gasoline as 0.32 and 0.31 km/MJ of fuel energy, respectively.

The difference between the efficiency of the engine running on these two fuels is negligible; therefore, we assume an efficiency of 0.32 km/MJ of fuel energy for the engine for both fuels. To relate 1 kg of a given fuel blend to the functional

Table 8 Characterization of the enzyme production step

Parameter	*Value*
Performance parameters	
Cellulase requirement for SSCF	15 FPU/g cellulose
Yield	200 FPU/(g cellulose + xylose)
Productivity	75 FPU/(L · hr)
Initial cellulose concentration	4%
Inputs	
Cellulosic hydrolysate	7,600 kg/hr
Water	4,474 kg/hr
Corn oil (antifoam)	64 kg/hr
Corn steep liquor	119 kg/hr
Ammonia (nutrient)	47 kg/hr
Other nutrients	47 kg/hr
Electricity	2,236 kW
Outputs	
Enzyme broth	11,455 kg/hr
Carbon dioxide (CO_2)	879 kg/hr
Furfural	8.2 kg/hr
Acetic acid (VOC)	2.8 kg/hr

Note: FPU = filter paper unit, a standard measure of enzyme activity for cellulases; VOC = volatile organic compound; SSCF = Simultaneous Saccharification and Cofermentation.

Table 9 Comparison of fuel performance for gasoline and E85 for the model year 2000 Ford Taurus FFV

Measure	*FFV on gasoline*	*FFV on E85*
City fuel economy in kilometers per liter (mi/gal)	8 (19)	6 (14)
Highway fuel economy in kilometers per liter (mi/gal)	12 (29)	9 (21)
Average fuel economy in kilometers per liter (mi/gal)	10 (23.5)	7.3 (17.2)
Carbon monoxide (g CO/km)	0.57	0.40
Total hydrocarbons (g HC/km)	0.035	0.032
Non-methane organic gases (g NMOG/km)	0.022	0.032
Nitrogen oxides (NO_x as g NO_2/km)	0.037	0.012
Formaldehyde (g HCHO/km)	0.0001	0.009

Table 10 Comparison of ethanol and gasoline properties

Property	*Ethanol*	*Gasoline*
Specific gravity	0.77	0.72
Energy density	20,000 MJ/L (76,000 Btu/gal)	32,200 MJ/L (115,000 Btu/gal)
Lower heating value	27.4 MJ/kg	44.7 MJ/kg

unit of 1 km driven, we use the following equations:

$$H_{\text{fuel}} = \frac{H_{\text{EtOH}}}{f_{\text{EtOH}}} + \frac{H_{\text{Gas}}}{1 - f_{\text{EtOH}}} \qquad (6)$$

where H_{fuel} is the lower heating value (LHV) of a fuel blend in megajoules per kilogram of blend, H_{EtOH} is the LHV of pure ethanol in megajoules per kilogram of ethanol, H_{Gas} is the LHV of pure gasoline in megajoules per kilogram of gasoline, and f_{EtOH} is the weight fraction of ethanol in the fuel blend;

$$\text{Fuel} = \frac{1}{\eta_{\text{Engine}} H_{\text{fuel}}} \qquad (7)$$

where Fuel is the kilograms of a fuel blend required to drive 1 km and η_{Engine} is the efficiency of the engine, estimated as 0.32 km/MJ fuel energy.

Distinguishing the energy from ethanol and energy from gasoline, as described in the previous equations, is a straightforward calculation. Likewise, all "pre-vehicle-use" life-cycle emissions can be readily separated based on the total mass of each fuel component in the fuel mixture. We can also readily distinguish biomass-derived tailpipe emissions of carbon from fossil-derived tailpipe emissions of carbon based on the total mass of ethanol in the fuel and the known carbon content of the ethanol. On the other hand, we cannot clearly attribute the other tailpipe emissions to the ethanol and gasoline fractions in the fuel. Because the chemistry of combustion is complex, there is no simple relationship between the level of individual tailpipe emissions and the amount of ethanol in the gasoline. Thus, energy and greenhouse gas emissions in the study are reported for the ethanol fraction of the fuel blend (equivalent to an E100 fuel blend) as well as for E10 and E85, whereas all other air emissions are reported for E85 only.

Modeling the Gasoline Life Cycle

Modeling of the gasoline life cycle is based on updates of previously published life-cycle studies comparing gasoline and diesel fuel with ethanol and biodiesel (Riley and Tyson 1994; Sheehan et al. 1998, 2002). It includes production and transport of both foreign and domestic crude oil. We model gasoline production and distribution for the Midwest region of the United States. Gasoline performance and emissions data are from U.S. EPA certification data for the model year 2000 Ford Taurus FFV fueled with gasoline instead of E85 (U.S. EPA 2000, 2002).

Findings

We highlight results of the study for a few of the key sustainability metrics identified by our stakeholders (table 1). As suggested by our stakeholders, we present the results of this study both from the perspective of the farm and the vehicle, that is, we look at life-cycle flows normalized to a hectare of Iowa farmland as well as normalized to 1 km of travel. Furthermore, although our system is defined for a vehicle running on E85, we have set up the model so that we can vary the ethanol content in the fuel. The analysis for different fuel blends applies only to energy and greenhouse gas life-cycle flows. For air emissions other than greenhouse gases, we report results only for E85 because of the inability to apportion tailpipe emissions between the ethanol and gasoline components. Looking at pure ethanol (E100) as a fuel offers the advantage of being able to remove the confounding influences of gasoline in the case of E85.

Avoided flows from the gasoline life cycle, as shown in figure 1, are subtracted from the system. Net results that are negative indicate that the avoided flows from gasoline are greater than the total flows from the production and use of ethanol.

An important point to emphasize is that our results apply to a scenario for corn production in Iowa that does not exist today. It is, in fact, a scenario that maximizes stover availability.

Energy Security

We measure the long-term energy security impacts of replacing gasoline with stover-derived ethanol in terms of its effect on consumption of nonrenewable energy. The gasoline life cycle consumes 3.63 MJ of nonrenewable energy to drive 1 km (results not shown here). Driving 1 km on E100 reduces fossil energy consumption by 3.70 MJ (figure 11), an effective savings of 102%. Decreasing the amount of ethanol in the fuel mix proportionately reduces the savings in nonrenewable energy use.

To understand why the savings in nonrenewable energy can be greater than 100%, we need to look at where the demands (and offsets) for fossil energy occur (figure 12). For E100, the farm is the greatest source of fossil energy demand. Only 16% of the energy demand in this stage of the life cycle is associated with diesel tractor operations (figure 13). The majority of energy demand on the farm is for fertilizer production.

By comparison, the remaining fossil energy demands for transport of stover and fuel ethanol are small. These three stages represent a total nonrenewable energy demand of 0.73 MJ/km. The conversion facility provides an offset in fossil energy associated with the displacement of conventional electricity by its electricity coproduct. Because this offset (− 0.80 MJ/km) is larger than the total consumption of fossil energy in the other stages of the life cycle, the system has a net negative consumption of fossil energy (− 0.07 MJ/km) even before accounting for the avoided fossil energy of the gasoline life cycle.

Figure 14 compares the nonrenewable energy consumption of E85-fueled travel for ethanol made from corn grain and other lignocellulosic biomass sources. These estimates include the nonrenewable energy consumed to make and use

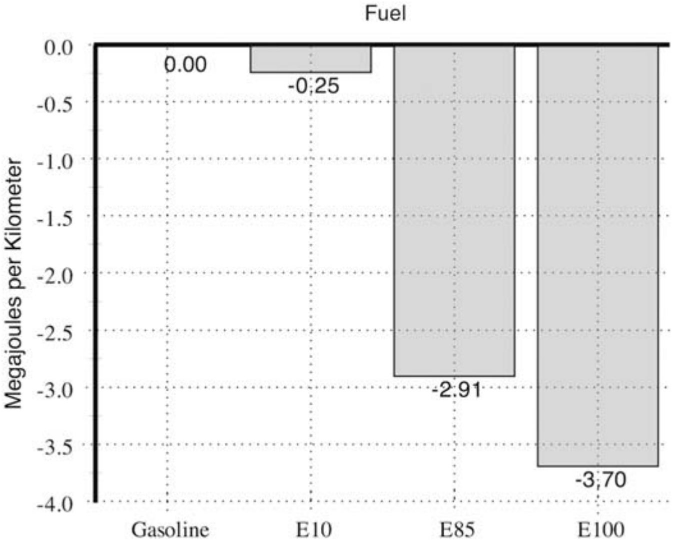


Figure 11 Nonrenewable energy use for various fuel blends. Negative values indicate avoided non-renewable energy use.

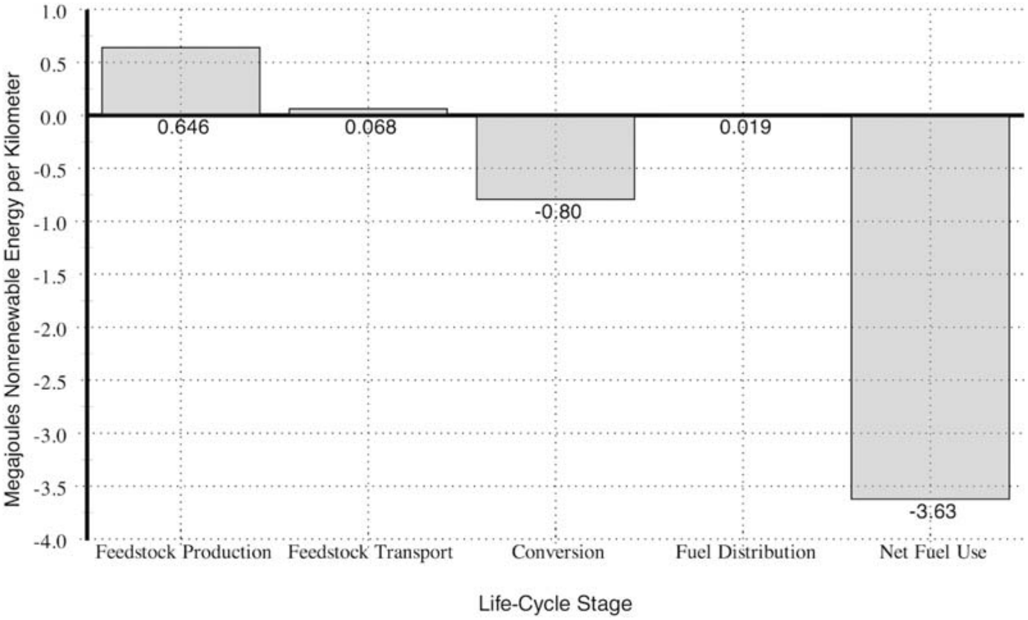


Figure 12 Sources and offsets for nonrenewable energy demand in the ethanol life cycle.

the 15% v/v of gasoline in the fuel. Also, in order to be comparable to other reported energy estimates, the corn stover fossil energy estimates do not include the credit for the displacement of flows from the gasoline life cycle. Our findings for fossil savings for stover-derived ethanol are similar to the savings found in previous studies of ethanol made from other forms of lignocellulosic biomass (Wang et al. 1999), all of which are significantly better than the savings associated with today's corn-grain-based fuel ethanol.

Although savings in nonrenewable energy represent a long-term measure of energy security for society, savings in petroleum are the most pertinent measure of increased energy security in the near term. We estimate that stover-derived eth-

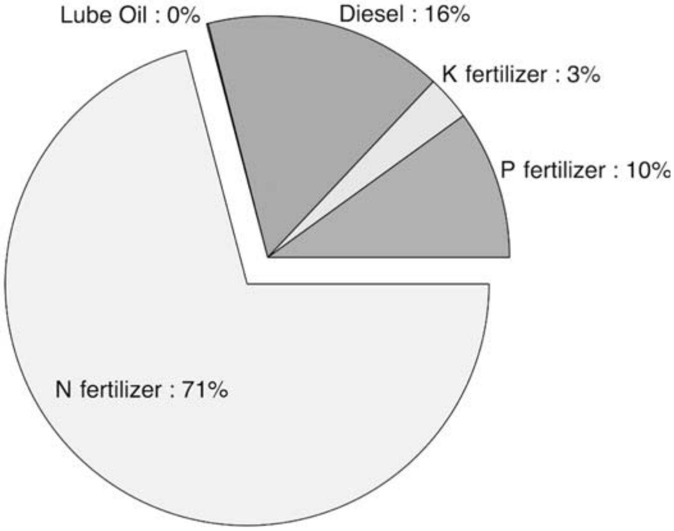
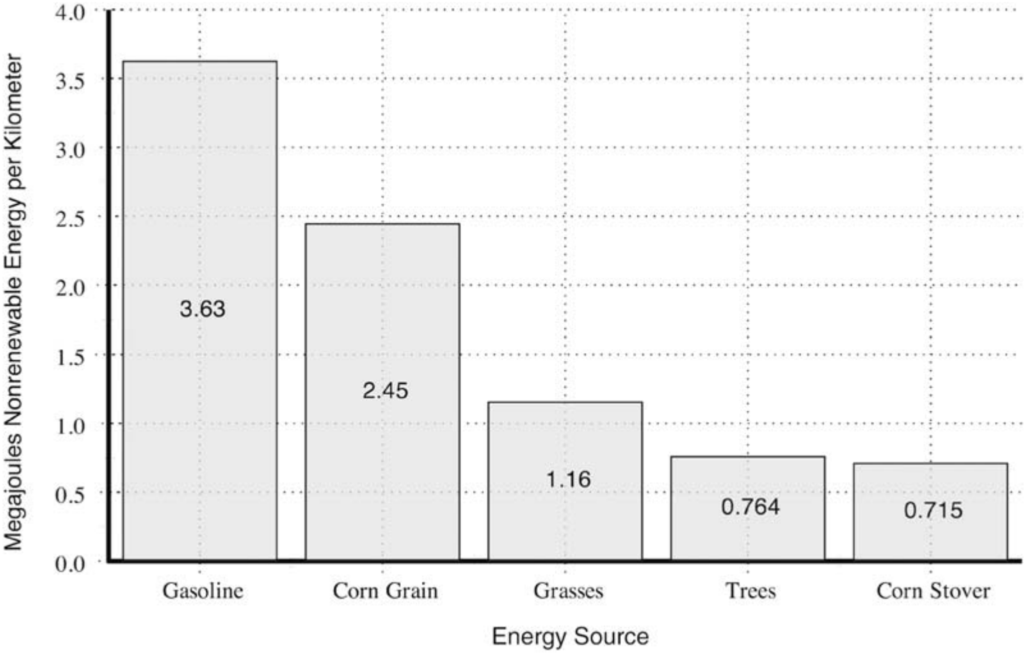


Figure 13 Sources of energy demand on the farm.



Note: The corn stover fossil energy estimates shown here do not include the credit for the displacement of flows from the gasoline life cycle.

Figure 14 Comparison of nonrenewable energy consumption for E85 made from different feedstocks.

anol in the form of E100 reduces petroleum consumption by 95% for each kilometer driven.

Looking at fossil energy resource demand from the point of view of the farm in our life-cycle system offers an opportunity to see the farm in a unique light. Linking the farm to the car via ethanol production from corn stover turns the farmer into an energy supplier of some importance. We estimate that the life-cycle benefits of driving on ethanol made from corn stover allow farmers to reduce our dependence on both coal (a savings of 497 kg/ha/yr) and oil (a savings of 1,127 kg/ha/yr), although this comes at the expense of increased natural gas consumption (an increase of 153 kg/ha/yr).

The net reduction in petroleum of 1,127 kg/ha/yr amounts to a savings of 8.4 barrels of crude oil/ha/yr for farmers who opt to participate in sustainable collection of corn stover. If we were to extrapolate this result to all of the 32 million hectares of corn grain planted in the United States in 2002 (NASS 2003), we would be looking at potential savings of roughly 740,000 barrels of crude oil/day, a savings of less than 4% of the current U.S. appetite for oil. We present these numbers just to make clear that we do not see corn stover as the sole answer to U.S. energy security problems. Still, it offers the opportunity to provide oil savings comparable to the 800,000 barrels/day in foreign oil savings projected for the opening of the Alaskan Natural Wildlife Reserve to oil drilling and exploration (U.S. DOE 2002), but with no new land use impacts and no new crop introduction. Corn stover represents a good first step toward a bioenergy supply based on more productive energy crops such as switchgrass, which could potentially have significant impact on the U.S. energy supply (McLaughlin et al. 2002).

Soil Sustainability

Because sustainability of the soil is inherently a land issue, we present results here that are normalized per unit of land rather than per kilometer traveled. In this study, we have considered the effects of stover removal on erosion as well as on soil carbon. In the case of soil erosion, we have constrained the rate of stover removal to keep soil erosion within tolerable soil-loss limits. These same constraints seem also to work well for ensuring maintenance of soil organic matter.

Figure 15 shows a spectrum of possible aggregate (area-weighted) statewide soil carbon profiles ranging from the extremes of maximum carbon sequestration to maximum utilization of biomass carbon for fuel production. Maximum carbon sequestration corresponds to the case of farmers' switching from their current tilling practices and crop rotations to no-till with continuous production of corn and no removal of corn stover. At "zero removal," the life-cycle model predicts an increase of 32% in the level of soil carbon. Even at the maximum rate of stover removal, soil carbon levels show a modest increase over the 90-year period modeled.

Thus, we have been able to demonstrate in this study that there are, indeed, scenarios in which corn stover can be collected while maintaining or increasing soil carbon levels. This begs the question as to whether or not the combination of no-till practice and continuous production of corn represents a sustainable or sensible farm management system with respect to other important concerns, including increased pest and disease management problems and increased fertilizer use.

Climate Change

Because we have introduced the dynamics of soil carbon in our model, climate change impacts estimated in this study include the year-to-year variation in the rate of exchange of CO_2 between the soil and the atmosphere. Figure 16 shows the statewide emissions of CO_2 over the 90-year period modeled in this study. Two sources of CO_2 emissions exist: fossil energy use (or avoidance) and flows of CO_2 to or from the soil. Displacing gasoline with E100 reduces fossil CO_2 emissions by 267 g of CO_2/km. The savings of fossil CO_2 from avoided use of gasoline amount to 236 g of CO_2/km. In the first few years of stover collection, there is a small release of CO_2 from the soil, followed by a period of CO_2 uptake, which peaks at around 15 years and then begins to diminish as the soil approaches a new equilibrium condition. The soil carbon effects are an order of magnitude smaller than the fossil CO_2 effects, indicating that we have chosen farm practices that minimize the effect of stover removal on soil organic matter.

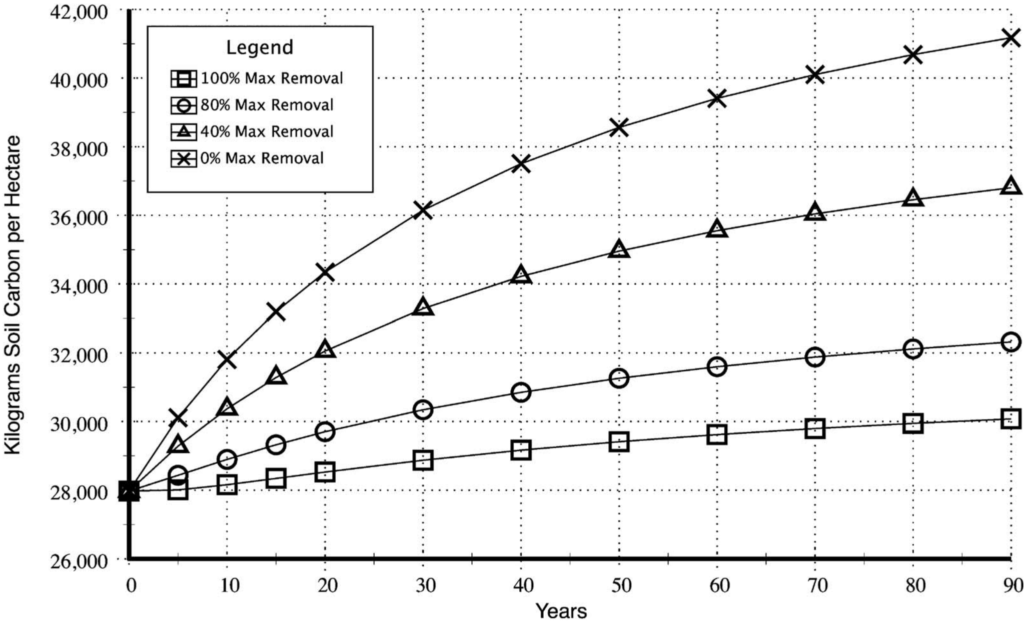


Figure 15 Statewide soil carbon level versus time for different stover removal rates (100% corresponds to the maximum stover removal rate for maintenance of tolerable soil loss due to erosion).

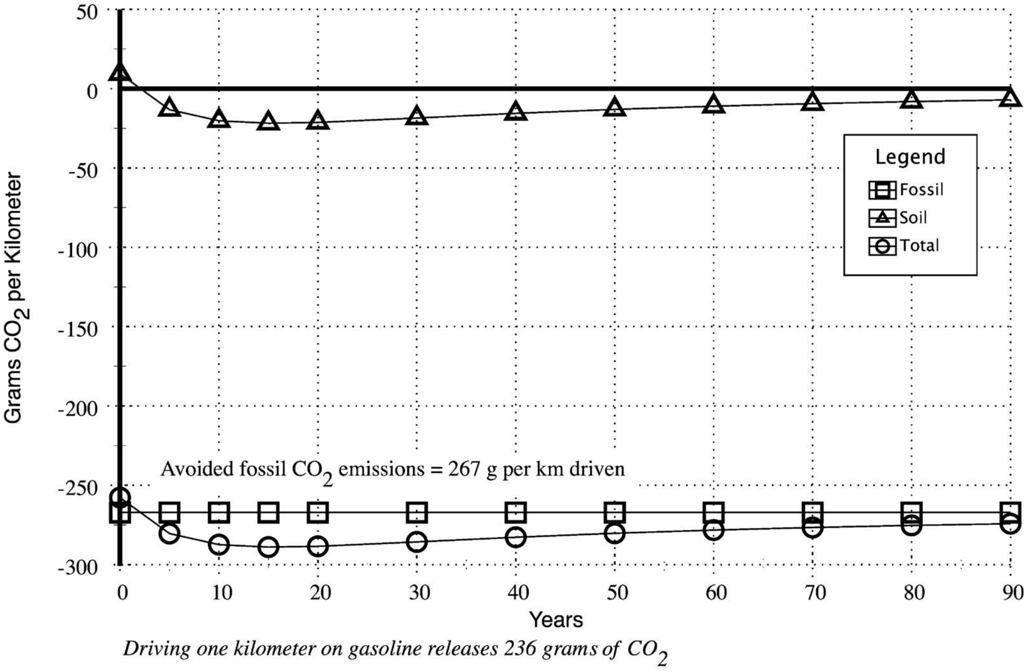


Figure 16 CO_2 emissions per kilometer versus time.

In addition to CO_2, we track two other important greenhouse gases: methane (CH_4) and nitrous oxide (N_2O). The total emissions of CO_2, CH_4, and N_2O for the gasoline life cycle are 239 g of CO_2 equivalent/km. Figure 17 shows the total emissions of CO_2, CH_4, and N_2O at time zero (initial introduction of maximum stover removal), converted to an equivalent CO_2 basis, in the life-cycle system for E10, E85, and E100. For each kilometer traveled using the ethanol fraction of the fuel (or for 1 km driven using E100), total emissions of greenhouse gases drop by 254 g/km, a 106% reduction relative to 1 km driven using gasoline.

Biomass carbon in stover is completely recycled in this system and does not contribute to atmospheric greenhouse concentrations (figure 18). The amount of biomass carbon released as CO_2 at the conversion facility from the fermentation and lignin combustion and at the vehicle tailpipe is approximately equal to the amount of biomass carbon contained in the collected corn stover.

The net impact on greenhouse gases comes from the avoidance of fossil CO_2 and other greenhouse gas emissions associated with the gasoline life cycle and from any direct emissions of fossil CO_2 and other greenhouse gases that occur in the ethanol production portion of the life cycle. Sources and offsets of greenhouse gases for the life-cycle system at time zero are shown in figure 19. The farm is the largest source of greenhouse gas emissions. The emissions of CO_2 from fossil use and from the initial release of soil carbon that occurs when stover collection is first introduced overshadow the emissions of methane and N_2O.

The Economics of Stover for Ethanol in Iowa

The life-cycle model tracks all direct capital and operating costs from the farm to the production of 1 L of fuel-grade ethanol, all of which occurs in Iowa. We model each ethanol facility as it comes on line, making use of incrementally more expensive sources of delivered feedstock. The cost per liter of ethanol, including profit to the farmer and to the ethanol producer, is shown for each new, 261 million liters per year (69 million gallons per year or 2,000 mt stover/day) facility in figure 20. Up to about 7.08 billion liters (1.87 billion gallons) of annual ethanol capacity can be established in Iowa before costs begin to rise rapidly above \$0.33/L (\$1.25/gal).

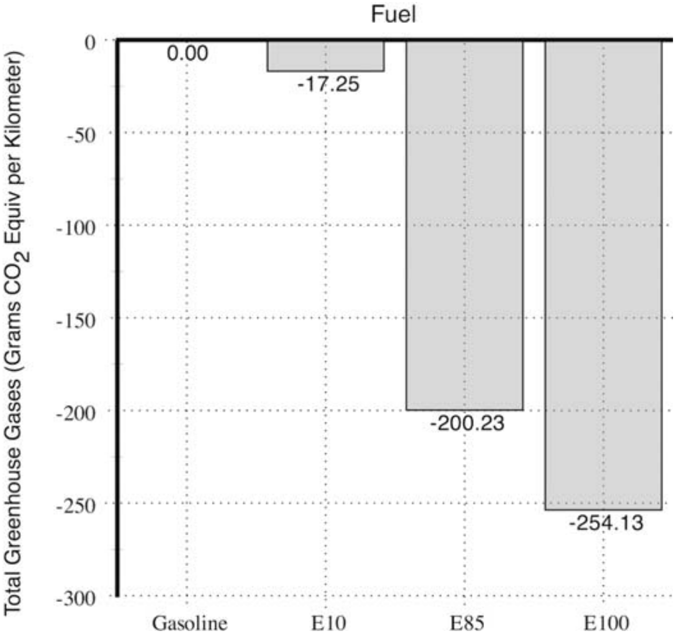


Figure 17 Total greenhouse gas emissions for various blends of ethanol made from corn stover.

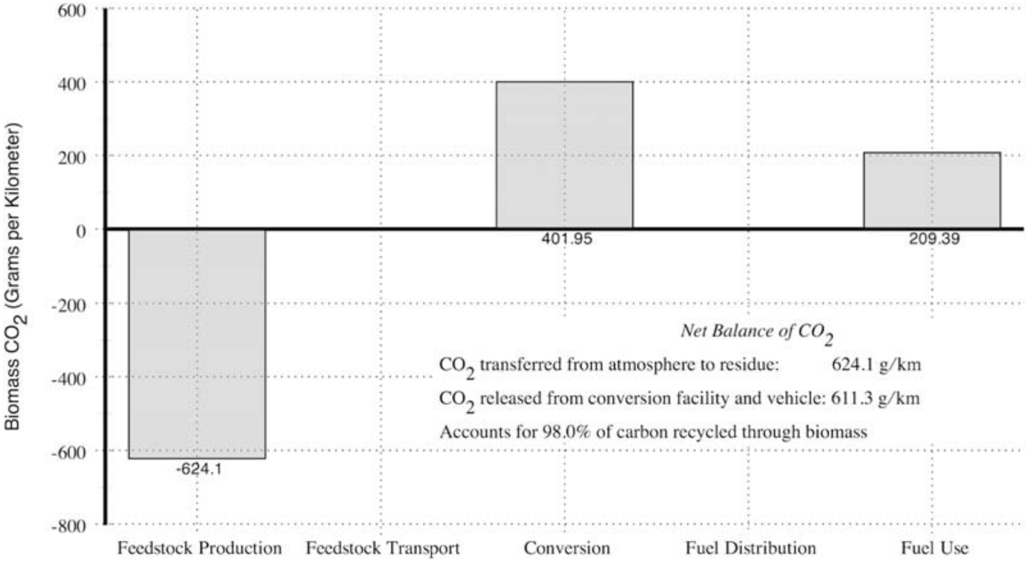
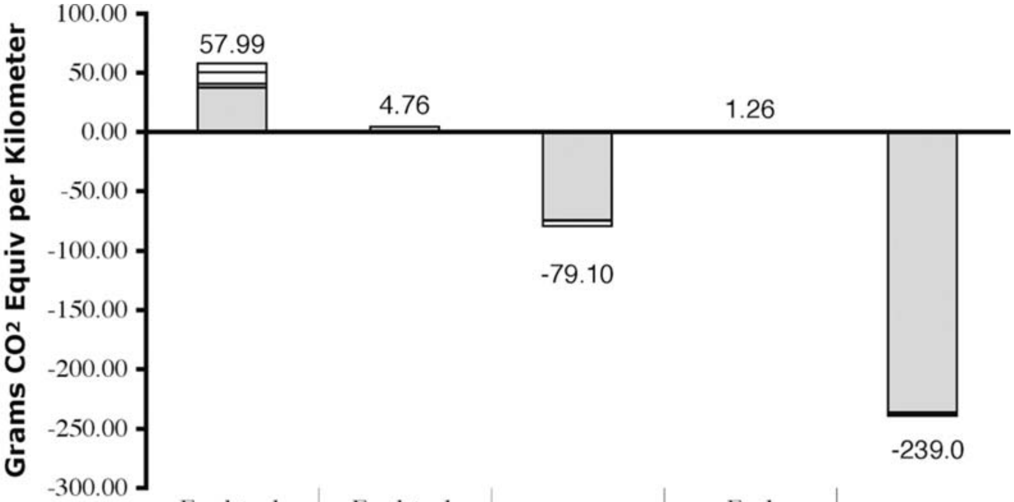
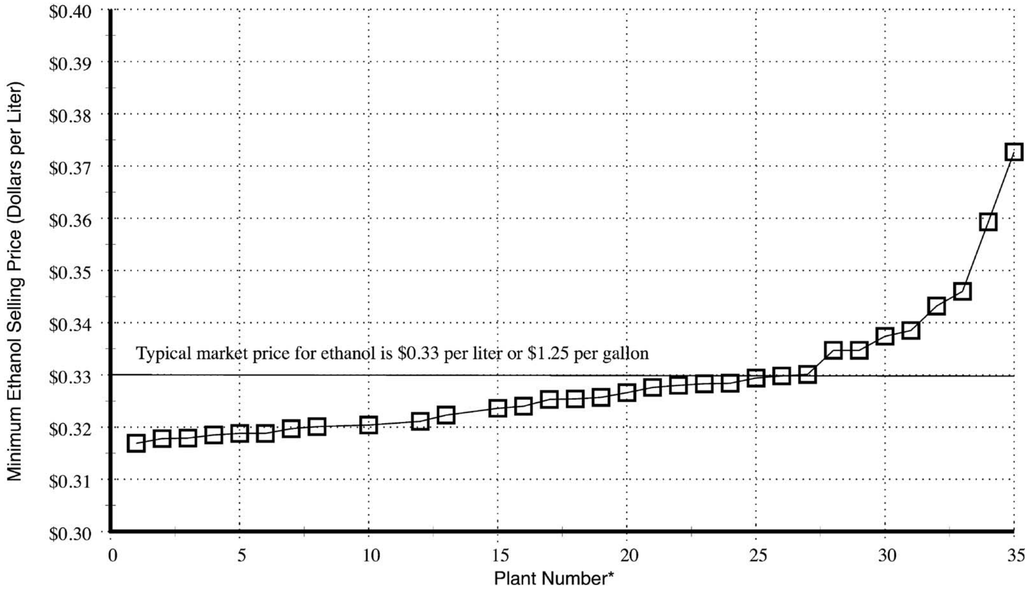


Figure 18 Recycling of biomass carbon collected as stover for ethanol production and use.



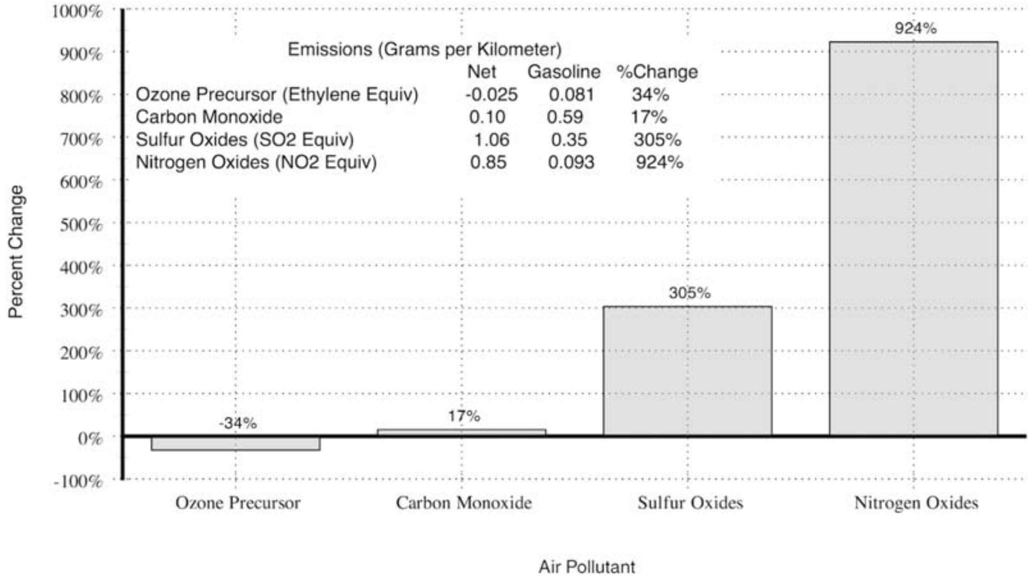
	Feedstock Production	Feedstock Transport	Conversion	Fuel Distribution	Fuel Use
Total GHG	57.99	4.76	-79.10	1.26	-239.0
☐ N2O	7.41	0.16	-4.11	0.03	-1.1
☐ CO2 soil	9.38	0.00	0.00	0.00	0.0
■ CH4	3.67	0.04	-0.58	0.01	-1.9
▨ CO2 Fossil	37.53	4.56	-74.41	1.22	-236.1

Figure 19 A snapshot of the sources and offsets of greenhouse gases in the ethanol life cycle taken at time zero for maximum stover removal.



**Each plant processes 2,000 metric tons per day, yielding 261 million liters per year (69 million gallons per year)*

Figure 20 Cost of ethanol as a function of industry size.



Emissions (Grams per Kilometer)

	Net	Gasoline	%Change
Ozone Precursor (Ethylene Equiv)	-0.025	0.081	34%
Carbon Monoxide	0.10	0.59	17%
Sulfur Oxides (SO2 Equiv)	1.06	0.35	305%
Nitrogen Oxides (NO2 Equiv)	0.85	0.093	924%

Figure 21 Impact of stover-derived ethanol for an E85 fuel blend.

Air Quality

Our results for air quality demonstrate the power of life-cycle assessment to identify areas of potential trade-offs and targets for technology improvement. Whereas the substitution of gasoline by ethanol causes a small decrease in the amount of ozone-forming hydrocarbons, the life-cycle emissions of CO, NO*x*, and SO*x* are substantially higher (figure 21). Nitrogen oxide emissions are almost exclusively the result of emissions from the soil on the farm. Sulfur oxide emissions are almost exclusively from the combustion of lignin residue in the ethanol facility. The dramatically higher nitrogen emissions point out the importance of applying better nutrient management practices on the farm. Sulfur oxide emissions in the ethanol facility could be corrected through better pollution controls on the boiler/burner system.

Conclusions

We have developed a life-cycle model that can serve as an appropriate framework for discussing the benefits and trade-offs of substituting gasoline with ethanol made from corn stover. It is the first model that comprehensively addresses the impacts of stover collection on soil health, measured in terms of both of soil erosion and soil organic matter. These results by no means definitively answer the question of whether stover is a sustainable source of energy for transportation. Rather, we see these results as demonstrative of the kind of "what if" scenarios that can be assessed with such a model. In the current study, we have used the model to look at one possible scenario of farm practices and stover removal that can maintain soil quality while providing substantial production of transportation fuel. Many other aspects of the farm must be considered before we can answer the question of how to collect and use stover sustainably. Our model can provide the means for meaningful debate about the benefits and trade-offs of producing energy from stover.

Notes

1. One hectare (ha) = 10,000 square meters (SI) ≈ 2.47 acres.
2. Editor's note: For analyses of land use in the context of life-cycle assessment, see the work by Dornburg and colleagues (2003) in this issue of the *Journal of Industrial Ecology*, as well as the work by van den Broek and colleagues (2001).
3. Tilling practices in the U.S. are often characterized as conventional, moderate or no-till. At one extreme, conventional tilling involves aggressive mechanical turnover of the soil that leads to high rates of soil organic matter loss and erosion by wind and rain. No-till leaves the soil undisturbed, providing protection from erosion and loss of soil organic carbon to the atmosphere. Moderate tilling is intermediate between these two extremes.
4. One metric ton = 1 megagram (Mg, SI) ≈ 1.102 short tons.
5. Based on a dry weight conversion of 25.4 kg (56 lb) per bushel of corn.
6. One megajoule (MJ) = 10^6 joules (J, SI) ≈ 239 kilocalories (kcal) ≈ 948 British Thermal Units (BTU).

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