Improvements in Life Cycle Energy Efficiency and Greenhouse Gas Emissions of Corn-Ethanol

Adam J. Liska, Haishun S. Yang, Virgil R. Bremer, Terry J. Klopfenstein, Daniel T. Walters, Galen E. Erickson, and Kenneth G. Cassman

Keywords:

biofuel
corn-ethanol
greenhouse gas (GHG) emissions
industrial ecology
life cycle assessment (LCA)
net energy

Supplementary material is available on the *JIE* Web site

Address correspondence to:
Kenneth G. Cassman
Department of Agronomy and Horticulture
University of Nebraska
Lincoln, NE 68583-0724
kcassman1@unl.edu

DOI: 10.1111/j.1530-9290.2008.105.x

Volume 00, Number 0

Summary

Corn-ethanol production is expanding rapidly with the adoption of improved technologies to increase energy efficiency and profitability in crop production, ethanol conversion, and coproduct use. Life cycle assessment can evaluate the impact of these changes on environmental performance metrics. To this end, we analyzed the life cycles of corn-ethanol systems accounting for the majority of U.S. capacity to estimate greenhouse gas (GHG) emissions and energy efficiencies on the basis of updated values for crop management and yields, biorefinery operation, and coproduct utilization. Direct-effect GHG emissions were estimated to be equivalent to a 48% to 59% reduction compared to gasoline, a twofold to threefold greater reduction than reported in previous studies. Ethanol-to-petroleum output/input ratios ranged from 10:1 to 13:1 but could be increased to 19:1 if farmers adopted high-yield progressive crop and soil management practices. An advanced closed-loop biorefinery with anaerobic digestion reduced GHG emissions by 67% and increased the net energy ratio to 2.2, from 1.5 to 1.8 for the most common systems. Such improved technologies have the potential to move corn-ethanol closer to the hypothetical performance of cellulosic biofuels. Likewise, the larger GHG reductions estimated in this study allow a greater buffer for inclusion of indirect-effect land-use change emissions while still meeting regulatory GHG reduction targets. These results suggest that corn-ethanol systems have substantially greater potential to mitigate GHG emissions and reduce dependence on imported petroleum for transportation fuels than reported previously.

Introduction

Corn-ethanol biofuel production in the United States is expanding rapidly in response to a sudden rise in petroleum prices and supportive federal subsidies. From a base of 12.9 billion liters (3.4 billion gallons [bg]) from 81 facilities in 2004, annual production capacity increased to 29.9 billion liters (7.9 bg) from 139 biorefineries in January 2008 (RFA 2008). With an additional 20.8 billion liters (5.5 bg) of capacity from 61 facilities currently under construction, total annual production potential will likely reach 50.7 billion liters (13.4 bg) within 1–2 years, with facilities built since 2004 representing 75% of production capacity. This level of production is ahead of the mandated grain-based ethanol production schedule in the Energy Independence and Security Act (EISA) of 2007, which peaks at 57 billion liters (15 bg) in 2015 (U.S. Congress 2007). At this level of production, corn-ethanol will replace about 10% of total U.S. gasoline use on a volumetric basis and nearly 17% of gasoline derived from imported oil.

Biofuels have been justified and supported by federal subsidies largely on the basis of two assumptions about the public goods that result from their use, namely, (1) that they reduce dependence on imported oil, and (2) that they reduce greenhouse gas (GHG) emissions (carbon dioxide [CO_2], methane [CH_4], and nitrous oxide [N_2O]) when they replace petroleum-derived gasoline or diesel transportation fuels.[1] In the case of corn-ethanol, however, several recent reports estimate a relatively small net energy ratio (NER) and GHG emissions reduction compared to gasoline (Farrell et al. 2006; Wang et al. 2007) or a net increase in GHG emissions when both direct and indirect emissions are considered (Searchinger et al. 2008). These studies rely on estimates of energy efficiencies in older ethanol plants that were built before the recent investment boom in new ethanol biorefineries that initiated production on or after January 2005. These recently built facilities now represent about 60% of total ethanol production and will account for 75% by the end of 2009.

These newer biorefineries have increased energy efficiency and reduced GHG emissions through the use of improved technologies, such as thermocompressors for condensing steam and increasing heat reuse; thermal oxidizers for combustion of volatile organic compounds (VOCs) and waste heat recovery; and raw-starch hydrolysis, which reduces heat requirements during fermentation. Likewise, a large number of new biorefineries are located in close proximity to cattle feeding or dairy operations, because the highest value use of coproduct distillers grains is for cattle feed, compared to their value in poultry or swine rations (Klopfenstein et al. 2008). Close proximity to livestock feeding operations means that biorefineries do not need to dry distillers grains to facilitate long-distance transport to livestock feeding sites, which saves energy and reduces GHG emissions. Corn yields also have been increasing steadily at 114 kg ha^{-1} (1.8 bu ac^{-1}) due to improvements in both crop genetics and agronomic management practices (Duvick and Cassman 1999; Cassman and Liska 2007). For example, nitrogen fertilizer efficiency, estimated as the increase in grain yield due to applied nitrogen, has increased by 36% since 1980 (Cassman et al. 2002), and nitrogen fertilizer accounts for a large portion of energy inputs and GHG emissions in corn production (Adviento-Borbe et al. 2007). Similarly, the proportion of farmers adopting conservation tillage practices that reduce diesel fuel use has risen from 26% in 1990 to 41% in 2004 (CTIC 2004).

The degree to which recent technological improvements in crop production, ethanol biorefining, and coproduct utilization affect life cycle GHG emissions and net energy yield (NEY) of corn-ethanol systems has not been thoroughly evaluated. Widespread concerns about the impact of corn-ethanol on GHG emissions and its potential to replace petroleum-based transportation fuels require such updates. For example, the 2007 EISA mandates that life cycle GHG emissions of corn-ethanol, cellulosic ethanol, and advanced biofuels achieve 20%, 60%, and 50% GHG emissions reductions relative to gasoline, respectively (US Congress 2007). California is currently in the process of developing regulations to implement a low-carbon fuel standard (LCFS), with the goal of reducing GHG emissions from motor fuels by 10% by 2020 compared to present levels (Arons et al. 2007). Global concerns about climate change are the motivation for establishment of an emissions trading market in the Europe Union and the Chicago Climate Exchange in the United States (Ellerman and Buchner 2007). In addition, cap-and-trade systems for GHG reduction will be implemented in seven northeastern states under the Regional Greenhouse Gas Initiative (www.rggi.org) and in a five-state Western Climate Initiative, with a national program looming (Kintisch 2007). Given these trends, standard metrics and life cycle assessment (LCA) methods using updated industry data are needed to provide accurate estimates of the GHG emissions from biofuels to (1) comply with national renewable fuel standards and state-level LCFSs, (2) participate in emerging markets that allow monetization of GHG mitigation (McElroy 2007; Liska and Cassman 2008), and (3) reduce negative environmental impacts of biofuels at regional, national, and international levels (Lewandowski and Faaij 2006; Roundtable on Sustainable Biofuels, http://cgse.epfl.ch/page65660.html).

The recent legislative mandates to achieve specified levels of GHG reductions through the use of biofuels and the lack of published information about how the emerging ethanol industry is currently performing in relation to these mandates provide justification for the objectives of the current study. Our goal is to quantify the NEY and GHG emissions of corn-ethanol systems on the basis of an integrated understanding of how current systems are operating with regard to crop and soil management, ethanol biorefining, and coproduct utilization by livestock. Emissions from the indirect effects of land use change that occur in response to commodity price increases attributable to expanded biofuel production (e.g., Searchinger et al. 2008) are not considered in our study, because such indirect effects are applied generally to all corn-ethanol at a national or global level and are not specific to a particular corn-ethanol biorefinery facility and associated corn supply. Instead, our focus is on direct-effect life cycle GHG emissions and the degree of variation due to differences in the efficiencies of crop production, ethanol conversion, and coproduct utilization of recently built ethanol biorefineries and related advanced systems. This information is captured with LCA software called the Biofuel Energy Systems Simulator (available at www.bess.unl.edu).

LCA of Corn-Ethanol Systems

Direct-effect life cycle energy and GHG assessment of corn-ethanol considers the energy used for feedstock production and harvesting, including fossil fuels (primarily diesel) for field operations and electricity for grain drying and irrigation (Liska and Cassman 2008). Energy expended in crop production also includes upstream costs for the production of fertilizer, pesticides, and seed; depreciable cost of manufacturing farm machinery; and the energy required in the production of fossil fuels and electricity. Energy used in the conversion of corn to ethanol includes transportation of grain to the biorefinery, grain milling, starch liquefaction and hydrolysis, fermentation to biofuel, and coproduct processing and transport. Energy used for the construction of the biorefinery itself is also included in the assessment and is prorated over the life of the facility.

Most previous LCA studies evaluated the efficiency of the entire U.S. corn-ethanol industry, which requires the use of aggregate data on average crop and biorefinery performance parameters (Farrell et al. 2006). These studies rely on U.S. Corn Belt averages for corn yields, husbandry practices, and crop production input rates based on weighted state averages and average biorefinery efficiency based on both wet and dry mill types. Such estimates do not capture the variability among individual biorefineries, and they utilize data on crop production and ethanol plant energy requirements that are obsolete compared to plants built within the past 3 years, which account for the majority of current ethanol production.

There are also different methods for determining coproduct energy credits. The approach used most widely is the displacement method, which assumes that coproducts from corn-ethanol production substitute for other products that require energy in their production. For corn-ethanol, distillers grains coproducts are the unfermentable components in corn grain, including protein, oil, and lignocellulosic seed coat material (Klopfenstein et al. 2008). As such, distillers grains represent a nutritious animal feed, especially for ruminants, such as cattle. Therefore, most life cycle energy and GHG analyses give a displacement credit for this coproduct as cattle feed, because this is the highest value use, and the expansion of corn-ethanol production capacity has had little impact on cattle numbers.

To determine environmental impacts to meet emerging regulatory requirements, one must assess an individual ethanol biorefinery and supporting cropping system. An analysis of regional cropping systems is important because biorefineries receive a majority of their feedstock from local sources—a trend that will likely continue as corn-ethanol production expands and utilizes a greater portion of total U.S. corn production. Cropping system productivity and efficiency also have significant variability depending on regional differences in climate and soil quality, crop yield levels, input use efficiencies, and irrigation practices.

Researchers can evaluate "forward-looking" LCAs of potential improvements in biofuel production systems by performing sensitivity analyses that identify the technology options with the greatest potential impact on energy yield and efficiency and GHG emissions reductions. Such forward-looking analyses can help guide the design of future biofuel systems and identify research priorities for the greatest potential impact on possible environmental benefits and petroleum replacement.

Although there are a number of existing models that perform life cycle energy and GHG emissions assessments of biofuel systems (Wang et al. 2007; Farrell et al. 2006), we developed the Biofuel Energy Systems Simulator (BESS) software to facilitate detailed evaluation and comparison of different types of corn-ethanol systems in a "seed-to-fuel" life cycle. The seed-to-fuel life cycle boundary was selected because it is the basis for meeting GHG emissions reductions under the 2007 EISA and for California's LCFS. Compared to other models, the BESS software performs a more detailed seed-to-fuel assessment of an individual corn-ethanol facility and its associated feedstock supply, with full documentation and reporting of all parameters and conversion efficiencies used. It can also evaluate the average performance of a specified type of ethanol plant at a state or regional level. The software allows modification of all input parameters, which enables sensitivity analysis of different biorefinery types and feedstock supply. Although the BESS software follows the general life cycle boundaries and calculation methods of the RG Biofuel Analysis Meta-Model (EBAMM model) (Farrell et al. 2007), BESS includes more thorough evaluation of N_2O emissions from crop production, allows greater detail in biorefinery operations while utilizing more recent industry data, and uses a dynamic coproduct crediting scheme based on updated feeding practices.

Methodology

Model Interface and Engine

The BESS model was created with Microsoft Excel as its internal engine and Delphi programming software for development of its graphic interface. It is Microsoft Windows compatible. The BESS model has four component submodels for (1) crop production, (2) ethanol biorefinery, (3) cattle feedlot, and (4) anaerobic digestion (AD) as used in a closed-loop biorefinery. The annual production capacity of an individual biorefinery determines the required inputs of grain, energy, material, and natural resources (including fossil fuels, land, and water). The model has an extensive user's guide documenting model operation, assumptions, equations, parameter values, and references. The interface enables the user to set all input parameters to create customized corn-ethanol system scenarios and to compare multiple scenarios with output graphs and reports. The software (version BESS2008.3.1, including the *User's Guide*) is available at www.bess.unl.edu. Input data and assumptions are described in the following sections and in Supplementary Material on the Web.

Crop Production Data

Crop yields are taken from U.S. Department of Agriculture, National Agricultural Statistics Service (USDA-NASS) survey database. Crop production energy input rates (gasoline, diesel, liquefied petroleum gas [LPG], natural gas, electricity) are from the most recent USDA survey conducted by the Economic Research Service (see USDA-ERS 2001; see also Supplementary

Material on the Web and BESS *User's Guide* for more detail). Unfortunately, more recent USDA energy input surveys will not be available in the future, because funding is no longer allocated for collecting these data (McBride 2007). Default scenarios for a given state use the crop yield and input data for that state (USDA-ERS 2005). The Midwest scenarios utilize weighted-average input rates based on harvested corn area in the 12 Midwest states,[2] a region that accounted for 88% of total U.S. corn production in 2005. The progressive agricultural system (high-yield progressive cropping system with a standard natural gas biorefinery [HYP-NG]) is based on experimental data from Nebraska obtained from a production-scale field experiment that utilized innovative crop and soil management practices to achieve high yields with improved efficiencies for both irrigation and nutrient management (Verma et al. 2005).

Ethanol Biorefinery Data

The majority of ethanol plants built since 2004 and currently under construction in the United states are natural-gas-powered dry-grind mills. BESS version 2008.3.1 includes statistics from four recent surveys of ethanol plants (see table 1). Survey 1 includes 22 plants with a total annual capacity of 6.8 billion liters (L; 1.8 billion gallons). It was conducted by the Renewable Fuels Association and Argonne National Laboratories in 2006 and is one of the largest surveys conducted in recent years. It includes both wet and dry mills powered by coal or natural gas. Our study only uses performance values for the dry-mill plants in this survey (www.ethanolrfa.org/objects/documents/1652/2007_analysis_of_the_efficiency_of_the_us_ethanol_industry.pdf).

Survey 2 is an original survey we performed as a part of the USDA NC506 Regional Research project Sustainable Biorefining Systems for Corn Ethanol in the North-Central Region. It included eight ethanol plants in six states across the Corn Belt that began operation on or after January 2005. Data shown in table 1 were obtained directly from the plant managers. Plant capacities ranged from 182 to 212 million L per year (48 to 56 million gallons), for a total production capacity of 1.6 billion L in 2006 (420 million gallons), which was about 9% of total U.S. corn-ethanol production in that year.

Survey 3 represents data obtained from the Nebraska Department of Environmental Quality (NDEQ), which collects plant performance statistics to ensure compliance with air quality regulations. The nine ethanol plants in this data set included facilities that produced dry, wet, or a mixture of dry and wet distillers grains. They ranged from 83 to 220 million L annual production capacity (22 to 58 million gallons) and represented 1.4 billion L of total production (366 million gallons) in 2006, which was roughly 8% of total U.S. production. Survey 3a is a subset of the biorefineries included in Survey 3; it includes four plants that only produce wet distillers grains. Survey 4 represents data collected by the Iowa Department of Natural Resources (IDNR) for nine ethanol plants from 2004 to 2006 in compliance with state and federal air quality standards. These plants produce 1.5 billion L annually (400 million gallons), or about 8% of total 2006 U.S. ethanol production.

Surveys 3 and 4 contain no overlapping plants; Survey 2 contains one plant also found in Survey 4; and it is impossible to determine whether there is any overlap between Survey 1 and the other surveys, because only aggregate data are available to the public, without attribution to a specific biorefinery. In total, the unique ethanol production capacity included in Surveys 2–4 represents 4.3 billion L, or 23% of total U.S. ethanol production capacity in 2006. The largest recent survey of ethanol plants was performed by Christianson & Associates, and data from this survey provide an additional reference point. This 2007 survey included 33 ethanol plants from across the Corn Belt, with 97% of the production capacity coming from natural-gas-powered dry-mill facilities. Although the Christianson & Associates data are not used directly in any of the BESS scenarios, the average amount of energy used in the surveyed plants was remarkably similar to the averages from Surveys 1–4 (http://www.ethanolrfa.org/objects/documents/1916/usethanolefficiencyimprovements08.pdf).

Surveys 1 and 2 are for denatured ethanol, whereas Surveys 3 and 4 are for anhydrous ethanol, because data were not available for rates of denaturant added (typical addition levels range

Table 1 Performance of the evaluated corn-ethanol systems in the Midwest Corn Belt states, Iowa, and Nebraska with selected input values and output metrics for eight default scenarios in the BESS model

Simulation scenarios		*MW-NG*	*MW-NNG*	*IA-NG*	*NE-NG*	*NE-NGW*	*NE- CL*	*NE-Coal*	*HYP-NG*
Agricultural energy inputs by cropping region									
Region		MW	MW	IA	NE	NE	NE	NE	HYP
Energy inputs	GJ Mg^{-1}	1.7	1.7	1.4	2.3	2.3	1.9	2.3	1.8
Biorefinery energy inputs by type, according to survey data									
Survey data		RFA[1]	UNL[2]	IDNR[4]	NDEQ[3]	NDEQ[3a]	NDEQ[3a]	EPA[a]	NDEQ[3]
Energy source		NG	NG	NG	NG	NG	CL	Coal	NG
Thermal energy	MJ L^{-1}	7.69	4.62	6.95	6.85	5.44	5.44	6.10	6.85
TE, drying DG	MJ L^{-1}	ns	2.98	ns	0.76	0.00	0.00	4.00	0.76
Electricity	kWh L^{-1}	0.185	0.174	0.185	0.185	0.185	0.291	0.230	0.185
Conversion yield	L kg^{-1}	0.419	0.432	0.393	0.408	0.423	0.423	0.419	0.408
Dry DGS	%	35	66	22	32	0	0	100	32
Modified DGS	%	30	31	23	32	0	0	0	32
Wet DGS	%	35	3	55	36	100	100	0	36
Capital energy	MJ L^{-1}	0.13	0.13	0.13	0.13	0.13	0.26	0.13	0.13
System performance metrics									
Net energy ratio	MJ MJ^{-1}	1.61	1.64	1.76	1.50	1.79	2.23	1.29	1.60
Ethanol to petrol.	MJ MJ^{-1}	12.3	12.5	12.9	10.1	10.9	9.3	10.3	18.8
GHG intensity	$gCO_2e\ MJ^{-1}$	45.1	45.0	42.0	48.1	37.5	30.6	76.0	43.8
GHG reduction	%	51	51	54	48	59	67	17	52
Ethanol yield	L ha^{-1}	4,010	4,134	4,205	3,970	4,116	4,116	4,077	5,590

Note: Survey data are from studies described in the Methodology section under the Ethanol Biorefinery Data subheading, and superscripts denote the numbers assigned in this section to the specific survey that was the source of these data. In the closed-loop system, anaerobic digestion compensates for a portion of the natural gas requirement, set here as a baseline. Production of distillers grain types was estimated from natural gas use or from survey data (see Supplementary Material on the Web). MW = Midwest; IA = Iowa; NE = Nebraska; HYP = high- yield progressive; NG = natural gas; NNG = new natural gas; NGW = natural gas with wet distillers grains only; CL = closed-loop facility with anaerobic digestion; TE = thermal energy; DGS = distillers grains plus solubles; ns = not specified.

[a] EPA data are based on expert engineering estimates (EPA-EEA 2006).

from 2% to 4%). Results from Surveys 3 and 4 are thus conservative, as more fuel volume would be produced per unit of input. And although addition of denaturant would increase GHG emissions slightly, there is relatively little impact on life cycle emissions intensity as measured in grams of CO_2 equivalent per megajoule ($gCO_2e\ MJ^{-1}$), because the energy content of gasoline is incorporated into the denominator of this intensity ratio and has a higher energy value than ethanol. Results from Surveys 2–4 above are production-weighted averages based on annual productivity of the plants in the surveys.

One BESS scenario simulates a closed-loop biorefinery with anaerobic digestion of coproducts and cattle manure. The associated natural gas offset and system parameters for this scenario were developed in cooperation with Prime Biosolutions (Omaha, NE; http://www.primebiosolutions.com/) on the basis of the estimated efficiency of the closed-loop facility recently constructed in Mead, Nebraska. (See Supplementary Material on the Web and the BESS *User's Guide* for greater detail.)

Coproduct Cattle Feeding

Model calculations for determining a dynamic coproduct energy and GHG credit for distillers grains were based on their use in cattle feedlot rations. Factors that determine the magnitude of this credit include the percentage of inclusion in cattle diets, transportation distance from the ethanol plant to the feedlot, and cattle performance, which was based on extensive cattle feeding research at the University of Nebraska (Klopfenstein et al. 2008). It is assumed that conventional cattle feeding occurs in an open feedlot, because the large majority of cattle are produced in such feedlots. The BESS model utilizes the amount and type of coproduct created by the biorefinery to calculate the number of cattle needed to utilize all coproducts produced. Production energy costs for urea were previously estimated by industry standards for fertilizer production. A detailed account of the scientific basis for this coproduct crediting scheme is provided in the BESS *User's Guide*. An additional manuscript is in preparation with a complete description and evaluation of the coproduct credit model.

GHG Emission Factors

The BESS model includes all GHG emissions from the burning of fossil fuels used directly in crop production, grain transportation, biorefinery energy use, and coproduct transport. All upstream energy costs and associated GHG emissions with production of fossil fuels, fertilizer inputs, and electricity used in the production life cycle are also included (see Supplementary Material on the Web and BESS *User's Guide* for details). Nonfossil fuel GHG emissions include N_2O from additions of nitrogen (N) from nitrogen fertilizer and manure, losses from volatilization, leaching and runoff, and crop residue; methane emissions from enteric fermentation are reduced in the coproduct crediting scheme and from manure capture in the closed-loop system. Emission factors were primarily from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC et al. 2006). National average emissions from electricity were derived from "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2005" (US EPA 2007) and were used for default scenarios (on average, CO_2 accounts for more than 99% of electricity GHG emissions; see Supplementary Material on the Web). For the analysis shown in figure 4, state-level CO_2 emissions from electricity generation were obtained from the Environmental Protection Agency's *Year 2004 Summary Tables* (April 2007) from eGRID2006 Version 2.1, and CH_4 and N_2O emissions were national averages. Emissions of N_2O-N from corn production were calculated to be approximately 1.8% of applied N fertilizer as well as additional losses from the N in applied manure, recycled crop residues, and N lost as nitrate (IPCC et al. 2006). Net change in soil carbon was assumed to be zero, because recent studies document that most corn-based cropping systems are neutral with regard to the overall carbon balance at the field level (Verma et al. 2005; Baker et al. 2007; Blanco-Canqui and Lal 2008).

Corn-Ethanol System Scenarios

Eight default scenarios are included in the BESS model. Six represent common types of corn-ethanol biorefineries, whereas two represent improved technologies for crop production

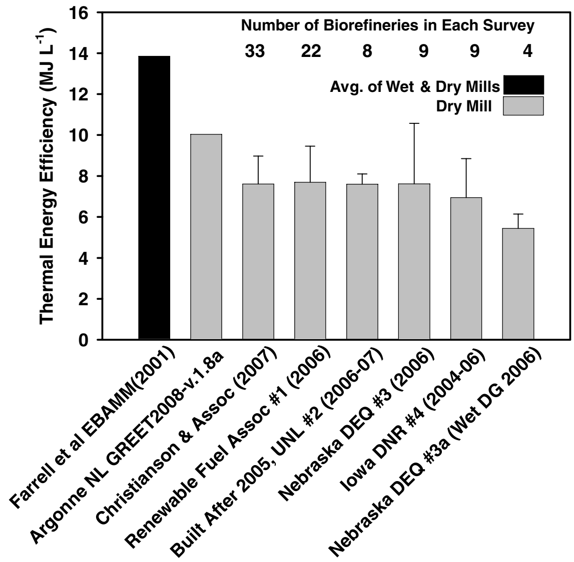

Figure 1 Biorefinery thermal energy efficiency (MJ L^{-1} ethanol) in corn-ethanol production; previous estimates (found in EBAMM and GREET) are compared to more recent survey data from natural-gas-powered dry mills in the Corn Belt. Estimates are labeled by survey organization, survey number as described in the Methodology section, and year of biorefinery operation in parentheses. Standard deviations of survey results are shown with error bars. EBAMM = RG Biofuel Analysis Meta-Model; GREET = Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation.

(high-yield, progressive crop and soil management) or biorefinery operation and coproduct use (closed loop). Dry-mill types are linked with average corn production for the U.S. Midwest, Iowa (IA), Nebraska (NE) or a progressive no-tillage irrigated high-yield cropping system in Eastern NE (Verma et al. 2005; see table 1). The NE state average cropping system was additionally coupled with three additional biorefinery configurations: (1) a natural-gas-powered dry-mill producing only wet distillers grains and solubles (DGS) based on a survey of four plants in NE (NE-NGW); (2) a closed-loop biorefinery assumes that a natural-gas-powered dry-mill ethanol plant is located adjacent to a cattle feedlot that uses all the wet DGS in feed rations and that the manure and urine are collected as feedstock for an anaerobic digestion (AD) unit, which produces methane to power the ethanol plant thermal energy inputs (NE-CL); and (3) a coal-powered dry-mill biorefinery that produces dry DGS is based on data from Energy and Environment Analysis, Inc. (2006; NE-Coal; see table 1).

Results and Discussion

LCA of Biorefinery Types

The majority of current U.S. corn-ethanol biorefineries are dry mills (82% of total U.S. production capacity in 2006; RFA 2008), as opposed to wet mills that separate gluten from starch before fermentation, and nearly all of these facilities are powered by natural gas. Likewise, most of the plants under construction are also dry mills powered by natural gas. The results we report here are based on a representative cross-section of this type of biorefinery; they are derived from surveys of individual facilities located in six Corn Belt states that accounted for 23% of total U.S. ethanol production in 2006 (1.13 billion gallons).

The results from our analyses indicate a substantial decrease in the amount of thermal energy required by these natural-gas-powered corn-ethanol biorefineries compared to earlier estimates (see figure 1). The estimates of biorefinery energy use from the most recent surveys show remarkable consistency, even though the data were obtained independently and represent a wide geographical distribution within the Corn Belt. These recent survey values for biorefinery energy use are used in the LCA results that follow based on the default scenarios analyzed by the BESS software.

The eight corn-ethanol scenarios had net energy ratio (NER) values from 1.29 to 2.23 and GHG intensities ranging from 31 to 76 gCO_2e MJ^{-1} (see table 1). For the most common biorefinery types, which are represented by the first five scenarios, NER ranged from 1.50 to 1.79,

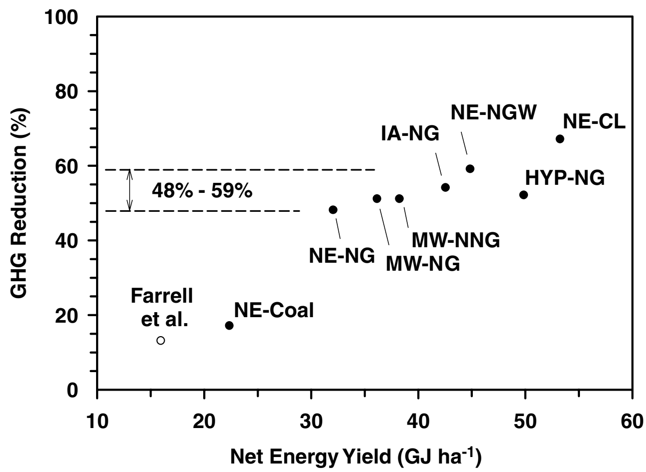

Figure 2 Net energy yield (NEY) and greenhouse gas (GHG) emissions reduction compared to gasoline from different types of corn-ethanol systems used as default scenarios in the BESS model (www.bess.unl.edu). NEY includes ethanol plus coproduct energy credit minus energy inputs. MW = Midwest; IA = Iowa; NE = Nebraska; HYP = high-yield progressive; NG = natural gas; NNG = new natural gas; NGW = natural gas with wet distillers grains only; CL = closed-loop facility with anaerobic digestion.

and GHG intensity ranged from 38 to 48 gCO_2e MJ^{-1}. The largest ethanol yield relative to harvest area or petroleum input was achieved by the HYP-NG, which produced nearly 19 units of ethanol output per unit of petroleum input, on an energy-equivalent basis. The most common corn-ethanol systems reduced GHG emissions by 48% to 59% compared to gasoline, which has a GHG intensity of 92 gCO_2e MJ^{-1} (Arons et al. 2007; see figure 2). NEYs ranged from 22 to 53 gigajoules per hectare (GJ ha^{-1}) and tended to be correlated with GHG reduction. Although ethanol plants with a coal-based thermal energy source (NE-Coal) had the lowest NER, NEY, and GHG reduction potential, this type of biorefinery accounts for a small proportion of U.S. corn-ethanol production.

The highest NER (2.23), the smallest GHG intensity (31 gCO_2e MJ^{-1}), and the greatest reduction in GHG emissions (67%) compared to gasoline occur in the closed-loop biorefinery system, where 56% of natural gas use is offset by biogas produced on site (see table 1). In the closed-loop system, all coproduct distillers grains are consumed at a cattle feedlot adjacent to the ethanol biorefinery. Coproduct distillers grains are fed wet to cattle and displace other feed requirements up to 50% of total intake (Klopfenstein et al. 2008). Cattle manure and urine are collected via slotted floors and processed in an AD system that produces methane. The AD unit is also assumed to be supplied with organic matter from coproduct syrups from the biorefinery. Maintaining the cattle feedlot on site adds no additional energy costs to the corn-ethanol system life cycle, because it is assumed that the feedlot is independent from the biofuel industry. The energy in methane from the AD unit is decreased by greater capital costs for infrastructure and increased electricity rates for operations (see table 1). Although coproduct distillers grains represent only a portion of the cattle diet and other feeds are required, all of the manure and resulting methane produced in the AD unit is credited to displace natural gas in the ethanol plant, because manure would not be harvested for energy from conventional open-pen feedlots. Moreover, nutrients in the manure are conserved in the AD process and are subsequently recovered for application to cropland, just as they are in manure. Thus, capturing the reduced carbon in manure with AD utilizes a carbon-neutral energy source not previously captured due to the natural oxidation of carbon in manure.

Emissions of GHGs in a closed-loop system are additionally reduced by capture of manure methane and N. Methane from manure that would have been emitted if the cattle were fed in a traditional open feedlot is reduced by manure collection. The N excreted from the coproduct-fed cattle and from coproduct solubles from the biorefinery ends up in the aqueous output from the AD unit. The N is removed from this stream by means of an osmosis separation and is used to replace N fertilizer in crop production, which gives it an energy and GHG emissions offset for upstream production of an equivalent amount of N fertilizer. The N credit due to the closed-loop system is equal to the proportion of dietary N excreted by the cattle due to the inclusion of wet distillers grains in the diet minus the coproduct-inclusion-rate-equivalent amount of N that would have been captured by an open-pen feedlot with conventional manure-handling systems, where about 49% of excreted N is volatilized from the pen surface (see BESS *User's Guide*). Besides the N retained in cattle, the capture of N is assumed to be 85% efficient in the closed-loop system, with an additional 15% loss of N at various stages in the cycle of production and feeding of coproducts to AD, removal of N, and field application.

Coproduct Energy Credits and Impact on GHG Emissions

Coproduct substitutes for a portion of a conventional corn-based cattle diet and is therefore allocated an energy credit for displacing conventional feed. A previous estimate of the energy credit attributed to distillers grains was 4.13 megajoules per liter (MJ L^{-1}) of ethanol (Farrell et al. 2006). This energy credit was estimated from a National Research Council report in 2000, which assumed that coproducts displaced corn, urea, soybean meal, and oil at 15% inclusion in the cattle diet. In response to the large increase in availability of distillers grains coproduct from ethanol production and the rise in soybean prices, cattle diets now largely exclude soybean meal and include a larger proportion of distillers grains coproduct (Klopfenstein et al. 2008). Thus, the energy and GHG credits attributable to feeding distillers grains must be based on current practices for formulating cattle diets.

Because the method of coproduct crediting has a large impact on life cycle energy efficiency and GHG emissions (see figure 3), the BESS model includes a detailed cattle feedlot component to estimate these effects. It assumes that the cattle feedlot industry will remain at a relatively constant size and exists independently of the biofuel industry—that is, the same number of cattle will be fed regardless of expansion of ethanol production capacity of 57 billion liters by 2015, as mandated in the 2007 EISA. The cattle component of the BESS model calculates a partial budget of the cattle feedlot considering the difference between a conventional diet and a cattle diet containing a mixture of dry DGS, partially-dried "modified" DGS, and wet DGS. The model then calculates the amount of energy and GHG emissions that would have been expended to produce the feed components that were displaced by the coproducts.

The crop production component of the model is used to calculate the energy requirement to produce a unit of corn (GJ Mg^{-1} grain; see BESS *User's Guide*) and associated GHG emissions. Corn grain consumption displaced by use of distillers grains reduces positive life cycle emissions by 20% for a typical natural-gas-powered biorefinery in Iowa (see table 2). Urea is also displaced by distillers grains in cattle rations, which reduces emissions by 5%. As cattle are on feed fewer days, methane emissions from enteric fermentation are reduced. An additional fossil fuel cost for transportation and feeding coproduct distillers grains is subtracted from the corn and urea feed substitution credit; the result is a final net coproduct energy credit, which ranges from 3 to 5 MJ L^{-1} depending on the proportion of coproduct substitution in the diet, average transport distance, and the type and level of distillers grains substituted in the feed rations. In total, the GHG credits attributable to coproducts ranged from 19% to 38% of total life cycle emissions (see figure 3).

Impact of Regionally Variable Corn Production

Feedstock yield and production inputs have a large impact on biofuel system efficiency, GHG emissions, and NEY. Although the BESS model

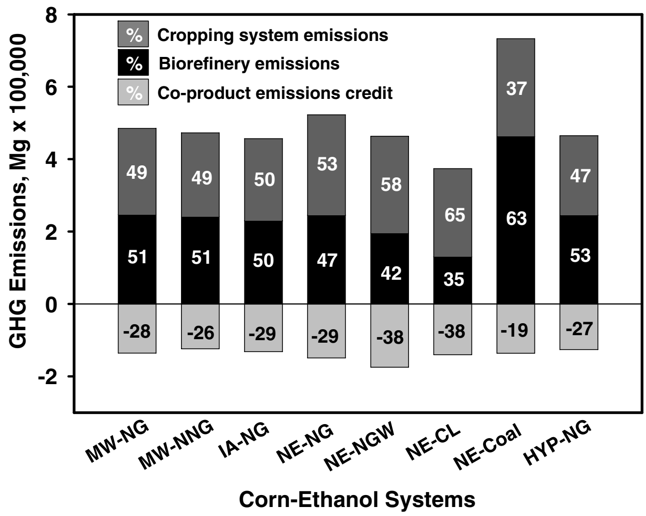

Figure 3 Greenhouse gas (GHG) emissions from each component of the corn-ethanol life cycle for different corn-ethanol systems. Values are based on BESS default scenarios for biorefineries with an annual ethanol production capacity of 379 million liters. Contributions of individual GHGs can be seen in the BESS model output results (www.bess.unl.edu). MW = Midwest; IA = Iowa; NE = Nebraska; HYP = high-yield progressive; NG = natural gas; NNG = new natural gas; NGW = natural gas with wet distillers grains only; CL = closed-loop facility with anaerobic digestion.

allows the user to specify default input parameters for crop production if they are available for a specific biorefinery and its associated feedstock supply, the default scenarios rely on data aggregated at the state or Midwest regional levels. Although crop production represents 37% to 65% of life cycle emissions in the eight corn-ethanol systems modeled (see figure 3), there are large differences among states due to differences in average crop yields and input requirements for corn production. Differences in soil properties, climate, and access to irrigation are largely responsible for these geospatial patterns. In 2003–2005, for example, the highest average county-level corn yield in the United States was 13.6 megagrams per hectare (Mg ha^{-1}), which was 43% greater than the Corn Belt average (9.5 Mg ha^{-1}) and 66% greater than the national average corn yield (8.2 Mg ha^{-1}). Likewise, corn requires irrigation in the drier western Corn Belt and Great Plains states (e.g., NE, Kansas, Colorado, Texas) but is grown almost exclusively under rain-fed conditions in the more humid eastern Corn Belt states. Although irrigation increases the energy intensity of crop production, it also increases crop yields and nitrogen use efficiency while reducing year-to-year yield variation. Higher feedlot cattle density in dry western states allows use of wet DGS as feed in local feedlots, which saves energy for drying and transportation of coproducts (see table 1, NE-NGW).

Land use productivity issues indicate that biofuel energy yield per unit area (e.g., NEY) is a critical metric to indicate the extent of competition among bioenergy, food crops, and native environments (Naylor et al. 2007; Liska and Cassman 2008). The NEY of the corn-ethanol production life cycle was highest in Iowa and lowest in Texas (see figure 4a). The energy intensity of corn production was found to increase from north to south, ranging from 1.4 to 4.1 MJ of energy input per kilogram (kg) grain yield. The southern United States has less soil organic matter, which requires higher N fertilizer inputs, and generally produces lower corn yields due to warmer temperatures, which shortens the grain-filling period. Nitrogen use efficiency (defined as kilograms of grain per kilogram N applied) ranges from 46 to 122 from Kentucky to New York. Irrigation in the West increases energy inputs. The

Table 2 Greenhouse gas (GHG) emissions inventory of the corn-ethanol life cycle (LC) for a natural gas dry mill biorefinery in Iowa (BESS model, IA-NG)

Component	*GHG emission category*	*gCO$_2$e MJ^{-1}*	*Mg CO$_2$e*[a]	*% of LC*
Crop production	Nitrogen fertilizer (N)	4.26	34,069	7.46
	Phosphorus fertilizer (P)	0.953	7,618	1.67
	Potassium fertilizer (K)	0.542	4,337	0.950
	Lime	2.82	22,577	4.95
	Herbicides	1.51	12,079	2.65
	Insecticides	0.018	141	0.031
	Seed	0.193	1,540	0.337
	Gasoline	0.355	2,837	0.621
	Diesel	1.73	13,848	3.03
	LPG	1.24	9,932	2.18
	Natural gas	0	0	0
	Electricity	0.348	2,785	0.610
	Depreciable capital	0.268	2,144	0.470
	N_2O emissions[b]	14.1	112,550	24.7
	Total	**28.3**	**226,456**	49.6
Biorefinery	Natural gas input	19.7	157,356	34.5
	Natural gas input: drying DGS[c]	0	0	0
	Electricity input	6.53	52,201	11.4
	Depreciable capital	0.458	3,663	0.802
	Grain transportation	2.11	16,851	3.69
	Total	**28.8**	**230,071**	50.4
Coproduct credit	Diesel	0.216	1,731	0.379
	Urea production	−2.62	−20,956	−4.59
	Corn production	−11.4	−91,501	−20.0
	Enteric fermentation (CH_4)	−2.64	−21,102	−4.62
	Total	**−16.5**	**−131,828**	−28.9
Transportation of ethanol from biorefinery		1.40	11,196	0
Life cycle net GHG emissions		42.0	335,895	100
GHG intensity of ethanol (g CO2e MJ^{-1})		42.0	335,895	
GHG intensity of gasoline,[d] (g CO2e MJ^{-1})		92.0	735,715	
GHG reduction relative to gasoline (%)		50.0	399,819	54.3%

Note: LPG = liquefied petroleum gas; DGS = distillers and grain solubles.
[a]Based on a 379 million liter annual capacity. [b]Includes emissions from nitrogen (N) inputs (synthetic fertilizer, manure N) and N losses (volatilization, leaching and runoff, crop residue; IPCC et al. 2006; see Supplementary Materials on the Web and BESS *User's Guide* for details). [c]Natural gas used for drying distillers grains was not specified in the survey data and is included in the total natural gas use. [d]Arons et al. 2007.

combination of these factors causes GHG emissions per Mg of grain yield to vary between 226 and 426 kilograms of carbon dioxide equivalent per megagram (kg CO_2e Mg^{-1}) grain, from New York to Texas (see figure 4b). This variation in crop production causes life cycle GHG reductions to vary widely among states, from 40% to 56% GHG reduction compared to gasoline, given an equivalent, recently built natural-gas-powered ethanol biorefinery.

GHG Inventory of Life Cycle Emissions

A GHG emissions inventory is useful for determining the impact of various system components on life cycle results. In this analysis of

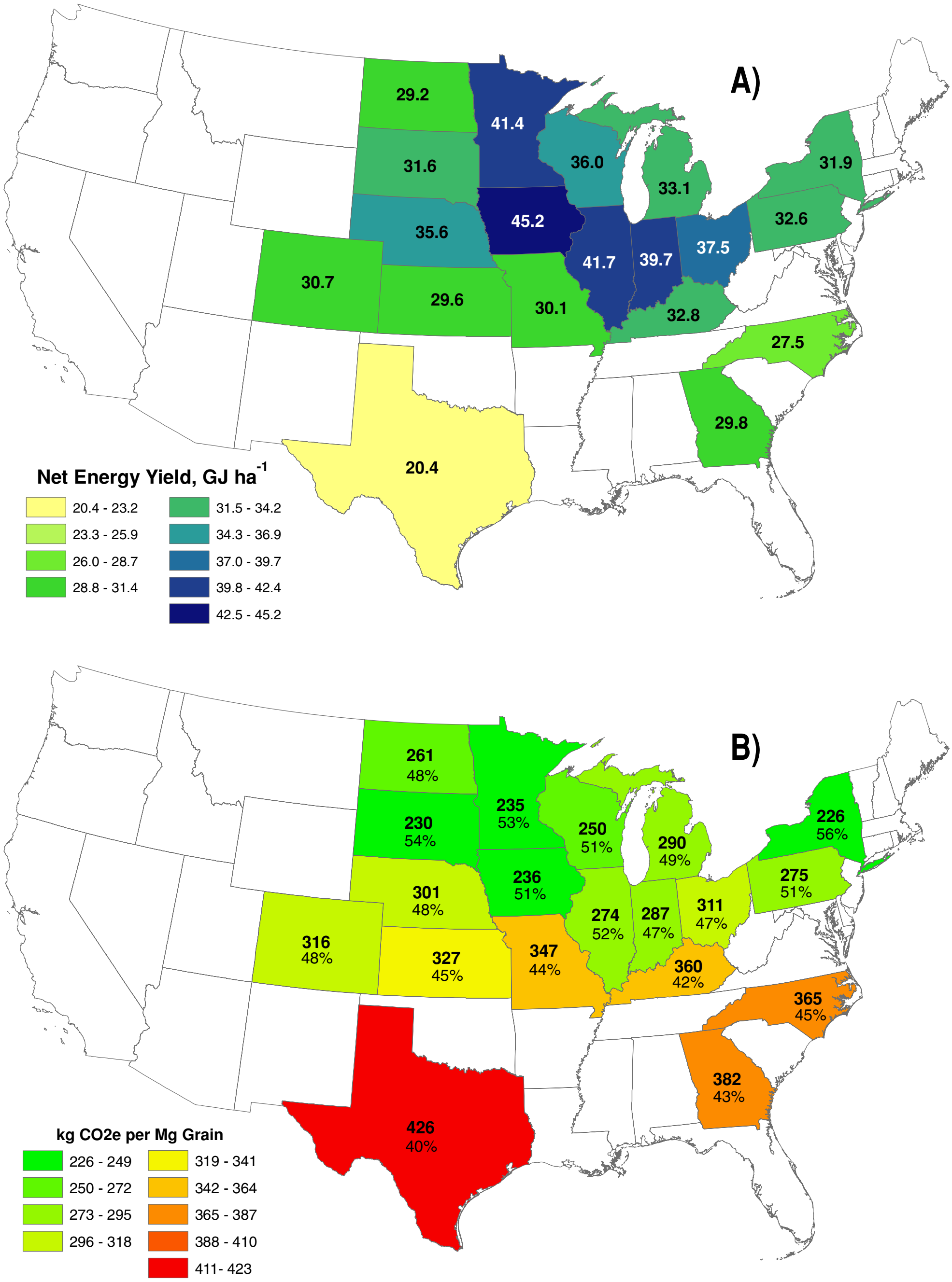

Figure 4 Regional variability in corn-ethanol system performance due to differences in inputs to and outputs from crop production: (A) Net energy yield of the corn-ethanol production life cycle, given a new natural gas biorefinery (see table 1, MW-NNG). (B) Greenhouse gas intensity of corn production (kg CO_2e Mg^{-1} grain), and life cycle GHG reductions of corn-ethanol compared to gasoline (%), given a new natural gas biorefinery. Results were calculated with the BESS model (www.bess.unl.edu).

corn-ethanol, 37% to 65% of life cycle GHG emissions come from the crop production phase, whereas the remaining 35% to 63% are produced by the biorefinery (see figure 3). For example, crop production contributed 50% of positive life cycle GHG emissions in a natural-gas-powered biorefinery in Iowa (IA-NG); N_2O emissions from N fertilizer, manure N, and other indirect losses accounted for nearly half of crop production emissions and 25% of life cycle emissions (see table 2). The biorefinery contributed the other 50% of positive GHG life cycle emissions, and the coproduct credit represents a 29% reduction in GHG emissions.

The sum of the emissions inventory minus the emissions saved by feeding the coproduct results in a life cycle GHG intensity of fuel ethanol at 42 $gCO_2e\ MJ^{-1}$ (see table 2). This represents a 54% reduction in life cycle emissions compared to gasoline; emissions are reduced by nearly 400,000 megagrams of CO_2 equivalents (Mg CO_2e) for a 379 million liter (100 million gallon) ethanol biorefinery.

Toward Certification of Biofuel GHG Intensity and Emissions Trading

The BESS model provides a framework for developing standardized assessment procedures for biofuels. The default scenarios evaluate performance of the most common types of U.S. corn-ethanol production facilities, and the output provides an estimate of GHG emissions compared to gasoline. Regulations and compliance processes to meet the emissions thresholds stipulated by legal mandates, such as the EISA of 2007, will require development of standardized life cycle metrics and assessment protocols for biofuel systems (Liska and Cassman 2008). Scientific consensus among the regulating agencies at state, national, and international levels is needed for the establishment of system boundaries, constant and dynamic input parameters and their values, and the metrics employed. Explicit, transparent, and well-documented LCA software, such as BESS, can serve as a platform for building such a consensus. Government agencies, researchers, the private sector, and environmental advocacy groups from regional, national, and international levels are currently engaged in a dialogue to develop a biofuel GHG emission certification process (Lewandowski and Faaij 2006; Roundtable on Sustainable Biofuels, http://cgse.epfl.ch/page65660.html).

Of existing models to evaluate the GHG intensity of the corn-ethanol production life cycle, all lack an adequate user interface for regulatory and compliance purposes (Arons et al. 2007). In addition, most existing models utilize outdated values for key input parameters for crop production and yields, the amount of energy required by a typical ethanol biorefinery to convert corn to ethanol and process the coproducts, and the manner in which coproducts are used in livestock diets. Differences in the coproduct credits in BESS compared to earlier models are largely due to three factors: (1) Distillers grains are considered an energy source rather than a source of protein, because the feed has threefold greater protein content than corn (Klopfenstein et al. 2008); (2) N_2O emissions associated with displaced corn result in a larger GHG emissions credit; and (3) wet DGS has a higher feeding efficiency compared to dry DGS. Taken together, use of updated input parameters across the life cycle results in substantial differences in estimates of GHG emissions from corn-ethanol (see table 3).

When GHG emissions from crop production, biorefinery, and coproduct savings are evaluated according to recent data, the magnitude of direct-effect GHG emission reductions is twofold to threefold greater than the 17% to 24% previously reported from existing models with older performance data (see table 3). Such a large difference will affect the regulation of GHG emissions from corn-ethanol systems under the 2007 EISA and state-level LCFS, because the production life cycle can tolerate an additional GHG "debt" from the indirect effects of land use change and still meet GHG emissions standards.

GHG emissions trading markets could provide an additional revenue stream if the corn-ethanol systems can achieve verifiable reductions in GHG emissions compared to gasoline. For example, when the mandated annual production capacity of 57 billion liters occurs by 2022, a 50% GHG reduction could have an annual value of \$330 million at current Chicago Climate Exchange prices of \$6 per Mg CO_2e.

Table 3 Comparison of results from different models for life cycle greenhouse gas (GHG) emissions from dry-mill corn-ethanol systems ($gCO_2e\ MJ^{-1}$)

Emissions	*GREET*	*BEACCON*	*EBAMM*	*BESS (MW-NNG)*	*BESS (NE-NG)*	*BESS (NE-NGW)*
Crop production	44	44	37	29	35	34
Biorefinery	43	37	64	30	31	25
Coproduct credit	−17	−17	−25	−16	−19	−22
Denaturant	–	6	–	–	–	–
Land use change	–	1	–	–	–	–
GWI	70	71	76	45	48	38
Gasoline	92	92	92	92	92	92
GHG reduction (%)	24	23	17	51	48	59

Note: GREET version 1.8a is available from: http://www.transportation.anl.gov/software/GREET/. BEACCON version 1.1 is available from www.lifecycleassociates.com; it is largely based on GREET. EBAMM version 1.1-1 (Farrell et al. 2006), "Ethanol Today" avg. 2001 ethanol plant, data for wet and dry mills, see figure 1; BESS model default scenarios. The BESS model has a dynamic coproduct credit that is primarily dependent on the GHG intensity of crop production and the yield of ethanol per unit gram at the biorefinery. MW = Midwest; NNG = new natural gas; NG = natural gas; NE = Nebraska; NGW = gas with wet distillers grains only.

Under a fully implemented cap-and-trade program, however, GHG prices are projected to be \$49 per Mg CO_2e (Kintisch 2007), which gives a total GHG trading value of \$2.7 billion per year. It is noteworthy that current prices under the European Union's Emissions Trading Scheme are €23 per Mg (www.pointcarbon.com, Oct. 9, 2008), which is equivalent to US\$31 at current exchange rates.

As more costly petroleum reserves (e.g., tar sands) are developed, the emissions intensity of conventional gasoline will increase substantially compared to current petroleum. Coal-to-liquids and oil shale are estimated to have nearly twice the GHG intensity as petroleum obtained from near-surface land and coastal oil fields (Bordetsky et al. 2007). Therefore, the magnitude of GHG mitigation potential of biofuel systems has the potential to increase over time.

Conclusions

Recent improvements in crop production, biorefinery operation, and coproduct utilization in U.S. corn-ethanol systems result in greater GHG emissions reduction, energy efficiency, and ethanol-to-petroleum output/input ratios compared to previous studies. Direct-effect GHG emissions reductions were found to be 48% to 59% compared to gasoline, which is two to three times greater than estimated in previous reports (Farrell et al. 2006). The NER has improved from 1.2 in previous studies to 1.5 to 1.8 on the basis of updated data. Ethanol-to-petroleum ratios were 10:1 to 13:1 for today's typical corn-ethanol systems but could increase to 19:1 with progressive crop management that increases both yield and input use efficiency. A closed-loop biorefinery with an AD system reduces GHG emission by 67% and increases the net energy ratio to 2.2. Such improved performance moves corn-ethanol much closer to the hypothetical estimates for cellulosic biofuels.

Acknowledgements

We appreciate support from the Western Governor's Association, U.S. Department of Energy, Nebraska Energy Office, USDA-CSREES NC506 Regional Research, Environmental Defense, and the Agricultural Research Division and Nebraska Center for Energy Sciences Research at the University of Nebraska. Survey statistics were provided by the Renewable Fuels Association (thanks to Kristy Moore), Nebraska Department of Environmental Quality, Iowa Department of Natural Resources, and Christianson & Associates (Willmar, MN). We thank Daniel Kenney and Patrick Tracy, Prime Biosolutions (Omaha, NE), for help analyzing the closed-loop system; Maribeth Milner, Agronomy and Horticulture, UNL, for GIS support; and Rick Koelsch, Biological Systems Engineering, UNL, for assistance with emission factors from anaerobic digestion.

Note

1. Editor's Note: For further information on the industrial ecology of biofuels and other biobased products, see the special issue of the Journal of Industrial Ecology on Biobased Products (Volume 7, Number 3-4).
2. The 12 Midwest states are South Dakota, Minnesota, Iowa, Wisconsin, North Dakota, Illinois, Indiana, Michigan, Nebraska, Ohio, Kansas, and Missouri.

References

Adviento-Borbe, M. A. A., M. L. Haddix, D. L. Binder, D. T. Walters, and A. Dobermann. 2007. Soil greenhouse gas fluxes and global warming potential in four high-yielding maize systems. *Global Change Biology* 13(9): 1972–1988.

Arons, S. M., A. R. Brandt, M. A. Delucchi, A. Eggert, A. E. Farrell, B. K. Haya, J. Hughes, B. M. Jenkins, A. D. Jones, D. M. Kammen, S. R. Kaffka, C. R. Knittel, et al. 2007. *A low-carbon fuel standard for California, Part 1: Technical analysis*. Berkeley: University of California, Berkeley.

Baker, J. M., T. E. Ochsner, R. T. Venterea, and T. J. Griffis. 2007. Tillage and soil carbon sequestration—What do we really know? *Agriculture, Ecosystems, and Environment* 118(1–4): 1–5.

Blanco-Canqui, H. and R. Lal. 2008. No-tillage and soil-profile carbon sequestration: An on-farm assessment. *Soil Science Society of America Journal* 72(3): 693–701.

Bordetsky, A., S. Casey-Lefkowitz, D. Lovaas, E. Martin-Perera, M. Nakagawa, B. Randall, and D. Woynillowicz. 2007. *Driving it home: Choosing the right path for fueling North America's transportation future*. Drayton Valley, Alberta, Canada: Natural Resources Defense Council, Western Resources Advocates, Pembina Institute.

Cassman, K. G. and A. J. Liska. 2007. Food and fuel for all: Realistic or foolish? *Biofuels, Bioproducts, and Biorefining* 1(1): 18–23.

Cassman, K. G., A. D. Dobermann, and D. T. Walters. 2002. Agroecosystems, N-use efficiency, and N management. *AMBIO* 31(2): 132–140.

CTIC (Conservation Technology Information Center). 2004. *Crop residue management survey*. West Lafayette, IN: CTIC.

Duvick, D. N. and K. G. Cassman. 1999. Post-green-revolution trends in yield potential of temperate maize in the north-central United States. *Crop Science* 39(6): 1622–1630.

Ellerman, A. D. and B. K. Buchner. 2007. The European Union Emissions Trading Scheme: Origins, allocation, and early results. *Review of Environmental Economics and Policy* 1(1): 66–87.

EPA-EEA (U.S. Environmental Protection Agency, Energy and Environmental Analysis, Inc.) 2006. *Baseline energy consumption estimates for natural gas and coal-based ethanol plants—the potential impact of combined heat and power (CHP)*. Washington, DC: Combined Heat and Power Partnership of the EPA.

Farrell, A. E., R. J. Plevin, B. T. Turner, A. D. Jones, M. O'Hare, and D. M. Kammen. 2006. Ethanol can contribute to energy and environmental goals. *Science* 311(5760): 506–508.

IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. *Prepared by the National Greenhouse Gas Inventories Programme*, Eggleston, H. S., Buendia, L. Miwa, K., Ngara, T. and Tanabe, K. Hayama, Japan: IGES.

Kintisch, E. 2007. Senate bill would provide billions for deploying cleaner technologies. *Science* 318(5857): 1708–1709.

Klopfenstein, T. J., G. E. Erickson, and V. R. Bremer. 2008. Board-invited review: Use of distillers byproducts in the beef cattle feeding industry. *Journal of Animal Science* 86(5): 1223–1231.

Lewandowski, I. and A. P. C. Faaij. 2006. Steps towards the development of a certification system for sustainable bio-energy trade. *Biomass and Bioenergy* 30(2): 83–104.

Liska, A. J. and K. G. Cassman. 2008. Towards standardization of life-cycle metrics for biofuels: Greenhouse gas emissions mitigation and net energy yield. *Journal of Biobased Materials and Bioenergy* 2(3): 187–203.

McBride, W. 2007. Personal communication with William McBride, Agricultural Economist, U.S. Department of Agriculture, Economic Research Service, Washington D.C., 16 November.

McElroy, A. K. 2007. Capturing carbon opportunities. *Ethanol Producer Magazine* 13(July): 142.

Naylor, R. L., A. J. Liska, M. B. Burke, W. P. Falcon, J. Gaskell, S. D. Rozelle, and K. G. Cassman. 2007. The ripple effect: Biofuels, food security, and the environment. *Environment* 49(9): 30–43.

RFA (Renewable Fuels Association). 2008. *Changing the climate: Ethanol industry outlook 2008*. Washington, DC: RFA.

Searchinger, T., R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.-H. Yu. 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319(5867): 1238–1240.

US Congress. 2007. *Energy Independence and Security Act of 2007*.

USDA-ERS (U.S. Department of Agriculture, Economic Research Service). 2001. *Energy use on major field crops in surveyed states*. Washington, DC: USDA-ERS.

USDA-ERS. 2005. *Agricultural resource management survey*. Washington, DC: USDA-ERS.

US EPA (U.S. Environmental Protection Agency). 2007. *Inventory of U.S. Greenhouse Gas Emissions and Sinks*: 1990–2005. Washington, D.C.: US EPA.

Verma, S. B., A. Dobermann, K. G. Cassman, D. T. Walters, J. M. Knops, T. J. Arkebauer, A. E. Suyker, G. G. Burba, B. Amos, H. S. Yang, D. Ginting, K. G. Hubbard, et al. 2005. Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems. *Agricultural and Forestry Meteorology* 131(1–2): 77–96.

Wang, M., M. Wu, and H. Huo. 2007. Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types. *Environmental Research Letters* 2(2): 024001.

About the Authors

Adam Liska is a postdoctoral research associate, **Haishun Yang** is a research assistant professor, and **Daniel Walters** is a professor in the Department of Agronomy and Horticulture at the University of Nebraska—Lincoln in Lincoln, Nebraska. **Virgil Bremer** is coordinator of ethanol projects, **Terry Klopfenstein** is a professor, and **Galen Erickson** is an associate professor in the Department of Animal Science at the University of Nebraska—Lincoln**. Kenneth Cassman** is the director of the Nebraska Center for Energy Science Research and a professor in the Department of Agronomy and Horticulture, also at the University of Nebraska—Lincoln.

Supplementary Material

The following supplementary material is available for this article:

Appendix: Life-Cycle Energy & Emissions Analysis Model for Corn-Ethanol Biofuel Production Systems.

Please note: Blackwell Publishing is not responsible for the content or functionality of any supplementary materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.