

Illinois
Department of
Commerce and
Community
Affairs

Norm Sims,
Director

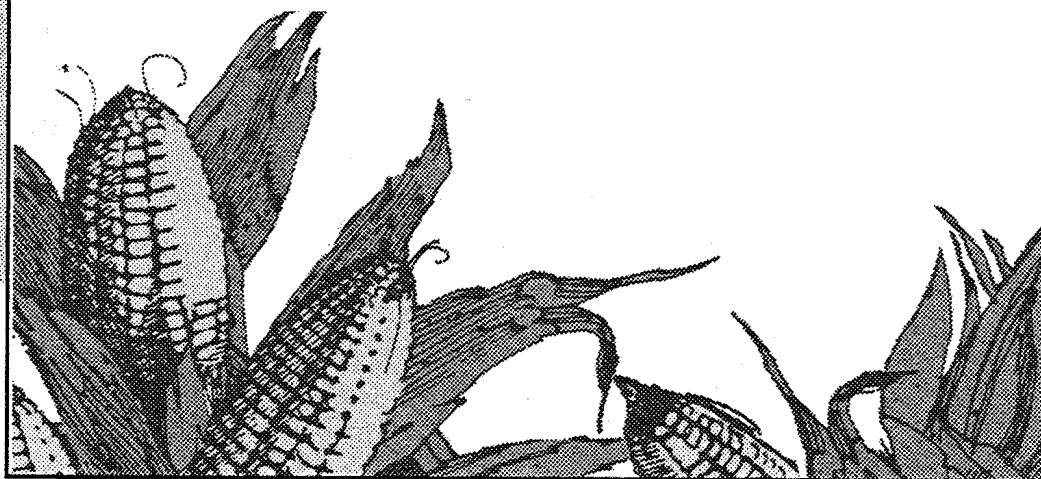


Bureau of
Energy and
Recycling

DCCA

Fuel-Cycle Fossil Energy Use and Greenhouse Gas Emissions of Fuel Ethanol Produced from U.S. Midwest Corn

CENTER FOR TRANSPORTATION RESEARCH
ARGONNE NATIONAL LABORATORY



**Fuel-Cycle Fossil Energy Use and Greenhouse Gas Emissions of Fuel Ethanol
Produced from U.S. Midwest Corn**

Michael Wang

Christopher Saricks

May Wu

Center for Transportation Research

Argonne National Laboratory

Prepared for Illinois Department of Commerce and Community Affairs

Project Manager: David Loos

December 19, 1997



STATE OF ILLINOIS
OFFICE OF THE GOVERNOR
SPRINGFIELD 62706

JIM EDGAR
GOVERNOR

December, 1997

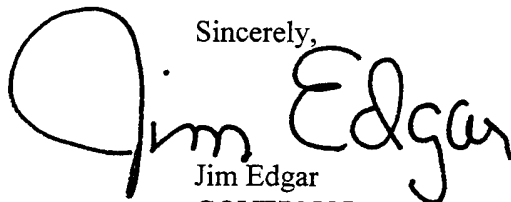
Illinois is very pleased to have sponsored and published the results of this research study on ethanol. The results clearly identify that ethanol outperformed conventional and reformulated gasoline with respect to energy use and reducing greenhouse gas emissions.

The institution responsible for this study, Argonne National Laboratory, is the recognized leader in modeling fuel cycle fossil energy use and greenhouse gas emissions related to the transportation sector. The scientists at Argonne concluded from this analysis that use of corn-based ethanol achieves net energy savings and greenhouse gas emissions reductions. Ethanol produced from corn accounts for 99% of the fuel ethanol in the marketplace.

Using updated data representing more current farming practices and new efficiencies in the ethanol industry, the study survived a rigorous review process. It is my hope that this will start to put to rest any doubts that corn-to-ethanol blends will reduce greenhouse gas emissions compared to both present and future gasolines.

What this means for the agriculture community, ethanol producers, environmentalists, and policy makers is that ethanol fuel deserves a major role in any global climate change strategy to reduce greenhouse gas emissions in the transportation sector. Ethanol can improve our nation's trade balance through reducing our petroleum imports and increasing our exports of ethanol co-products. Ethanol as an oxygenate reduces carbon monoxide emissions and low level ozone. Ethanol provides a huge economic boost (\$4.5 billion) to the agricultural sector in the Midwest. Now ethanol should be considered one of the primary weapons in reducing greenhouse gas emissions in the transportation sector.

As Governor of the State of Illinois, I am proud to promote this record of achievement.

Sincerely,

Jim Edgar
GOVERNOR

EXECUTIVE SUMMARY

This study has been undertaken at the request of the Illinois Department of Commerce and Community Affairs (DCCA) on the twin premises that (1) data and information essential to an informed choice about the corn-to-ethanol cycle are in need of updating, thanks to scientific and technological advances in both corn farming and ethanol production; and (2) generalized national estimates of energy intensities and greenhouse gas (GHG) production are of less relevance than estimates based specifically on activities and practices in the principal domestic corn production and milling region -- the upper Midwest.

Argonne National Laboratory (ANL) contracted with DCCA to apply the ANL Greenhouse gas, Regulated Emissions and Energy in Transportation (GREET) full-fuel-cycle analysis model with updated information appropriate to corn operations in America's heartland in an effort to examine the role of corn-feedstock ethanol with respect to GHG emissions given present and near future production technology and practice. Information about these technologies and practices has been obtained from a panel of outside experts consisting of representatives of the U.S. Department of Agriculture, midwestern universities with expertise in corn production and soil emissions, and acknowledged authorities in the field of ethanol plant engineering, design, and operations. A draft version of this report was peer reviewed by these contributors and their comments have been incorporated. Among key findings is that, for all cases examined on a mass emission per travel mile basis, the corn-to-ethanol fuel cycle for Midwest-produced ethanol utilized as *both* E85 and E10 outperforms that of conventional (current) and of reformulated (future) gasoline with respect to energy use and greenhouse gas production. In many cases, the superiority of the energy and GHG result is quite pronounced (i.e., well outside the range of model "noise").

An important facet of this work has been the conduct of sensitivity analyses using GREET, which could enable development of a ranking of the factors in the corn-to-ethanol cycle that are most important with respect to GHG generation. This could assure that efforts to reduce that generation are more effectively targeted.

The intent and scope of this study was limited to revision and upgrading of the GREET model to address corn farming and ethanol production in four Midwest states (Illinois, Iowa, Nebraska, and Minnesota) that collectively account for (1) about half of the total domestic corn harvest in a given year, (2) about 90 percent of the U.S. total 1.58 billion gallon ethanol annual production capacity, and (3) about 95% of total domestic ethanol production. That is, while the model still covers all alternative fuels and five criteria pollutants, no efforts have been made in this project to update input data on other fuels and the criteria pollutants.

A weighted energy intensity for corn farming of less than 20,000 Btu/bushel was calculated for the four-state analysis, a value that should be considered conservative. The study also estimated (or re-estimated) energy requirements for fertilizer and pesticide manufacture, transportation to farms, and field application; transportation of harvested corn to ethanol plants; nitrous oxide emissions from cultivated cornfields; energy use and greenhouse gas (GHG) emissions of ethanol production in current average and future technology wet and dry mills; and end use fuel efficiency and GHG emissions from ethanol-fueled vehicles. Because cogeneration

is present in virtually all wet mills, recently built wet milling plants have total process energy requirements comparable to those for dry mills (i.e., slightly over 40,000 Btu/gallon). Ongoing and future efficiency improvements from retrofits and advanced new plant designs should bring average process energy requirements well under 35,000 Btu/gallon for all mills.

Our base case analysis estimates energy use and emissions for a present situation that includes technologies already in place and for a future situation in which technologies, especially ethanol production technologies, are expected to improve. The future case is to be applied for year 2005. Under the base cases, energy use and emissions are calculated for cars and light-duty trucks using E85 (85% ethanol and 15% gasoline by volume) and E10 (10% ethanol and 90% gasoline by volume). Baseline gasoline vehicles are fueled with conventional gasoline under the current base case, and with reformulated gasoline under the future base case. We also designed various sensitivity analysis cases to test the importance of key parameters in determining fuel-cycle energy use and GHG emissions. These were conducted for passenger cars for both current and future cases, but not for light-duty trucks as the relative changes in energy use and emissions between passenger cars and light-duty trucks are similar.

Co-product energy use attribution remains the single key factor in estimating ethanol's relative benefits because this value can range from 0 to 50 percent depending on the attribution method chosen. In general, wet mills produce a broader slate of high value end products which would be economically justifiable even if ethanol were not being produced, but the same cannot be said of dry mills, whose only other product for which an established market exists is distillers dried grain solids. If dry mills are not economically sustainable absent ethanol production, it could be argued that no co-product energy use attribution is warranted for them.

GHG reductions (but not energy use) appear surprisingly sensitive to the value chosen for combined soil and leached N-fertilizer conversion to nitrous oxide, which falls in the range 0-2 percent. This narrow range of nitrous oxide emissions produces a range of near 20% in projected GHG savings for both present and future gasoline comparisons, the highest sensitivity ratio (approx. 1:4) within the value range for any variable explored. Meanwhile, the fuel cycle GHG production for use of E10 blend is 2% to 3% less than that of the corresponding gasoline. Fuel cycle energy and GHG savings profiles for present and future light duty trucks operating on E85 and E10 match those for automobiles.

Although it is important to remember that our analysis has relied on the judgment of our panel of outside experts that near-term increases in corn-based ethanol demand can easily be accommodated by planting on land that has historically been devoted to growing corn and soybeans, we have concluded that, at least for the four states that we examined, use of corn-based ethanol achieves net energy savings and greenhouse gas emissions reductions in all blended fuel forms.

I. INTRODUCTION

Concern about global “greenhouse” warming and its short- and long-term effects on world economies and human habitat has led to recognition that a reduction in the rate of atmospheric carbon loading due to combustion activities may help slow the progress of such warming. This, in turn, has kindled an interest in transportation fuels that contain lower carbon per unit of energy delivered and/or that are produced from renewable sources so that less or no net carbon is added to the atmosphere from fuel combustion. One such fuel is ethanol (C_2H_5OH), an alcohol currently produced in the United States by fermentation and distillation associated with wet- and dry-mill processing of feed grain (primarily corn). While a crop-based fuel such as ethanol has the implicit advantage over petroleum that it is both (1) renewable and (2) characterized by zero net carbon emissions of fuel combustion (combustion-source carbon dioxide is absorbed from the atmosphere by feedstock plants during photosynthesis), the activities involved in its feedstock cultivation and milling themselves consume energy, which is now provided chiefly by fossil fuels. The study documented in this report nevertheless reached the conclusion that, for all cases examined on a mass emission per travel mile basis, the corn-to-ethanol fuel cycle for Midwest-produced ethanol utilized as *both* E85 and E10 outperforms that of conventional (current) and of reformulated (future) gasoline with respect to energy use and greenhouse gas production..

Corn production is vital to the economies of many states, especially in the upper Midwest. The market for corn and corn products could be significantly enhanced in the near and medium term by a major upturn in the use of ethanol as a transportation fuel, at least until the emergence of commercially viable enzymatic processes yielding large quantities of cheaper ethanol from low-value cellulosic biomass. Thus, there is considerable interest in the potential for ethanol to achieve greenhouse gas reductions by substituting for gasoline, especially in light of the recent Kyoto Conference, at which United States negotiators renewed a commitment to controlling indigenous greenhouse gas emissions by 2012 to a level below that of 1990. Will the *current* and *near future* ethanol pathway prove compatible with to efforts to check the growth of and eventually reduce those emissions?

Analysts are not agreed on the absolute magnitudes of difference between petroleum and ethanol fuel for each phase of the production and use cycle. Different assumptions have been applied about the energy intensiveness and fuel inputs of virtually every process, giving rise to a wide range of energy use and GHG emission estimates for each link in the chain of extraction (for petroleum, the wellhead; for ethanol, the cornfield), production (refining of petroleum and milling of ethanol), distribution (to point of dispensing into vehicle), and end use. Example results from previous full-cycle analyses are summarized in Table I - 1. Our present study utilized updated information appropriate to corn operations in America’s heartland in an effort to examine the role of corn-feedstock ethanol with respect to GHG emissions under present and near future production technology and practice. Information about these technologies and practices has been obtained from a panel of outside experts consisting of representatives of the U.S. Department of Agriculture, midwestern universities with expertise in corn production and soil emissions, and acknowledged authorities in the field of ethanol plant engineering, design,

and operations. A draft version of this report was peer reviewed by these contributors and their comments have been incorporated.

Table I-1 Summary of Major Corn-Ethanol Studies

Author	Fuel	Range of GHG changes^a	Remarks
U.S. EPA, 1989	E100	-22% to -21%	CO ₂ only; co-product credits are based on displaced products
	E85	-6% to -5%	
Ho et al. 1990	E100	15% to 36%	The range reflects assumptions about ethanol production technologies
Marland et al., 1991	E100	-40% to -20%	Co-product credits are based on both market values and displaced products
Delucchi, 1991	E100	+25% (-65% to + 80%) -20% (-70% to 0%)	Coal as the process fuel in ethanol plants Natural gas as the process fuel in ethanol plants
Ahmed et al., 1994	Ethanol as the oxygenate in RFG	-35% to 0%	Coal as the process fuel in ethanol plants
		-40% to -10%	Natural gas as the process fuel in ethanol plants
		-60% to -40%	Corn stover (waste) as the process fuel in ethanol plants
Delucchi, 1996	E95	+20.6%	Result cited here is for full fuel cycle only
Wang, 1996	E100	-31.7%	Co-product credits are based on energy content
	E85	-25.4%	Coal as the process fuel in ethanol plants; co-product credits are based on <i>energy content</i>
Wang, 1997	E85	-18.2%	Coal as the process fuel in ethanol plants; co-product credits are based on <i>market values</i>
	E85	-30.5%	Natural gas as the process fuel in ethanol plants; co-product credits are based on <i>market values</i>

^a A negative number means a reduction and a positive number means an increase.

As Table I-1 shows, previous studies have estimated GHG emissions of corn-based ethanol to vary from a decrease of 70% to an increase of 80% relative to the gasoline fuel cycle.

The uncertainties in corn ethanol GHG emissions are caused by differences in key assumptions regarding energy intensity of corn farming, corn yield, nitrous oxide (N₂O) emissions from nitrogen fertilizer, energy intensity of ethanol plants, type of process fuel used in ethanol plants, and the way in which emissions and energy use are allocated between ethanol and co-products. Some of these assumptions remain valid, others require updating, and some may be accurate for ethanol fuel cycle effects on a national scale but less so on a regional scale. These issues will be addressed in this report.

This study has been undertaken at the request of the Illinois Department of Commerce and Community Affairs (DCCA) on the twin premises that (1) data and information essential to an informed choice about the corn-to-ethanol cycle are in need of updating, thanks to scientific and technological advances in both corn farming and ethanol production; and (2) generalized national estimates of energy intensities and greenhouse gas (GHG) production are of less relevance than estimates based specifically on activities and practices in the principal domestic corn production and milling region--the upper Midwest. Argonne National Laboratory (ANL) contracted with DCCA to apply the ANL Greenhouse gas, Regulated Emissions and Energy in Transportation (GREET) full-fuel-cycle analysis model with updated information appropriate to corn operations in America's heartland in an effort either to uphold or to refute the conjecture that ethanol is a net inhibitor of GHG emissions given present and near future production technology and practice. Moreover, the conduct of sensitivity analyses using GREET enables development of a ranking of the factors in the ethanol cycle that are most important with respect to GHG generation. This could assure that efforts to reduce that generation are more effectively targeted.

II. THE GREET MODEL AND STUDY FRAMEWORK

For a given transportation fuel, a fuel cycle includes the following chain of processes: primary energy recovery; primary energy transportation and storage; fuel production; fuel transportation, storage, and distribution; and vehicular fuel combustion. Usually, fuel-cycle activities before vehicular fuel combustion are referred to as upstream activities. The full fuel-cycle analysis for corn to ethanol includes corn farming, ethanol production, ethanol transportation and distribution, and ethanol combustion in motor vehicles. For corn farming, this study includes production of farming inputs (i.e., fertilizers, herbicide, pesticide, and fuels) and farming operations. Figure 1 presents the corn-to-ethanol fuel cycle.

Energy is consumed and emissions are generated during upstream fuel-cycle activities, as well as during vehicular activities. In each upstream activity, fossil energy is burned and emissions are generated. Also, fuel leakage and evaporation that ultimately generate emissions are associated with upstream activities. GREET takes into consideration all emissions and energy consuming sources and includes various fuel-cycle paths including the corn-to-ethanol path (Wang 1996). GREET calculates fuel-cycle grams-per-mile (g/mi) emissions and Btu-per-mile (Btu/mi) energy use for each fuel cycle. It includes emissions of five criteria pollutants (volatile organic compounds [VOC], carbon monoxide [CO], nitrogen oxide [NO_x], particulate matter with size smaller than 10 microns [PM₁₀], and sulfur oxides [SO_x]) and three GHGs

(methane [CH₄], nitrous oxide [N₂O], and carbon dioxide [CO₂]). The three GHGs are further combined together with their global warming potentials as CO₂-equivalent GHG emissions. GREET calculates energy consumption for three types of energy: total energy (all energy sources), fossil energy (petroleum, natural gas, and coal), and petroleum only. For a given fuel-cycle stage, energy use (in Btu per million Btu of energy throughput) is calculated. The calculated total energy use for the particular stage is allocated into different process fuels (e.g., natural gas, residual oil, diesel, coal, and electricity). Fuel-specific energy use, together with

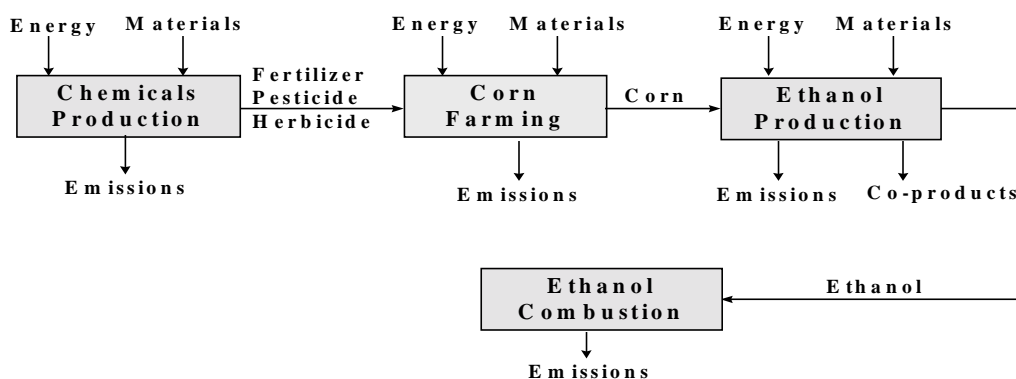


Figure 1 Flow Chart of the Corn-to-Ethanol Fuel Cycle

emission factors of the combustion technology for a specific fuel, is then used to calculate combustion emissions for the stage. GREET has an archive of combustion emission factors for various combustion technologies fueled with different fuels and equipped with different emission control technologies. Emission factors for VOC, CO, NO_x, PM₁₀, CH₄, and N₂O for combustion technologies are derived primarily from U.S. Environmental Protection Agency's (EPA's) AP-42 document. SO_x emission factors for most fuels are calculated on the assumption that all sulfur contained in process fuels is converted into sulfur dioxide (SO₂). CO₂ emissions are calculated with a carbon balance approach; that is, the carbon contained in the fuel burned, minus the carbon contained in combustion emissions of VOC, CO, and CH₄, is converted to CO₂. GHG emissions from vehicular fuel combustion are calculated in a similar way. Revision and upgrading of the GREET model to address corn farming and ethanol production in four Midwest states (Illinois, Iowa, Nebraska, and Minnesota) reflects the intent and scope of this study only. That is, while the model still covers all alternative fuels and five criteria pollutants, no efforts have been made in this project to update input data on other fuels and the five criteria pollutants. The revised model delivered with this report is appropriate for estimating GHG emissions and energy use of corn ethanol with data collected for this project, but ANL/CTR does not recommend using this version to estimate emissions of criteria pollutants and energy use

attributable to the full fuel cycle for other alternative fuels.

Energy use can be estimated for (1) all energy sources, (2) fossil energy (oil, natural gas, and coal), and (3) oil only. Results of (2) can show whether use of ethanol leads to a net energy savings, while those of (3) can show petroleum displacement potential by ethanol. We present results of fossil energy use in this report. The three GHGs are combined with their global warming potentials, which are 1, 21, and 310 for CO₂, CH₄, and N₂O, respectively.

This study assumes that both passenger cars and light trucks use ethanol, which is available in the form of either E85 (85% ethanol and 15% gasoline by volume) or E10 (10% ethanol and 90% gasoline by volume—an oxygenated fuel having about 3.5% oxygen by weight). E85 is used in flexible-fueled vehicles (FFVs) and E10 is used in any light-duty gasoline vehicle. However, we also consider cases in which the ethanol share of fuel in a “high-oxygen” gasoline or FFV scenario could be 17% (E17), 50% (E50) or 100% (E100) by volume.

Section III below presents and describes the specific modifications at each stage of the corn-to-ethanol fuel cycle and the justifications for them, citing all data sources giving rise to these changes. Section IV tabulates and discusses the results of the GHG comparison, employing the fuel cycles for conventional (for current year, 1997) and reformulated gasoline (for future year, 2005) as the baseline. Cars and light trucks are separately evaluated, and tabular results of sensitivity runs of the model that yield a ranking of the key parameters are presented and discussed. A final section offers conclusions from this analysis.

III. DATA COLLECTION EFFORTS AND KEY ASSUMPTIONS

III. 1 The Study Area

The four largest corn-producing states--Illinois, Iowa, Minnesota, and Nebraska--have been selected for inclusion in this analysis. Collectively they account for about half of the total domestic corn harvest in a given year, about 90 percent of the U.S. total 1.58 billion gallon ethanol production capacity, and (in most years) about 95% of total domestic ethanol production. Table III-1 reports representative total field corn harvested, acres planted, yield per planted acre, and (approximate) bushels of corn directed to ethanol at production sites within each state (NOTE: not all corn used in a state's ethanol production may originate in that state). It is worth noting that the vast majority of ethanol produced in Illinois and Iowa and about half of that produced in Nebraska and Minnesota is distilled from wet milling processes that generate multiple co-products optimally utilizing the protein and sugar components of the corn kernel (ethanol is derived from the starch), while remaining production capacity in these states employs the dry milling process from which there is but one principal co-product, distillers' dried grains.

III. 2 Energy and Chemicals Requirements of Corn Farming

Virtually all corn harvested in Illinois and Iowa is grown on land requiring no irrigation. There is a small amount of irrigated cropland in Minnesota, while in Nebraska, at least half of the cornfields are irrigated. Thus, while the energy use profiles of corn farming in the former three

states are very similar, Nebraska corn farming is somewhat more energy intensive, with the net result that the weighted mean crop production energy requirement in Btu/bushel is higher than if the computation were performed for Illinois and Iowa alone.

Table III-1 Corn Production and Ethanol Conversion Statistics for Study States

STATE	IL	IA	MN	NE	4 States
Typical recent harvest (billion Bu)	1.45	1.7	0.85	1.2	5.2
Million acres planted (1996)	11	12.7	7.5	8.5	39.7
Yield/planted acre (Bu)	132	134	113	141	131
Representative annual corn conversion to ethanol at in-state mills (million bushels)	210	155	35	125	525

Source: United States Department of Agriculture, National Agricultural Statistics Service, 1997, supplemented by statistical data from pages of each state's government agency Internet sites.

Table III-2 shows the individual and weighted energy requirements of corn farming in the four states (exclusive of fertilizer and pesticide production, which are handled separately, as discussed in Sections III.3 and III.5). The weighting factor is based on 1994-96 share of corn production from the February, 1997 edition of *Crop Values* (USDA/NASS/ERS, 1997). Values for each state are derived from Tables 2 and 3 of USDA ERS Report no. 721 (Shapouri et al., 1995), using lower heating values of 128,500 Btu/gal, 115,500 Btu/gal, 84,000 Btu/gal, and 928 Btu/scf for diesel, conventional gasoline, LPG, and NG, respectively. Based on extrapolation of recent trends from NASS (Fig. III.2 - 1), four-state annual average corn yield per acre is conservatively estimated for the current case (1997) at 130 bushels. The values shown for diesel equipment utilization for the easternmost three states may underestimate the actual current share of diesel-powered farm equipment in use, but no more recent comparable data have been found. Gasoline use includes powering for farm trucks used in fields, some tractors, and some spreading equipment. As the population of spark ignition implements continues to decline, the shift to diesel will result in modest overall efficiency improvement for equipment use and further reduce the total energy input requirement for corn farming. Thus, a weighted energy intensity for corn farming of *19,176 Btu/bushel* has been adopted for the four-state analysis. For reasons cited above, this value should be considered conservative.

Field corn cultivation generally requires application of nitrogen, phosphate, and potash fertilizers (and sometimes a lime application to more acidic soils) at the beginning of and/or (sometimes twice) during the growing season. Amounts applied per acre vary by state, generally as a function of soil mineral content and crop rotation practice (i.e., alternating corn with soybeans or other nitrogen-fixing crops every other year tends to help soil retain more nitrogen, reducing nitrogen fertilizer requirement during field corn years). NASS' "Agricultural Chemical Usage 1996 Field Crops Summary" (USDA/NASS/ERS, 9/3/97) was used together with state shares weighted according to planted acreage to yield a four-state average for fertilizer

application, by type, in grams per bushel corn yield. These results are shown in Table III-3.

Table III-2 Corn Farming Input Energy Requirements (Btu/bushel)

ITEM	IL	IA	MN	NE	TOTAL
Weighting Factor (based on bushels harvested, 1996)	0.280	0.330	0.165	0.225	1.0
Seed corn—diesel fuel	159	132	138	253	168
Diesel equipment	3,954	3,954	4,942	17,792	7,231
Gasoline equipment	3,554	2,665	2,665	3,554	3,114
LPG equipment	1,292	3,230	2,585	2,585	2,436
Electricity	97	40	226	783	254
Natural gas	437	0	0	11,716	2,759
Custom work—diesel	1,297	1,129	992	969	1,118
Drying--natural gas	821	1,332	1,202	1,049	1,104
Input hauling--same base distance to farm	992	992	992	992	992
TOTAL	12,603	13,474	13,742	39,693	19,176

Table III-3 Field Fertilizer Requirements in Corn Growing Years (grams/bushel)

ITEM	IL	IA	MN	NE	TOTAL
Weighting Factor (based on planted acreage)	0.277	0.320	0.189	0.214	1.0
Nitrogen (granular, N)	578	448	365	482	476
Phosphate (P ₂ O ₅)	234	172	175	93	173
Potash (K ₂ O)	335	216	196	31	206

III.3 Energy Intensity of Fertilizer Manufacture

The most recent documented analysis of energy use and intensity at nitrogen, phosphate, and potash production plants was conducted in 1992 by the Fertilizer Institute and incorporated in USDA ERS Report no. 721. It indicates that there has been a substantial improvement in plant

efficiencies since the early 1980s, with net energy intensity being reduced by up to 40 percent on average. Again, using lower heating values for energy inputs, and adding 2.5 Btu/gm for packaging and handling of raw material and product (transportation and application are already accounted for, see Sec. III.6 and III.2) the following average energy intensities (Btu/gm of active ingredient, weighted according to share of process fuel used in the production of each) have been transcribed into GREET1.3: **46.5** for N, **10.8** for P₂O₅, and **5.0** for K₂O.

III.4 N₂O Emissions from N-Fertilizers Applied in Corn Fields

The nitrogen fertilizer (N-fertilizer) applied to corn fields is extracted by corn plants as a plant nutrient, absorbed (chemically bound) into soil organic materials, entrapped in soil aggregates (chemically unbound), then (1) transformed to and emitted as N₂O through microbial nitrification and denitrification, (2) volatilized as NH₃, and (3) leached as nitrate from soil to streams and groundwater via surface runoff and the subsurface drainage system. The majority of N-fertilizer left in soil stabilizes in non-mobile organic form (Stevens et al., 1997). Some of the nitrogen in leached nitrate (nitrate-N) eventually re-bonds as N₂O and migrates to the atmosphere. For purposes of our estimate, we include both direct N₂O emissions from soil and those from leached nitrate-N. The N₂O emission rate, expressed as the percentage of nitrogen in fertilizer (fertilizer-N) that becomes the nitrogen in N₂O (N₂O-N), is determined by factors that include soil type (especially sand content), soil water content, soil pH, soil temperature, soil organic carbon, soil ammonium or nitrate content, N-fertilizer type, fertilizer application form (e.g., liquid or powder), fertilizer application frequency, time of application, weather, crop type, vegetation, farming practice, and microbial organisms in the soil. In addition, the amount of N-fertilizer leached as nitrate is determined by such factors as soil type (especially sand content), hydrogeology, and depth of water table.

To estimate total N₂O emissions from an acre of fertilized corn, we reviewed numerous studies on fertilizer-induced N₂O emissions from cornfields. We have established an extensive database of results from about 30 studies conducted during the period 1978-97. For this study, our focus was on N₂O emissions from cornfields in the U.S. Midwest. The database includes N₂O emissions from both crop rotation systems (corn after soybeans) and continuous corn systems. The data sources and their estimation of N₂O emission rate are summarized in Appendix A. We have separated fertilizer-induced N₂O emissions from background emissions by subtracting emissions of control fields (where no N-fertilizer is applied) from the total emissions of cornfields where fertilizers were applied.

From the data presented in Appendix A, we estimate an average cornfield N₂O emission rate (expressed as percentage of fertilizer-N converted to N₂O-N) as **1.22%**, with all data falling in a range from 0% to 3.2% (and most data falling within 1.0% to 1.8%).

Microbial processes are responsible to N-fertilizer-derived N₂O emissions in farming. Under *aerobic* conditions, ammonium is oxidized to nitrate and N₂O by nitrifiers in the process of nitrification. *Anaerobically*, nitrate (NO₃⁻) is first converted to nitrite (NO₂⁻), then to N₂O which is finally reduced to N₂ through denitrification. The extent to which both processes operate depends on such factors as oxygen partial pressure, available organic carbon, and soil pH. Both nitrification and denitrification contribute to N₂O formation from N-fertilizer and emissions from

soil. N-fertilizer lost through leaching is in the form of NO_3^- -- the mobile form of nitrogen; this nitrate in water is converted to N_2O primarily through microbial denitrification, and up to 1% of initial nitrate nitrogen undergoes denitrification and emission as $\text{N}_2\text{O-N}$ (Qian et al.1997). Thus, to estimate $\text{N}_2\text{O-N}$ emissions from N-fertilizer-derived NO_3^- leached into the drainage system, runoff streams and groundwater, we have used 1% as the conversion factor for transformation of nitrate nitrogen to $\text{N}_2\text{O-N}$.

To estimate the amount of nitrate from N-fertilizer in surface runoff, the subsurface drainage system, and groundwater, we reviewed nine relevant studies (see Appendix A). From the available data for midwest cornfields, we have derived an average rate of 24% for total fertilizer-N converting to nitrate nitrogen (NO_3^- -N) through leaching. With our assumed conversion factor of 1% from nitrate to N_2O emissions, we estimate a rate of 0.24% of N_2O emissions due to leaching. Summing soil direct emissions and leaching thus produces a total N_2O emission rate of **1.5%**, the value we use in our study.

Our N_2O emissions estimates are uncertain for several reasons. First, some of the studies reviewed did not include control fields where background N_2O emissions could be measured. a Nitrogen deposition with precipitation is a known source of background N_2O emissions. Nitrogen deposited with precipitation was reported in the studies as ranging from 7 to 12 kgN/hectare (Baker and Johnson, 1981; Johnson and Baker, 1984), a range equal to 4-7% of nitrogen fertilizer applied at a rate of 170kgN/hectare. Second, none of the reviewed studies measured *both* direct soil N_2O emissions and nitrogen loss through leaching. There is a balance between leaching and soil denitrification. That is, with a fixed amount of fertilizer input, an increase in soil direct N_2O emissions may imply decreased nitrogen loss through leaching, and vice versa. Measurement of emissions from both sources in a single field would address the balance issue. Third, the rate of microbial denitrification activity in a river is much less intensive than in ground water. Nitrate concentration is diluted once the stream from runoff or the drainage system enters the river. Further, in natural environmental conditions occurring in ground water, conversion of nitrate is not likely to be complete, but, in the absence of actual data on this issue, we have assumed that the NO_3^- -N due to leaching is completely denitrified. Fourth, solubility of N_2O in water is very high, compared to that of other inorganic gases (Table A3, Appendix A). The solubility of N_2O is 56 and 27 times higher than that of N_2 and O_2 , respectively. At some reported concentrations, most N_2O in water is likely to remain in aqueous form, rather than converting to a gas for release to the atmosphere. Finally, differences in N_2O measurement methods among the studies may explain some of the variation in reported N_2O emissions (Christensen et al., 1996).

III.5 Pesticide Requirements and Energy Intensity of Pesticide Manufacture

Corn cultivation generally requires application of both herbicide and insecticide to planted acreage during and after sowing. Genetic modification and hybridization to produce hardier, insect-resistant strains of field corn have proven successful in recent years, such that the rate of insecticide application, with a few exceptions where rootworm remains a problem, appears to be headed consistently downward in the upper Midwest. Not so the case with herbicide: favorable growing conditions and nutrient-rich soils that help increase corn yields also favor volunteer vegetation, which often must be controlled by herbicide applications both at the

beginning of and during the growing season. Also, increasingly common non-tilling practices in modern farming tend to require additional herbicide applications.

In addition to fertilizer use, USDA through NASS and its ERS has tracked pesticide application trends in a number of publications, notably *Pesticide and Fertilizer Use and Trends in US Agriculture* (Lin et al, 1995) and, as with fertilizer, “Agricultural Chemical Usage: Field Crops Summary” (USDA/NASS/ERS, 9/3/97). These publications indicate stable popularity in the study states of the three herbicide agents most-commonly applied in corn cultivation--atrazine, metolachlor, and cyanazine--but, since the early 1990s, a supplanting of the fourth most popular agent, alachlor, by acetochlor. Active ingredient applied ranges from one to three pounds per planted acre, with cyanazine and metolachlor experiencing the higher rates of application in this range. Application rates during the 1960s and 1970s averaged one pound per acre in the study states, clearly showing that the quantity of active ingredient applied has increased in recent years.

Table III-4 shows the state-specific and mean weighted (over *all* types of agent applied) herbicide application rates, based on 1996 data, for the top four corn herbicides in the study states, together with the total energy requirement (Btu/gm) for manufacture and packaging of each. The 1996 harvest has been selected as the basis for computation because it was generally good but not spectacular across the Midwest--a reasonable midpoint in the range of yields of the past decade that is also indicative of the effect of recent developments in cultivation practices and technology applied to corn farming. The shaded cell shows the value for herbicide application rate selected for use in GREET, and indicates together with the other entries in the last column that the overall application rate for herbicides other than the principal four is higher than the four-agent average. Manufacturing energy intensity values are derived from results published in 1987 (Green, 1987). It is possible that the energy intensity of herbicide manufacturing has declined in the last ten years, but we were unable to obtain more recent data on this variable. Furthermore, information was not found for acetochlor, so values for alachlor (very similar to those for metolachlor) were substituted.

Table III-5 shows the state-specific and mean weighted (by summed quantity) insecticide application rates, again based on 1996 data, for the four study states, as well as mean energy intensity, again from Green (1987). With the exception of Nebraska, application rates for active ingredient are quite low, as is the weighted average, which is used in the GREET computation.

Table III-4 Application Rates (gm/Bu) by State, 4-State Averages for All Agents Applied, and Energy Intensity (Manufacturing Btu/gm of active agent applied) of Principal Corn Herbicides

Active Ingredient	Atrazine	Cyanazine	Metolachlor	Acetochlor	Overall
Share: 1) among top 4	.312	.171	.281	.236	1.00
2) of total	.249	.137	.225	.189	.800
Application rate:					
IL	4.1	10.4	7.3	6.8	10.9
IA	3.2	8.4	8.0	6.9	9.9
MN	2.1	5.7	8.9	6.2	8.3
NE	3.5	6.4	5.2	5.8	8.1
4-State Average	3.3	8.1	7.3	6.5	9.5
Energy use (Btu/gm)	180	191	262	264	225

Table III-5 Application Rates (1996 grams/Bu) and Energy Intensity (1987 Btu/gm of active agent applied) of Corn Insecticide

State	gms/bu
IL	0.68
IA	0.49
MN	0.29
NE	1.26
4-State Average	0.68
Energy use (Btu/gm)	230

III.6. Transportation from Farm Chemical Plants to Farms, and Corn from Farms to Ethanol Plants

III.6.1. Chemicals Transportation

Transportation of chemicals (fertilizers, herbicide, and pesticide) from manufacturing plants to farms occurs in three steps: from manufacturing plants to bulk distribution centers, from distribution centers to mixers, and from mixers to farms. Table III-6 presents our assumptions regarding travel distance, transportation mode, and transportation energy intensity for each step. In Steps Two and Three, empty backhaul (i.e., round trip distance) is included in the energy calculation, while for Step One, the backhaul is assumed to be an unrelated revenue movement.

High energy intensity for plants to bulk centers is attributable to long distance travel, while that for mixers to farms is caused by the relatively small payload for class 6 trucks.

Table III-6 Key Assumptions and Results of Chemical Transportation

	Step One: Plant to Center	Step Two: Center to Mixer	Step Three: Mixer to Farm
Travel distance (mi., one way)	1060/520	50	30
Transportation mode	barge/rail	Class 8b truck	Class 6 truck
Energy use (Btu/ton)	294,940	105,620	220,000

For transportation between manufacturing plants and bulk distribution centers, both barge and rail modes are used. Nominal travel distances for barge and railroad hauls, respectively, are presented in Table III-7.

Table III-7 Distance between Chemical Plants and Bulk Distribution Centers

	IL	IA	NE	MN	4-State
Share based on planted corn acreage	0.277	0.320	0.214	0.189	1.000
Mean barge and rail travel destination	St. Louis	Dubuque	Omaha	Minneapolis	
barge travel distance ^a	750	1050	1250	1320	1060 ^b
Rail travel distance ^c	500	600	500	450	520 ^b

^a Barge travel origin is assumed to be New Orleans, which represents high-volume primary farm chemical production locations in Texas, Louisiana, Oklahoma, and Florida, from which the chemicals are trucked to the Port of New Orleans for shipment up the Mississippi.

^b The 4-state average is calculated using planted acreage as the weighting factor.

^c Rail travel origin is assumed to be Oklahoma City for Illinois, Iowa, and Nebraska, and Manitoba, Canada for Minnesota; Oklahoma is a high-volume farm chemical source for rail shipments to the core Midwestern states, while Canadian production plants serve much of Minnesota.

Energy use by barge is estimated to be 374 Btu/ton-mile, which was the national average for 1995 (Davis et al., 1997, Table 6.4). Emission factors for barges fueled with residual oil or bunker fuel are 27, 100, 50, 280 lb. per 10³ gallon of fuel for SO_x, CO, HC, and NO_x, respectively (EPA, 1991, p. II-3-2). Energy use by rail is estimated to 372 Btu/ton-mile, which was again the national average in 1995 (Davis et al., 1997, Table 6.7). Assuming locomotives are diesel-fueled, emission factors are estimated as 25, 130, 94, 370 lb. per 10³ gallon of diesel for PM, CO, HC, and NO_x, respectively (EPA, 1991, p. II-2-1).

Assuming a 50/50 tonnage split between barge and rail hauls, average energy use per ton of chemicals transported between plants and bulk centers is estimated to be 294,940 Btu per ton $([1060*374+520*372])/2$). Emissions are calculated with the energy use rate and the emission factors in grams per mmBtu of fuel used.

Travel distances (Table III-6) are indexed to locations of distribution centers in Illinois. Because Iowa abuts Illinois along the Mississippi, travel distances for Iowa should be similar to those for Illinois. Barges travel north to Omaha on the Missouri River, and most corn acreage in Nebraska is in the eastern part of the state. Thus, while travel distances from bulk centers to mixers and then to farms are assumed the same for Nebraska as for Illinois and Iowa, the barge travel distance to Nebraska is greater. Barges follow the Mississippi to Minnesota: as with Nebraska, the mean distance from bulk centers to mixers and then to farms is the same as for Illinois and Iowa, but barge travel distance is greater.

Class 8b trucks (>33,000 lb. GVW) are assumed to provide the shipment transport from bulk distribution centers to mixers. A typical class 8b tractor/trailer combination with full payload has a gross vehicle weight of 80,000 lb. The tractor weighs 12,000 - 15,000 lb., and the trailer around 10,000 lb. Thus, the maximum payload is 55,000 - 58,000 lb., with typical payload of 40,000 - 50,000 lb. We assume a payload of 45,000 lb. Fuel economy and emissions of the truck are estimated with the GREET model. In calculating energy use and emissions per ton of chemicals transported, the round-way travel distance of 100 miles is used (see Table III-6). That is, no payload is assumed for the trip from mixers to bulk centers. At a fuel economy of 4.86 miles per gasoline-equivalent gallon (estimated with GREET), transportation energy intensity is estimated as 105,624 Btu/ton.

Class 6 trucks (19,500 - 26,000 lb. GVW) are assumed to provide chemical transport from mixers to farms. A typical class 6 truck has a truck (tare) weight of 8,500 - 10,000 lb. Thus, the maximum payload is 11,000 - 16,000 lb. We assume a payload of 10,000 lb. Per-ton energy use and emissions are calculated based on a round-trip distance of 60 miles (see Table III-6). That is, no payload is assumed for the trip from farms to mixers. At a fuel economy of 6 miles per gallon (gasoline equivalent), transportation energy intensity is estimated as 220,000 Btu/ton.

III.6.2. Transportation of Corn from Farms to Ethanol Plants

Corn moves to ethanol plants in a two-step process, first in class 6 trucks from farms to collection stacks (a 20-mile round trip, on average), then in class 8a trucks from stacks to the ethanol plants (an 80-mile round trip). A payload of 15,000 lb. is assumed for the class 6 haul and 30,000 lb. for the class 8a haul. No goods are assumed to be hauled back from ethanol plants to stacks, or from stacks to farms. We apply values of 6 mpg for class 6 truck and 5.1 mpg for class 8a truck gasoline equivalent (see above) to compute haul energy, and of 56 lb. per bushel of corn to compute payload volume. Under these assumptions, fully-allocated energy use per bushel of corn transported is estimated as 4,081 Btu.

III.7. Energy Use and GHG Emissions of Ethanol Production

Ethanol plants are the largest fossil energy consuming process for the entire corn-to-ethanol fuel cycle. Ethanol production R&D efforts in the last two decades have concentrated on increasing ethanol yield and reducing plant energy use for the purpose of reducing monetary expenditure on process fuels in ethanol plants (fuel cost is the second largest cost of ethanol plant operation, next to feedstock corn cost). Advanced ethanol plant designs employ energy conservation technologies such as molecular sieve dehydration and cogeneration of steam and electricity. As a result, newly built ethanol plants are generally more energy efficient than plant capacity which has been on the ground for many years. However, energy use in existing ethanol plants has been also reduced through process integration. As part of our study, we collected information regarding recent trends in ethanol plant energy use from ethanol plant designers and operators. Using the information collected, we estimated total energy use and the split of energy use between ethanol production and co-product production.

In our analysis we have included both dry and wet milling ethanol plants. We estimate fuel-cycle energy use and emissions for the two types separately. General production processes of dry and wet milling plants are presented in Figures B1 and B2 of Appendix B. In reality, there are variations in production processes among the individual plants, but we endeavor to specify a representative plant for which ethanol production is the main purpose.

In general, few plants employ yeast recycling or CO₂ collecting. The majority of wet milling plants produce starch, high fructose corn syrup, and/or glucose as co-products. We assume that all the starch derived from corn in wet milling plants is targeted for ethanol conversion. Production of high fructose corn syrup, a high-value end product derived from corn kernel sugars, takes place in a different process stream and is therefore not included as an ethanol co-product. Our research shows that most plants include molecular sieve dehydration and that about half of ethanol plants employ cogeneration systems.

Table III-8 presents a summary of total energy input and energy allocation between corn farming products and ethanol production and co-product production in wet and dry milling plants, respectively. The farming allocation is based on relative market value of ethanol and non-ethanol product, while the milling energy allocation is based on process energy share. The table shows that *total* energy use per gallon of ethanol, on a current capacity-weighted basis, is similar for dry and wet milling plants (i.e., the wet milling value incorporates the 34,000 Btu/gallon energy consumption value for state-of-the art wet milling plants, which represent 70% of total wet mill capacity in the four states). As for energy allocation, Table III-8 shows that 66% to 69% of the total energy use in ethanol plants is attributable to ethanol production, with the remainder assigned to co-product production. Energy use share for co-products in dry milling plants is about 3% more than in wet milling plants. This is because a large amount of energy is consumed by the co-product drying process in dry milling plants. Our estimate of energy use and splits shown in Table III-8 is based on documentation for the values in Tables III-9 through III-12.

Table III-8 Summary of Base Case Energy Use (Btu/gallon) in Ethanol Plants, and Energy Allocation between Ethanol and Co-Products by (1) Mill Product Market Value for Corn Farming and (2) Process Energy Demand for Milling

	Dry milling	Wet milling
Total energy use before allocation (Btu/gal):		
Current (1997)	41,400	40,300
Near future (2005)	36,900	34,000
Process fuel share: current		
Natural gas	47%	20%
Coal	47%	80%
Electricity	6%	0%
Process fuel share: near future		
Natural gas	50%	20%
Coal	50%	80%
Electricity	0%	0%
Energy use allocation: corn farming		
Ethanol market value	76%	70%
Co-product market value	24%	30%
Energy use allocation: ethanol production		
Fuel ethanol	67%	69%
Co-products	33%	31%

Table III-9 Energy Consumption in Corn Ethanol Processing Plant Estimated by Some Studies

Energy Use: Btu/gal.		Cogeneration	CO ₂ as co-product	Remarks	Sources
Dry Milling	Wet Milling				
46,879	48,862	Yes	No		Shapouri et al. 1996
46,380	46,380	No	Yes	30% dry and 70% wet milling	Morris and Ahmed, 1992
37,386	54,977	No	No	Natural gas as fuel	Stanley Consultants, 1996
—	51,000-53,000	Yes	Yes	CO ₂ sold to gas plants	Welch, 1997
39,415		No	Unknown	Continuous fermentation	Buckland, 1997
53,261	53,089	No	No	Continuous fermentation	Wood, 1993
—	45,000-50,000	Yes	No	Continuous fermentation	Wood, 1997
38,096	—	No	No	Molecular sieve not used, simulation results	McAloon, 1978
39,000	—	Unknown	Unknown		Minnesota Ethanol Commission, 1991
—	34,000	Yes	Unknown	An ADM plant with capacity of 280MM gal. a year	Minnesota Ethanol Commission, 1991; Reeder, 1997
36900	—	No	No	Azeotropic dehydration with improved design	Madson, 1991
—	40,000-50,000	Yes	No		Merediz, 1997
40,000 <	—	Yes	No		Shroff, 1997

As Table III-9 shows, estimates of total energy use per gallon of ethanol produced vary from 36,900 to 53,260 Btu/gal and from 34,000 to 54,980 Btu/gal for dry and wet milling plants, respectively. Most estimates are within the range 36,000-46,000 Btu/gal for dry milling plants and 46,000-53,000 Btu/gal for wet milling plants. In our estimates, we did not incorporate data from Morris and Ahmed (1992), the lone study that averaged energy use rate for dry and wet milling plants (30% of capacity assigned to dry milling and 70% to wet milling).

Established wet milling plants are fueled primarily with coal, often supplemented by natural gas as described below. If cogeneration systems are employed, plants can usually generate enough electricity for their own consumption. Otherwise, ethanol plants obtain electricity from the supply grid. Even if coal is burned to generate steam and electricity, natural gas is often used in wet milling plants for direct drying of products because of (a) the high heat demand and (b) superior economics of natural gas for this purpose. Based on our contacts with industry, we have assumed that, for wet milling plants, 80% of total thermal energy required is supplied with coal, and the remaining 20% with natural gas. As dry milling plants are much smaller on average than wet milling plants, their cost savings from switching from natural gas to coal should be small. We expect that most dry milling plants are fueled with natural gas. However, we conservatively assume that 50% of the total thermal energy required in dry milling plants is supplied with natural gas, and the remaining 50% with coal.

Restrictive environmental regulations precluding new coal burning permits in many areas have led to new ethanol plant designs that primarily incorporate natural gas firing as the process fuel. Use of natural gas in ethanol plants results in less total CO₂ emissions from ethanol plants. We have included a case in our sensitivity analysis in which we assume that all ethanol plant thermal energy is provided with natural gas (see Section IV). Electricity use in ethanol plants accounts for 9-15% of their total energy consumption (Liegois, 1997; Buckland, 1997). Most established wet milling ethanol plants, which are usually large, are equipped with cogeneration systems to produce both steam and electricity. In contrast, many dry milling plants purchase electricity from the power grid. Use of cogeneration systems can help reduce plant energy use by as much as 30% (Ho, 1989). In general, a reduction of 10% in energy use is readily achieved by use of cogeneration systems (Graboski, 1997). With this reduction rate, if all plants employ cogeneration systems, the total energy consumption in ethanol plants would be 40,400 Btu/gal for dry milling plants and 40,300 Btu/gal for wet milling plants. In our base case analysis, we assume that 50% of dry milling and 100% of wet milling plants employ cogeneration systems, but that, for future cases, cogeneration use will be 100% in all mills.

The above energy use values reflect the amount of energy consumed for producing both ethanol and co-products. Co-products include distillers' dried grain solids (DDGS) in dry milling plants (Figure B1) and corn oil, germ, gluten meal, and gluten feed in wet milling plants (Figure B2). In most previous studies, emissions and energy use during both corn farming and ethanol production were allocated between ethanol and co-products with a co-product credit that is estimated using one of four methods: product replacement, market value, energy content, or weight (see Shapouri et al., 1995). In this study, we have made an attempt to separate energy use in ethanol plants into two values, one for ethanol production and the other for co-product production. The separation is based on energy use for a specific process in ethanol plants and whether the specific process is for ethanol or co-product production. The two flow charts presented in Figures B1 and B2 consist of three groups: corn milling, ethanol processing and co-product processing. The corn milling group includes operations that start from raw corn to starch; the ethanol processing group includes processes from starch saccharification to fuel ethanol; and the co-product processing group includes separation and drying of co-products. A large portion of the total energy used in ethanol plants is for process heating during corn milling. To be conservative, we allocate all the energy for the corn milling process to ethanol production, but

inside the plant gate, the energy used within the ethanol processing group and the co-product processing group is assigned to ethanol and co-products, respectively.

In dry milling plants, the most energy-intensive processes are cooking of corn, distillation and dehydration of ethanol, and evaporation and dewatering of DDGS (Figure B1). A summary of the energy allocation between ethanol and co-products in dry milling plants is presented in Table III-10. Most of the estimates in Table III-10 were obtained from firms in the business of designing ethanol plants. Data from Madson (1991) covered improved, energy-efficient ethanol plants, but without use of molecular sieve technology. Most estimates include both thermal and electric power. The value from Shroff (1997) is based on thermal energy input only, which is over 85% of total energy consumption in a typical ethanol plant.

Thermal energy use in wet milling plants is more complex. Major energy-consuming processes include liquefaction and distillation for ethanol, and steep water evaporation, germ, fiber and gluten dryer for co-products (Figure B2). Table III-11 summarizes results of energy allocation studies for wet milling plants.

Table III-12 gives the energy use allocation between ethanol and co-products with other allocation approaches from some other previous studies. As the table shows, the process-based energy allocation in ethanol plants, as calculated in our study, is close to the market value-based allocation for wet milling plants and to energy content-based allocation for dry milling plants.

Note that while we allocate energy use and emissions *within ethanol plants* on the basis of estimated energy use split between ethanol production and co-product production, we use the market value-based co-product credit for allocating energy use and emissions during *corn farming*. The result is 30% of energy and emissions assigned to co-products in the wet milling process and 24% in the dry milling process. In our sensitivity analysis, we included a case using replacement value for co-product credit in current and future prediction (Section IV).

Table III-10 Allocation of Energy Use Between Ethanol and Co-products for Dry Milling Ethanol Plants: Based on Production Processes

Allocation of Total Energy (%)		Remarks	Source
Ethanol	Co-Products		
70	30	Thermal energy only. 25% for cooker, 45% for distillation, and 30% for dryer	Shroff, 1997
75-80	20-25	Thermal energy and electricity. 20-25% for milling, 50-60% for ethanol processes, and 20-25% for co-product processes	Merediz, 1997
67	33	For thermal energy, 64% for ethanol and 36% for co-products. For electricity, 90% for ethanol and 10% for co-products	Liegeois, 1997
62	38	Thermal energy--39% for co-products; electrical energy--25% for co-products (natural gas-fired drier).	Buckland, 1997
56	44	Azeotropic dehydration and improved design	Madson, 1991

Table III-11 Allocation of Energy Use Between Ethanol and Co-products for Wet Milling Ethanol Plants: Based on Production Processes

Fraction of Total Energy (%)		Remarks	Sources
Ethanol	Co-Products		
72.2	27.8		Shapouri et al. 1996
68.8	31.2	Data from ethanol plant operations	Merediz, 1997a
68	32		Graboski, 1995
60-75	25-40	Corn oil extraction not considered	Merediz, 1997b

Table III-12 Comparison of Energy Use and Emissions Allocation Between Ethanol and Co-Product in Corn Ethanol Plants

Energy and Emissions Allocation (%)		Basis	Remarks	Source
Ethanol	Co-products			
57	43	Market value	Wet milling	Morris and Ahmed,, 1992
70	30	Market value	Wet milling	Shapouri et al., 1996
76	24	Market value	Dry milling	The same as above
57	43	Energy content	Wet milling	The same as above
61	39	Energy content	Dry milling	The same as above
48	52	Output weight basis	Wet milling	The same as above
49	51	Output weight basis	Dry milling	The same as above
81	19	Replacement value	Wet milling	The same as above
82	18	Replacement value	Dry milling	The same as above
81	19	Replacement value	Dry milling	Delucchi, 1993
69	31	Process energy basis	Wet milling	This study
66	34	Process energy basis	Dry milling	This study

III.8. End-use Vehicle Types and Fuel Economy

Both passenger cars and light trucks (pickups and minivans) are included in this study. While percentage changes in per-mile GHG emissions for both types will be similar, the absolute amount of emissions in grams per mile will obviously be different. In Section IV, we conduct various sensitivity analyses of key parameters on ethanol fuel-cycle GHG emissions using passenger cars. We estimate grams-per-mile GHG emissions for light trucks with our base case scenario (specified in Section IV) to show differences in grams-per-mile emissions between cars and light trucks.

At present, Ford is selling an FFV (flexible-fueled vehicle) Taurus (3.0 L engine), and Chrysler is selling its FFV minivan (3.3 L engine). Ford will produce an FFV Ranger pickup (3.0 L engine) beginning in model-year 1999, and an FFV Windstar minivan (3.0 L engine) in model year 2000. In our comparison between E85 FFVs and gasoline cars, we select Taurus-like mid-size cars, and in that between E85 FFVs and gasoline light trucks, we select light trucks similar to the Chrysler minivan, the Ford Ranger pickup, and the Ford Windstar. Table III-13 presents the gasoline fuel economy of baseline comparison vehicles. E85 use is restricted to new

FFVs, but E10 can be used in existing gasoline vehicles without any vehicle modifications. Thus, while the fuel economy shown for E85 FFVs is based on comparison with the few vehicle models listed above, fuel economy of vehicles using E10 is based on *all* new cars and all new light trucks.

Table III-13 Baseline Gasoline Vehicle Fuel Economy (on-road adjusted, combined urban and highway cycle)

	E85		E10	
	1997 MY	2005 MY	1997 MY	2005 MY
Passenger cars	23 ^a	25 ^c	28 ^d	30 ^c
Light trucks	19 ^b	21 ^c	21 ^d	22 ^c

^a Fuel economy of 1997 MY Taurus is 23 mpg (U.S. DOE, 1997).

^b Fuel economy is 20.3, 17.6, and 19.9 mpg for 1997 MY Chrysler minivan, Ford Ranger pickup, and Ford Windstar minivan, respectively (U.S. DOE, 1997).

^c Projections for 2005 MY vehicle fuel economy for a given vehicle type are based on fuel economy of the 1997 MY vehicle and new vehicle fuel economy improvement between 1997 and 2005 as predicted by Energy Information Administration (EIA, 1996).

^d Fuel economy averaged over all new cars and all new light trucks (EIA, 1996).

Gasoline-equivalent fuel economy of E85 FFVs is assumed to be 5% higher than that of baseline gasoline vehicles, a conservative assumption in light of recent fuel economy performance of production E85 Tauruses. Btu-equivalent fuel economy is assumed to be the same for E10 and gasoline (although in-use experience indicates that E10 has a slight fuel economy penalty *per unit volume*). Furthermore, 1997 MY baseline gasoline vehicles are assumed to be fueled with conventional gasoline and 2005 MY baseline gasoline vehicles with reformulated gasoline.

IV. RESULTS

This section presents results of fuel-cycle energy use and GHG emissions of using E85 and E10 relative to using gasoline (under the current case) and RFG (under the 2005 case). Our base case uses the values for key input parameters presented in Section III. Under this base case, we estimate energy use and emissions for a present situation that includes technologies already in place and for a future situation in which technologies, especially ethanol production technologies, are expected to improve. The future case is to be applied for year 2005. Under the base cases, energy use and emissions are calculated for cars and light-duty trucks using E85 and E10. Baseline gasoline vehicles are fueled with conventional gasoline under the current base case, and with reformulated gasoline under the future base case. Per-mile energy and GHG emissions results for the two base cases are presented in Tables IV-1 - IV-8.

**Table IV-1 Fuel-Cycle Energy Use and GHG Emissions: Passenger Cars Using E85
the Current Case**

(Fossil energy is in Btu/mi. and emissions are in CO₂-equivalent grams/mi.)

	Feedstock	Fuel	Vehicle Combustion	Total
Baseline GV:				
Fossil energy	146	1,009	5,022	6,177
GHGs	25.4	77.6	366.0	469.1
CO ₂	16.2	76.3	362.8	455.4
CH ₄	8.8	0.1	1.6	10.5
N ₂ O	0.5	1.2	1.6	3.2
Ethanol from Wet Milling Plants:				
Fossil energy	795	1,669	1,011	3,475
GHGs	110.2	145.3	68.8	324.3
CO ₂	58.5	143.7	66.2	268.1
CH ₄	1.9	0.9	1.0	3.8
N ₂ O	49.8	1.1	1.6	52.5
Ethanol from Dry Milling Plants:				
Fossil energy	828	1,742	1,011	3,581
GHGs	114.8	141.1	68.8	324.7
CO ₂	60.9	137.2	66.2	264.3
CH ₄	1.9	1.3	1.0	4.2
N ₂ O	52.0	2.6	1.6	56.2

**Table IV-2 Fuel-Cycle Energy Use and GHG Emissions: Passenger Cars Using E85
the Future Case
(Fossil energy is in Btu/mi. and emissions are in CO₂-equivalent grams/mi.)**

	Feedstock	Fuel	Vehicle Combustion	Total
Baseline GV:				
Fossil energy	131	1,077	4,520	5,728
GHGs	22.9	81.8	322.6	427.3
CO ₂	14.6	80.3	319.5	414.4
CH ₄	7.9	0.1	1.6	9.6
N ₂ O	0.4	1.4	1.6	3.3
Ethanol from Wet Milling Plants:				
Fossil energy	755	1,344	895	2,994
GHGs	102.5	116.1	58.4	277
CO ₂	55.8	114.5	55.8	226.1
CH ₄	1.7	0.7	1.0	3.4
N ₂ O	45.1	0.9	1.6	47.5
Ethanol from Dry Milling Plants:				
Fossil energy	747	1,400	895	3,042
GHGs	103.6	109.6	58.4	271.6
CO ₂	54.9	107.6	55.8	218.3
CH ₄	1.7	1.1	1.0	3.8
N ₂ O	47.1	0.9	1.6	49.4

**Table IV-3 Fuel-Cycle Energy Use and GHG Emissions: Light Trucks Using E85
the Current Case
(Fossil energy is in Btu/mi. and emissions are in CO₂-equivalent grams/mi.)**

	Feedstock	Fuel	Vehicle Combustion	Total
Baseline GV:				
Fossil energy	177	1,222	6,079	7,477
GHGs	30.8	94.0	446.1	570.9
CO ₂	19.6	92.4	442.9	555.0
CH ₄	10.6	0.1	1.6	12.3
N ₂ O	0.5	1.5	1.6	3.6
Ethanol from Wet Milling Plants:				
Fossil energy	962	2,020	1,224	4,207
GHGs	133.4	175.9	84.9	394.3
CO ₂	70.8	173.5	82.4	326.7
CH ₄	2.3	1.1	1.0	4.4
N ₂ O	60.3	1.3	1.6	63.2
Ethanol from Dry Milling Plants:				
Fossil energy	1,003	2,108	1,224	4,335
GHGs	139.0	170.8	84.9	394.7
CO ₂	73.7	166.0	82.4	322.1
CH ₄	2.3	1.6	1.0	4.9
N ₂ O	63.0	3.2	1.6	67.7

**Table IV-4 Fuel-Cycle Energy Use and GHG Emissions: Light Trucks Using E85
the Future Case
(Fossil energy is in Btu/mi. and emissions are in CO₂-equivalent grams/mi.)**

	Feedstock	Fuel	Vehicle Combustion	Total
Baseline GV:				
Fossil energy	156	1,282	5,381	6,819
GHGs	27.3	97.4	386.4	511.0
CO ₂	17.4	95.6	383.2	496.2
CH ₄	9.4	0.1	1.6	11.1
N ₂ O	0.3	1.1	1.1	2.5
Ethanol from Wet Milling Plants:				
Fossil energy	899	1,600	1,065	3,564
GHGs	122.1	138.2	71.1	331.3
CO ₂	66.4	136.3	68.5	271.1
CH ₄	2.0	0.8	1.0	3.8
N ₂ O	53.7	1.1	1.6	56.3
Ethanol from Dry Milling Plants:				
Fossil energy	889	1,667	1,065	3,621
GHGs	123.3	130.4	71.1	324.8
CO ₂	65.3	128.1	68.5	261.9
CH ₄	2.0	1.3	1.0	4.4
N ₂ O	56.0	1.0	1.6	58.6

**Table IV-5 Fuel-Cycle Energy Use and GHG Emissions: Passenger Cars Using E10
the Current Case
(Fossil energy is in Btu/mi. and emissions are in CO₂-equivalent grams/mi.)**

	Feedstock	Fuel	Vehicle Combustion	Total
Baseline GV:				
Fossil energy	120	829	4,125	5,074
GHGs	20.9	63.8	298.0	382.7
CO ₂	13.3	62.7	294.9	370.9
CH ₄	7.2	0.1	1.6	8.9
N ₂ O	0.4	1.0	1.6	2.9
Ethanol from Wet Milling Plants:				
Fossil energy	168	881	3,849	4,897
GHGs	27.2	69.0	277.4	373.6
CO ₂	16.5	67.9	274.2	358.6
CH ₄	6.7	0.1	1.6	8.4
N ₂ O	4.0	1.0	1.6	6.5
Ethanol from Dry Milling Plants:				
Fossil energy	170	886	3,849	4,905
GHGs	27.5	68.7	277.4	373.6
CO ₂	16.6	67.4	274.2	358.3
CH ₄	6.7	0.2	1.6	8.5
N ₂ O	4.2	1.1	1.6	6.8

**Table IV-6 Fuel-Cycle Energy Use and GHG Emissions: Passenger Cars Using E10
the Future Case
(Fossil energy is in Btu/mi. and emissions are in CO₂-equivalent grams/mi.)**

	Feedstock	Fuel	Vehicle Combustion	Total
Baseline GV:				
Fossil energy	109	897	3,767	4,774
GHGs	19.1	68.2	266.9	354.1
CO ₂	12.2	66.9	263.7	342.8
CH ₄	6.6	0.1	1.6	8.3
N ₂ O	0.3	1.2	1.6	3.0
Ethanol from Wet Milling Plants:				
Fossil energy	153	921	3,514	4,589
GHGs	24.8	71.0	248.2	344.0
CO ₂	15.0	69.7	245.0	329.8
CH ₄	6.2	0.1	1.6	7.9
N ₂ O	3.6	1.1	1.6	6.3
Ethanol from Dry Milling Plants:				
Fossil energy	155	925	3,514	4,595
GHGs	25.1	70.5	248.2	343.8
CO ₂	15.2	69.2	245.0	329.5
CH ₄	6.2	0.1	1.6	7.9
N ₂ O	3.8	1.1	1.6	6.5

**Table IV-7 Fuel-Cycle Energy Use and GHG Emissions: Light Trucks Using E10
the Current Case
(Fossil energy is in Btu/mi. and emissions are in CO₂-equivalent grams/mi.)**

	Feedstock	Fuel	Vehicle Combustion	Total
Baseline GV:				
Fossil energy	160	1,105	5,500	6,765
GHGs	27.9	85.0	402.2	515.1
CO ₂	17.8	83.6	399.1	500.4
CH ₄	9.6	0.1	1.6	11.3
N ₂ O	0.5	1.3	1.6	3.4
Ethanol from Wet Milling Plants:				
Fossil energy	224	1,174	5,132	6,530
GHGs	36.3	92.0	374.5	502.8
CO ₂	22.0	90.5	371.4	483.9
CH ₄	9.0	0.2	1.6	10.7
N ₂ O	5.3	1.3	1.6	8.2
Ethanol from Dry Milling Plants:				
Fossil energy	227	1,181	5,132	6,540
GHGs	36.7	91.6	374.5	502.8
CO ₂	22.2	89.9	371.4	483.5
CH ₄	9.0	0.2	1.6	10.8
N ₂ O	5.5	1.5	1.6	8.6

**Table IV-8 Fuel-Cycle Energy Use and GHG Emissions: Light Trucks Using E10
the Future Case
(Fossil energy is in Btu/mi. and emissions are in CO₂-equivalent grams/mi.)**

	Feedstock	Fuel	Vehicle Combustion	Total
Baseline GV:				
Fossil energy	149	1,224	5,136	6,509
GHGs	26.0	92.9	368.3	487.2
CO ₂	16.6	91.3	365.1	473.0
CH ₄	9.0	0.1	1.6	10.7
N ₂ O	0.5	1.6	1.6	3.6
Ethanol from Wet Milling Plants:				
Fossil energy	209	1,256	4,792	6,257
GHGs	33.9	96.8	342.8	473.4
CO ₂	20.5	95.1	339.6	455.2
CH ₄	8.4	0.2	1.6	10.1
N ₂ O	5.0	1.5	1.6	8.1
Ethanol from Dry Milling Plants:				
Fossil energy	212	1,262	4,792	6,266
GHGs	34.3	96.1	342.8	473.2
CO ₂	20.7	94.4	339.6	454.8
CH ₄	8.4	0.2	1.6	10.2
N ₂ O	5.2	1.5	1.6	8.2

From the results presented in the above eight tables, we also calculated reductions in per-mile fossil energy use and GHG emissions by ethanol *blended* as both E85 and E10. Calculated percentage reductions for the base case combinations are presented in Table IV-9. As the table shows, ethanol blended as E85 achieves 42% to 48% reductions in fossil energy use, and 30% to 36% reductions in GHG emissions. As for E10 blend, per-mile fossil energy use is reduced by 3.3% to 3.9%, and GHG emissions are reduced by 2.4% to 2.9%. The E10 blend reductions are smaller because only a small fraction of E10 (10% of the volume and less than 7% of the energy content) is ethanol.

Table IV-9 Per-Mile Energy Use and Emissions Reductions by E85 and E10 Blend (Relative to Conventional Gasoline for the Current Case and to RFG for the Future Case)

		Current Case		Future Case	
		Wet Milling	Dry Milling	Wet Milling	Dry Milling
E85 Blend:					
Cars	Fossil energy	43.7%	42.0%	47.7%	46.9%
	GHGs	30.9%	30.8%	35.2%	36.4%
Light trucks	Fossil energy	43.7%	42.0%	47.7%	46.9%
	GHGs	30.9%	30.9%	35.2%	36.4%
E10 Blend:					
Cars	Fossil energy	3.5%	3.3%	3.9%	3.7%
	GHGs	2.4%	2.4%	2.9%	2.9%
Light trucks	Fossil energy	3.5%	3.3%	3.9%	3.7%
	GHGs	2.4%	2.4%	2.8%	2.9%

Table III-9 shows energy and GHG emissions benefits of E85 and E10 blend fuels. One may inquire if the energy and emissions benefits of using one gallon of ethanol blended into E10 differ from those resulting when it is blended into E85. That is, if one gallon of ethanol is used, how much energy and GHG emissions benefit results regardless of its share of a blend? (Use of one gallon of ethanol requires about 1.18 gallons of E85 blend and 10 gallons of E10 blend.)

Because the energy and emissions changes in E85 and E10 blends are caused by the ethanol portion of the blends, the changes for one gallon of ethanol in each blend can be calculated by dividing the changes of the blends (as presented in Table IV-9) by the energy content share of ethanol in each blend. The energy content share of ethanol is 78.9% for E85 blend and 6.7% for E10 blend. Calculated energy and emissions changes by ethanol in each blend are presented in Table IV-10.

Table IV-10 Per-Mile Energy Use and Emissions Reductions by Ethanol Used in the Form of E85 and E10 Blend (Relative to Conventional Gasoline for the Current Case and to RFG for the Future Case)

		Current Case		Future Case	
		Wet Milling	Dry Milling	Wet Milling	Dry Milling
Ethanol in E85 Blend:					
Cars	Fossil energy	55.4%	53.3%	60.5%	59.4%
	GHGs	39.1%	39.0%	44.6%	46.2%
Light trucks	Fossil energy	55.4%	53.3%	60.5%	59.4%
	GHGs	39.2%	39.1%	44.6%	46.2%
Ethanol in E10 Blend:					
Cars	Fossil energy	51.9%	49.6%	57.9%	55.5%
	GHGs	35.7%	35.6%	42.6%	43.4%
Light trucks	Fossil energy	51.9%	49.6%	57.9%	55.9%
	GHGs	35.6%	35.5%	42.3%	43.0%

As Table IV-10 shows, use of ethanol in the form of either E85 or E10 results in 50% to 60% reductions in fossil energy use and 35% to 46% reductions in GHG emissions. Ethanol in E85 achieves a little more reduction than ethanol in E10, primarily because there is a 5% fuel economy gain over gasoline vehicles by vehicles fueled with E85 while vehicles fueled with E10 and gasoline have same fuel economy.

We designed various sensitivity analysis cases to test the importance of key parameters in determining fuel-cycle energy use and GHG emissions. Table IV-11 presents our sensitivity analysis cases. Sensitivity analyses were conducted for passenger cars for both current and future cases. They were not conducted for light-duty trucks since the relative changes in energy use and emissions between passenger cars and light-duty trucks are similar.

Relative reductions in fossil energy use and GHG emissions under each of the sensitivity cases, calculated from results in Tables IV-12 and IV-13, are presented in Figures 2 - 5. For fossil energy use, only the case of no co-product credit makes a significant difference, relative to the base case. Under this sensitivity case, fossil energy reduction benefit by E85 is reduced from above 40% to below 25% with current technology assumptions. With future technology assumptions, fossil energy benefit is reduced from about 50% to about 35%. Changes in GHG emissions reductions under the sensitivity cases are more dramatic. Co-product credit is the most significant factor determining GHG emissions benefit of E85.

With current technology assumptions, use of the replacement-based co-product credit results in about 8% reduction in E85 GHG emissions benefit. If no credit is assigned to co-

products, E85 GHG benefit is limited to about a 10% reduction. With future technology assumptions, E85 GHG emission benefit is reduced to about 30% and less than 20% reduction with the replacement-based credit and no credit approach, respectively. The next most important factor is N₂O emissions from cornfields. Without considering these agricultural emissions, E85 GHG emissions benefit is increased by an additional reduction of 10%. Effects of other factors on GHG emissions benefits are generally small.

Table IV-11 Sensitivity Analysis Cases

Sensitivity Case	Sensitivity Case Parametric Value	Base Case Parametric Value
All thermal energy from natural gas in ethanol plants	100% of thermal energy from natural gas in ethanol plants	20% of thermal energy from natural gas in wet milling plants and 50% in dry milling plants
No co-product credit	No credits assigned to co-products for corn farming and ethanol plant	For corn farming, a credit of 30% and 24% assigned to co-products from wet milling and dry milling plants; for ethanol production, 31% and 34% for wet and dry milling plants
Replacement-based co-product credit	For corn farming, a credit of 19% and 18% assigned to co-products from wet and dry milling plants	The same as above
Increased corn yield (for the future case only)	135 bushels/acre	130 bushels/acre
Increased ethanol yield	2.7 and 2.8 gal. ethanol per bushel of corn for wet and dry milling plants	2.5 and 2.6 gal. ethanol per bushel of corn for wet and dry milling plants
No N ₂ O emissions from corn fields	N ₂ O emissions from N-fertilizer in corn fields not considered	1.5% of fertilizer-N to N ₂ O-N assumed
2% N ₂ O emissions	2% of fertilizer-N to N ₂ O-N assumed	The same as above

**Table IV-12 Fuel-Cycle Energy Use and GHG Emissions of Passenger Cars Using E85:
the Current Case
(Fossil energy is in Btu/mi. and emissions are in CO₂-equivalent grams/mi.)**

	Wet Milling				Dry Milling			
	Feedstock	Fuel	Vehi. combustion	Total	Feedstock	Fuel	Vehi. combustion	Total
100% of thermal energy from NG in ethanol plants:								
Fossil	795	1,842	1,011	3,648	828	1,816	1,011	3,656
GHGs	110.2	133.9	68.8	312.9	114.8	130.2	68.8	313.9
CO ₂	58.5	127.4	66.2	252.1	60.9	124.2	66.2	251.3
CH ₄	1.9	1.9	1.0	4.9	1.9	2.0	1.0	4.9
N ₂ O	49.8	4.6	1.6	56.0	52.0	4.1	1.6	57.7
No co-product credit:								
Fossil	1,123	2,289	1,011	4,423	1,081	2,457	1,001	4,549
GHGs	155.3	200.48	68.8	424.5	149.5	199.5	68.8	417.8
CO ₂	82.1	197.8	66.2	346.2	79.1	193.8	66.2	339.1
CH ₄	2.0	1.2	1.0	4.3	2.0	1.9	1.0	4.9
N ₂ O	71.2	1.9	1.6	74.1	68.4	3.8	1.6	73.7
Replacement-based co-product credit:								
Fossil	915	1,909	1,011	3,835	891	2,067	1,011	3,970
GHGs	126.7	166.6	68.8	362.2	123.5	167.6	68.8	359.9
CO ₂	67.2	164.4	66.2	297.8	65.5	162.9	66.2	294.6
CH ₄	1.9	1.0	1.0	4.0	1.9	1.0	1.0	4.0
N ₂ O	57.7	1.2	1.6	60.4	56.1	3.1	1.6	60.8

Table IV-12 (Cont.)

Wet Milling					Dry Milling			
Feedstock	Fuel	Vehi. combustion	Total	Feedstock	Fuel	Vehi. combustion	Total	
Increased ethanol yield:								
Fossil	738	1,677	1,011	3,427	771	1,753	1,011	3,535
GHGs	102.4	146.0	68.8	317.3	107.0	142.0	68.8	317.8
CO ₂	54.4	144.1	66.2	264.7	56.8	138.0	66.2	261.0
CH ₄	1.9	0.9	1.0	3.8	1.9	1.3	1.0	4.3
N ₂ O	46.2	1.1	1.6	48.8	48.3	2.6	1.6	52.5
No N ₂ O from corn fields considered:								
Fossil	795	1,669	1,011	3,475	828	1,742	1,011	3,581
GHGs	61.9	145.3	68.8	276.0	64.4	141.1	68.8	274.3
CO ₂	58.5	143.7	66.2	268.1	60.9	137.2	66.2	264.3
CH ₄	1.9	0.9	1.0	3.8	1.9	1.3	1.0	4.3
N ₂ O	1.5	1.1	1.6	4.1	1.6	2.6	1.6	5.7
2% of fertilizer-N to N ₂ O-N:								
Fossil	795	1,669	1,011	3,475	828	1,742	1,011	3,581
GHGs	126.3	145.3	68.8	340.4	131.7	141.1	68.8	341.6
CO ₂	58.5	143.4	66.2	268.1	60.9	137.2	66.2	264.3
CH ₄	1.9	0.9	1.0	3.8	1.9	1.3	1.0	4.3
N ₂ O	65.9	1.1	1.6	68.6	68.8	2.6	1.6	73.0

**Table IV-13 Fuel-Cycle Energy Use and GHG Emissions of Passenger Cars Using E85:
the Future Case
(Fossil energy is in Btu/mi. and emissions are in CO2-equivalent grams/mi.)**

	Wet Milling				Dry Milling			
	Feedstock	Fuel	Vehi. Combustion	Total	Feedstock	Fuel	Vehi. combustion	Total
100% of thermal energy from NG in ethanol plants:								
Fossil	716	1,476	895	3,087	747	1,522	895	3,163
GHGs	99.4	107.4	58.4	265.2	103.6	109.2	58.4	271.2
CO ₂	52.7	102.3	55.8	210.8	54.9	104.2	55.8	214.9
CH ₄	1.7	1.5	1.0	4.2	1.7	1.6	1.0	4.3
N ₂ O	45.1	3.6	1.6	50.2	47.0	3.4	1.6	52.0
No co-product credit:								
Fossil	1,012	1817	895	3,723	974	1947	895	3,815
GHGs	140.1	158.2	58.4	356.7	134.9	152.5	58.4	345.8
CO ₂	74.0	156.0	55.8	285.9	71.3	149.7	55.8	276.8
CH ₄	1.7	1.0	1.0	3.7	1.7	1.6	1.0	4.4
N ₂ O	64.3	1.2	1.6	67.1	61.9	1.1	1.6	64.5
Replacement-based co-product credit:								
Fossil	825	1527	895	3,246	803	1649	895	3,347
GHGs	114.3	132.4	58.4	305.1	111.4	129.1	58.4	298.9
CO ₂	60.5	130.6	55.8	246.9	59.0	126.8	55.8	241.6
CH ₄	1.7	0.8	1.0	3.5	1.7	1.4	1.0	4.1
N ₂ O	52.1	1.0	1.6	54.7	50.7	1.0	1.6	53.3

Table IV-13 (Cont.)

Wet Milling					Dry Milling			
Feedstock	Fuel	Vehi. Combustion	Total		Feedstock	Fuel	Vehi. combustion	Total
Increased corn yield:								
Fossil	759	1,344	895	2,998	731	1,400	895	3,026
GHGs	104.6	116.1	58.4	279.1	100.8	109.6	58.4	268.8
CO ₂	55.8	114.5	55.8	226.2	53.8	107.6	55.8	217.2
CH ₄	1.7	0.7	1.0	3.4	1.7	1.1	1.0	3.8
N ₂ O	47.1	0.9	1.6	49.6	45.3	0.9	1.6	47.7
Increased ethanol yield:								
Fossil	720	1,349	895	2,964	695	1,409	895	2,998
GHGs	99.9	116.6	58.4	274.9	96.5	110.2	58.4	265.2
CO ₂	52.9	115.0	55.8	223.8	51.1	108.3	55.8	215.2
CH ₄	1.7	0.7	1.0	3.4	1.7	1.1	1.0	3.8
N ₂ O	45.3	0.9	1.6	47.8	43.7	0.9	1.6	46.1
No N ₂ O from corn fields considered								
Fossil	775	1,344	895	3,014	747	1,400	895	3,042
GHGs	60.1	116.1	58.4	234.6	58.0	109.6	58.4	226.0
CO ₂	56.9	114.5	55.8	227.3	54.9	107.6	55.8	218.3
CH ₄	1.7	0.7	1.0	3.4	1.7	1.1	1.0	3.8
N ₂ O	1.5	0.9	1.6	3.9	1.4	0.9	1.6	3.8
2% of fertilizer-N to N ₂ O-N								
Fossil	775	1,344	895	3,014	747	1,400	895	3,042
GHGs	123.4	116.1	58.4	297.9	118.8	109.6	58.4	286.8
CO ₂	56.9	114.5	55.8	227.3	54.9	107.6	55.8	218.3
CH ₄	1.7	0.7	1.0	3.4	1.7	1.1	1.0	3.8
N ₂ O	64.7	0.9	1.6	67.2	62.2	0.9	1.6	64.6

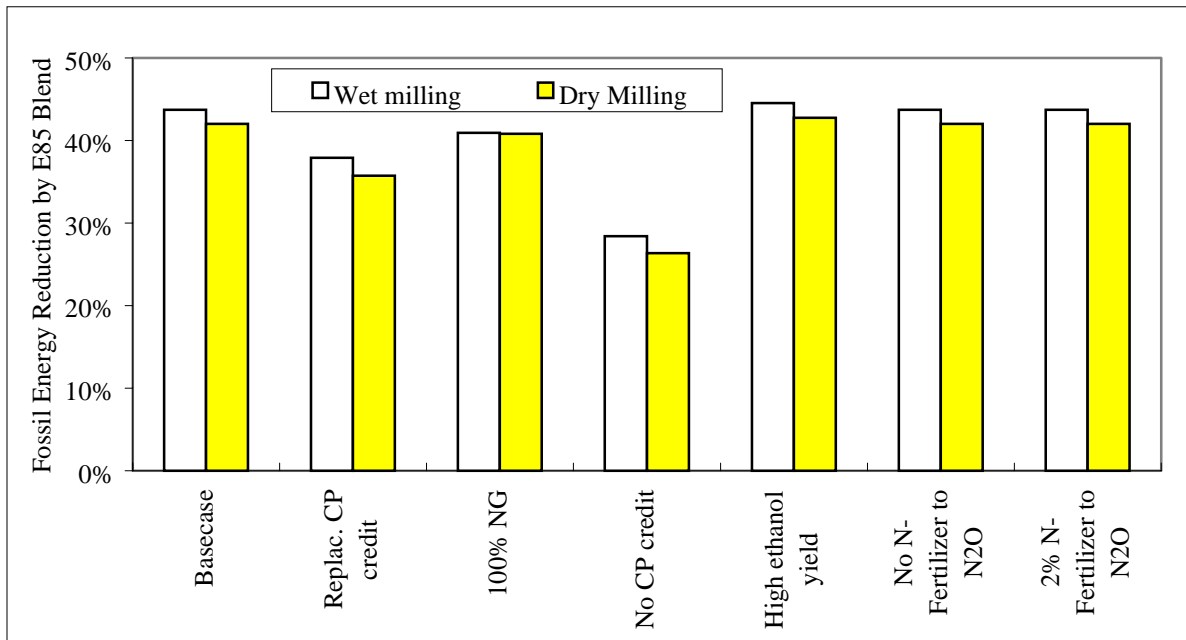


Figure 2 Reduction in Fossil Energy Use by E85 relative to Conventional Gasoline: Current Technologies

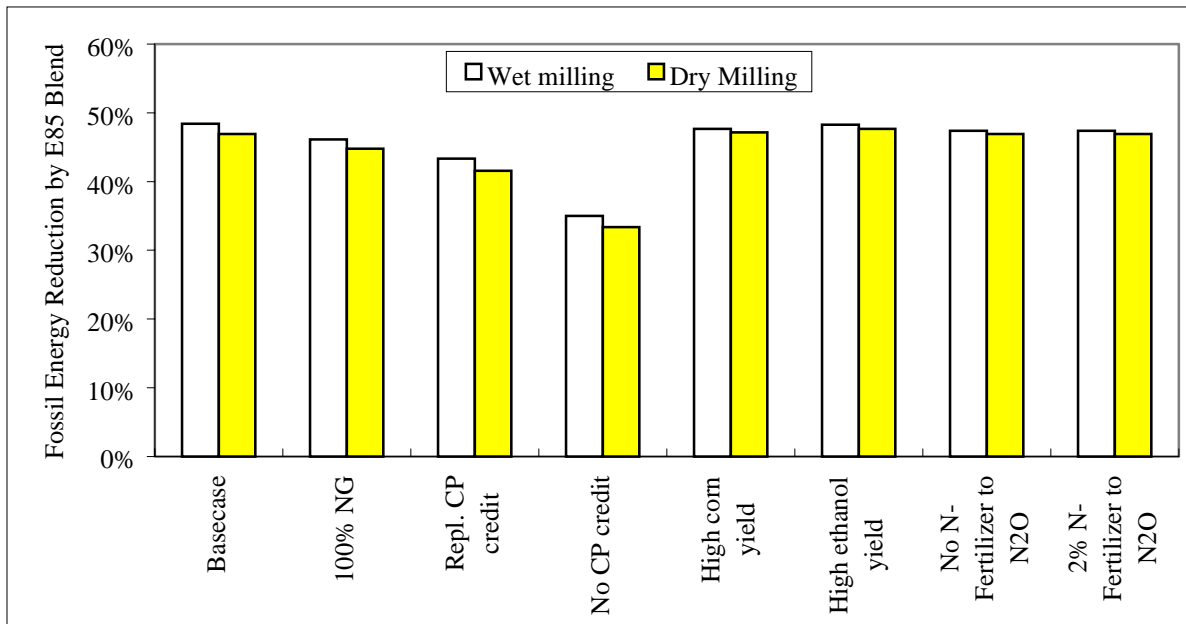


Figure 3 Reduction in Fossil Energy Use by E85 relative to Reformulated Gasoline: Future Technologies

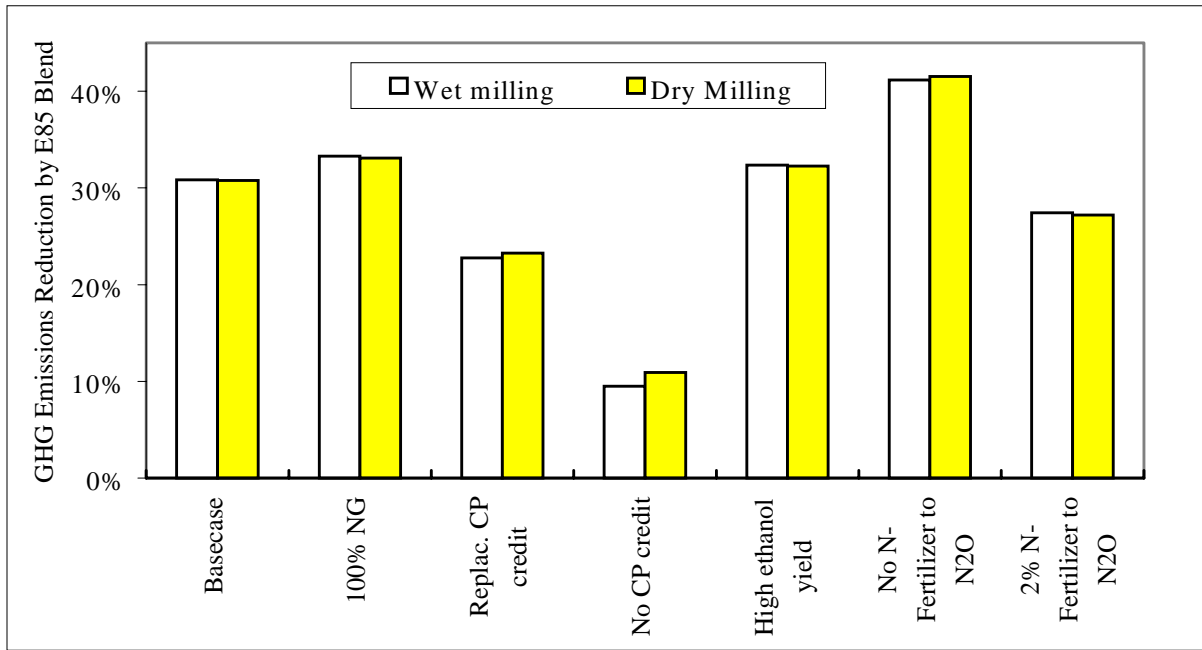


Figure 4 Reduction in GHG Emissions by E85 relative to Conventional Gasoline: Current Technologies

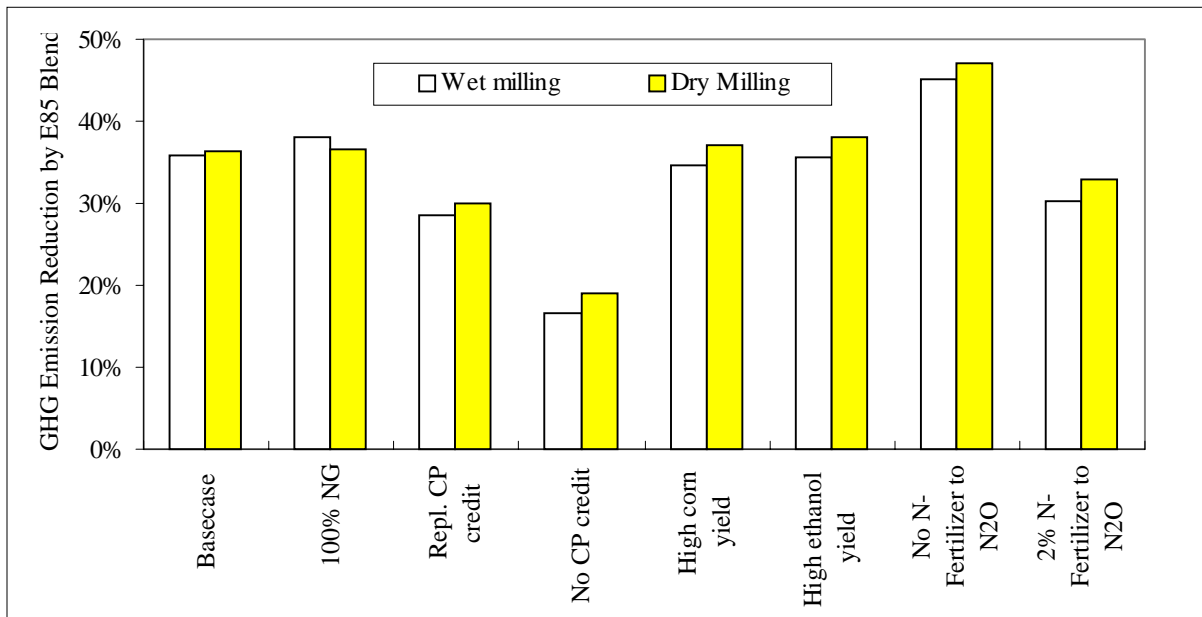


Figure 5 Reduction in GHG Emissions by E85 relative to Reformulated Gasoline: Future Technologies

V. CONCLUSIONS

For all the cases that we have examined in this study, the corn-to-ethanol fuel cycle for ethanol burned as E85 and E10 outperforms both that of conventional (current) and that of reformulated (future) gasoline with respect to energy use and greenhouse gas production on a mass emission per travel mile basis. In many cases, the superiority of the energy and GHG result is quite pronounced (i.e., well outside the range of model “noise”). However, the co-product energy use attribution remains the single key factor in estimating ethanol’s relative benefits because this value can range from 0 to 50 percent depending on the attribution method chosen. In general, wet mills produce a broader slate of high value end products which would be economically justifiable even if ethanol were not being produced, but the same cannot be said of dry mills, whose only other product for which an established market exists (DDGS) requires further processing to become an animal feed with value comparable to the gluten and germ product output of wet mills. If dry mills are not economically sustainable absent ethanol production, it could be argued that no co-product energy use attribution is warranted for them; however, current investment decisions for small-capacity dry mills are heavily influenced by existence of a local market for the DDGS co-product. Therefore, co-product attribution is appropriate for dry mills in the states studied.

GHG reductions (but not energy use) appear surprisingly sensitive to the value chosen for combined soil and leached N-fertilizer conversion to nitrous oxide which, as studies documented in Section III and Appendix A indicate, falls in the range of 0-2 percent. This narrow range of nitrous oxide emissions produces a range of near 20% in projected GHG savings for both present and future gasoline comparisons, the highest sensitivity ratio (approx. 1:4) within the value range for any variable explored. Meanwhile, the fuel cycle GHG production for use of E10 blend is about 2% to 3% less than that of the corresponding gasoline. Fuel cycle energy and GHG savings profiles for present and future light duty trucks operating on E85 and E10 match those for automobiles.

We conclude from this analysis that **use of corn-based ethanol achieves net energy savings and greenhouse gas emissions reductions**, at least for current and near-term crop and ethanol production conditions in the four states that we examined. If domestic use of corn-based ethanol is increased drastically (e.g., to 10 times as high as the current national usage level), corn farming practice and acreage under cultivation for meeting the drastically increased demand for ethanol could be significantly different from current conditions. The results presented in this report do not apply to that scenario.

APPENDIX A

N₂O EMISSIONS FROM N-FERTILIZER APPLICATIONS IN CORN FIELDS: LITERATURE REVIEW AND EMISSION ESTIMATION

Table A1 Summary of N₂O Emissions from Cornfields¹

Fertilizer²	Soil	Location	Control³	N₂O-N loss(%)⁴	Publication year
U/AN	medium	NY	Y	1.57	1979-87 summery
CN/AN	medium	NY	Y	0	''
MAN/AN	fine	WI	Y	1.80	''
MAN/AN/U	fine	WI	Y	1.78	''
A	fine	CO	N	1.30	''
AN	medium	WI	N	1.31(0.15-3.15)	''
AN/AC/AN	medium	NY	N	1.7 (1.2-2.2)	''
AA	Sandy clay	IA	Y	1.1 (0.52-1.67)	1981 ⁵
A	clay loam	CO	N	1.25	1981 ⁵
AS	clay loam	CO	Y	0.36	1986 ⁵
	sandy loam	CO	N	1.2	1987 ⁵
AN	silt loam	TN	Y	2.8 (2.6-3.0)	1996 ⁵
AA, UAN	silt loam	NE	N	1.0	1997 ⁵

N ₂ O-N loss:	Average = 1.22%	minimum = 0%	medium =1.30%, 1.57%
	maximum =3.15%		

1 This table summarizes direct N₂O emissions from soil.

2 U-urea, AN-ammonium nitrate; CN-calcium nitrate; MAN-manure; A-ammonium type; AS-ammonium sulfate; AC-ammonium chloride; UAN-urea ammonium nitrate; SN-sodium nitrate; SS-sewage sludge; and PN-potassium nitrate.

3 Y means that a control site with no fertilizer added was included in a given study for estimating soil N₂O emissions from the natural nitrogen cycle. N means that no control site was included. The difference in N₂O emissions between the experimental site (where N-fertilizer was applied) and the control site was calculated as the N₂O emissions attributable to N-fertilizer applications.

4 Percentage of N in fertilizer evolved as N in N₂O. Values in the parenthesis are range of the results.

5 These were not included in the 1979-1987 summary paper.

Notes:

- The average N₂O-N emissions from soil (1.22% here) were a simple mean of the values presented in Table A1.
- Minimum, maximum and medium values were determined from individual data in a given study before they were averaged together in this study.
- Results from two studies (Thornton et al., 1996, Bremner et al, 1981a) were not included in the estimation of average N₂O emissions here. Thornton et al. measured N₂O emissions in a cornfield in subtropical Tennessee. The soil and climatic conditions there are very different from those in the midwest. Bremner et al. (1981a) had a high fertilizer application rate of 250kgN/ha (AA) in their experiment, as compared to 180 kgN/ha (AA) in another study by the same authors in the same year (Bremner et al., 1981b). As a result, N₂O emissions in the former study, ranging from 4% to 6.8%, were 13 times as high as those in the latter study and were significantly higher than those from other studies (ranging from 0% to 3.15%).

Table A2 Summary of Fertilizer Nitrogen Leaching in Cornfields¹

System	Fertilizer	Soil	Location	Control	N loss(%) ²	Publication year
Continuous	UAN	silt loam	Iowa	Y	16.1(drainage)	1994
Continuous	UAN	silt loam	Iowa	Y	4.8(drainage)	1994
Rotation	—	silt loam	Iowa	Y	21.8(drainage)	1975
Rotation	Urea	silt loam	Iowa	Y	24.5(drainage)	1981
Rotation	UAN	clay loam	Iowa	Y	11.75(drainage)	1994
Rotation	AA, KI	silt loam	Iowa	Y	15.3(drainage)	1996
Continuous	AN, Urea	silt loam	Iowa	Y	17.4(runoff)	1979
Rotation	—	silt loam	Iowa	Y	20(runoff and drain.)	1984
Continuous	AN, PN	silt loam, clay loam, plain field sand	IL	Y	40(17-83.5) ³ (total loss) ⁴	1993
Continuous	AN	silt loam	IL	Y	20-44 (total loss) ⁴	1997

Average nitrogen loss to nitrate nitrogen through leaching as percentage of fertilizer nitrogen: **24%** (see notes below)

Notes:

- 1 This table summarizes fertilizer nitrogen loss to nitrate nitrogen through surface runoff, subsurface drainage, and groundwater.
- 2 Loss of fertilizer nitrogen to nitrate nitrogen through leaching as percentage of total fertilizer nitrogen.
- 3 Values in parenthesis are ranges.
- 4 The lost nitrogen includes fertilizer nitrogen emitted from soil as N₂O and nitrogen leached to water systems as NO₃⁻ via drainage, runoff and groundwater.

As Table A2 shows, the studies reviewed here presented nitrogen losses in three different aggregate levels. At the first level, drainage loss and runoff loss were presented separately. For these studies, we first averaged nitrogen loss for each of the two sources, and then added the averages for the two sources together. In particular, we estimated an average of nitrogen loss of 15.7% through drainage and 17.4% through surface runoff. Thus, a total loss of 33.1% through runoff and drainage together was estimated with studies presenting data at this level.

At the second level, nitrogen loss through drainage and runoff was presented together. The studies presenting data at this level showed an average loss of 20%. Putting these studies and the studies presenting data at the first level together, we approximated an average loss of **26.6%** for runoff and drainage together. As Table A2 shows, there are eight studies for these two groups. Since the eight studies reviewed here did not show significant nitrogen loss into groundwater (see details in Table A5 below), the estimated average was treated as the total loss of runoff, drainage, and groundwater.

At the third level, nitrogen loss from soil N₂O emissions and leaching (i.e., runoff, drainage, and groundwater) was presented together. A rule of thumb in estimating fertilizer nitrogen loss is that 1/3 of the total loss through leaching and 2/3 through soil N₂O emissions (Hoef, 1997). This rule was applied to the two aggregated data points in Table A2 (40% and 32%, the latter is the medium of the range of 20-44%) to approximate emissions through leaching. Thus, for the two aggregate data points, nitrogen loss through leaching is 13.3% and 10.7%, resulting in an average of **12%**.

Since we could not make a fair judgment on which studies were more representative than others, we used the number of data points for each group as the weight to average results from the studies together. In particular, average loss from leaching was calculated as:

$$(26.6\% \times 8 + 12\% \times 2) / 10 = \mathbf{24\%}$$

Two studies (Vomel et al., 1981, Ronen, et al., 1988) were not included in the above estimation for two reasons. First, both studies were conducted outside of the U.S., and soil, climatic, and groundwater hydrological conditions in those studies were different from those in

the U.S. midwest. Second, the study by Ronen et al. was conducted in a sandy aquifer in Israel where the site was irrigated with sewage for twenty years, and therefore groundwater was heavily contaminated with nitrate.

**Table A3 Comparison of Solubility of N₂O with Other Inorganic Gases
(at temperature of 0 °C)**

Compound	Solubility (cc/100g water)
N ₂ O	130.52
N ₂	2.35
NO	7.34
O ₂	4.89
H ₂	2.1

Source: Perry's Chemical Engineers' Handbook, 6th Edition, 1984

Table A4 Estimation of N-Fertilizer-Induced N₂O Emissions from Soil in Individual Studies

Author	Sample source	Environment/key results	N ₂ O information
Eichner, 1990	data from 104 experiments from 1979-1987, sorted with fertilizer, soil, crop, and soils.	Fertilizer used in corn: AN (13), U(2), A(2), AS(1), CN (1);	N ₂ O-N/N: 0.44AN (gnl) 1.29 % (corn, AN) (1/4 neg.result) (controlled)

Emissions sorted by fertilizer type in corn system:

fertilizer	*control?	% of N fertilizer evolved as N ₂ O
U/AN	Y	1.57
CN/AN	Y	0
MAN/AN	Y	1.80
MAN/AN/U	Y	1.78
A	N	1.30
AN	N	1.31(0.15-3.15)
AN/AC/AN	N	1.70 (1.2-2.2)

*Control: fertilizer not added (soil N₂O emissions from natural nitrogen cycle).

Anderson, et al., 1987	Virginia: corn , soybean, grass, planted garden; sandy loam soil. Colorado: Winter wheat, fallow; clay loam soil.	VA:2% om. acidic fertilizer type NA CO:1.4% om. slightly basic. fertilizer type NA. N ₂ O emission variable and sensitive to soil moisture and temp.	loss 1.2% as N ₂ O-N from N _f (no control, VA, corn) N ₂ O emissions not estimated (large database of 350 suggested)
------------------------	---	---	---

Table A4 (Cont.)

Author	Sample source	Environment/key results	N ₂ O information
Mosier and Hutchinson 1981	corn field in Colorado. Nunn clay loam	1.3% om. 200kgNha ⁻¹ fertilizer: NH₃-N , pH7.8 N ₂ O emission increase with soil water content, decrease as growing season progresses, and as total deN reduces	1.25% N ₂ O emission from N _f (no control) flux: 520 gN ha ⁻¹ d ⁻¹ (1 st d after 1 st irrigation), 30 gNha ⁻¹ d ⁻¹ (1 st d after 2 nd irrigation).bkgd: 3.8 gNha ⁻¹ d ⁻¹
Mosier, et al. 1986	Colorado: corn and barley. Nunn clay loam	AS : 200 kgNha ⁻¹ per year; 1.8% om. Redox 270-550mV, not sufficient for large amt. of (NO ₃ →N ₂ O) and not enough for N ₂ O→N ₂ . N ₂ O emission increased with soil water content	Max. emission: July (corn) May (barley) N ₂ /N ₂ O (fallow soil): 0-60 N ₂ O loss: 1.5% (w/o control) 0.36% (w/ control) N ₂ O+N ₂ loss: 2.5% flux _{ave.} (corn): 62 gNha ⁻¹ d ⁻¹ ,
Mosier, et al. 1982	Colorado, <u>barley</u> calcareous Otero sandy loam	AN: 56,112,224 kgNha ⁻¹ SS: 69,71,356 kgNha ⁻¹ 1.7% om. N ₂ O emissions increased linearly with amt. of AN applied, and soil water content. AN treatment effect became insignificant after six weeks.	N ₂ O emissions: (w/ control) 0.4-0.7% (AN) 0.38-0.95% (SS)
Watson, et al. 1990	summary paper (3) (Ronen, et al. 88; Conrad, et al. 83; Bremner, et al. 81)	N ₂ O emissions from fertilizer vary with type of fertilizer, soil, temp, weather, and farming practice.	N ₂ O/N _f emissions: 0.01-2% (0.01-1.1TgN/yr.) Total (emissions + leaching): 0.01-4% (0.01-2.2 TgN/yr.)
Conrad, et al. 1983	Loess. <u>Beet field</u> Meadow, grass; Lawn grass, clover; Lawn grass. Mainz, Germany	Org.C=0.5-2.6%. 100 kgN ha ⁻¹ applied as NO₃⁻ and ACI (aq). Low spatial variability of N ₂ O emissions. Emissions increased with temp., vary with vegetation cover, soil type, soil moisture, fertilizer type, and form. N ₂ O emitted was produced in the uppermost soil layer, and follows Arrhenius equation. ACI had higher emissions than AN. (Ref. Vomel and Ewert, 1981)	N ₂ O emissions: (sampling period and post s.p.) 0.01-0.073% NO ₃ ⁻ 0.009-0.376% ACI 0.94% ACI into 10 ^{cm} soil. N ₂ O emissions from leaching: 0.01-4% (assuming leaching = field emissions)
Tortoso, et al. 1990	Soil from Sidney Nebr.	N ₂ O production pathway. Identified chemoautotrophic ammonium oxidizing bacteria are predominant source of N ₂ O and NO in soil by nitrification.	

Table A4 (Cont.)

Author	Sample source	Environment/key results	N ₂ O information
Williams, et al. 1992a	Summary	Estimated an algorithm for spatial and seasonal variation of NO emissions by temp. and land use.	NO emission model
Williams, et al. 1992b	Summary	Spatial and temporal variation of N ₂ O emissions as a function of temp. water content, soil	N ₂ O emissions: 6.8% (UreaN, poorly drained soil, Iowa.
Bremner, 1981		composition, nutrient availability vegetation, disturbances. etc. Nitrification is a more important N ₂ O source than denitrification. Model developed based on denitrification also worked well.	<1% (typical, crop NA) N ₂ O emissions: (corn, fertilized) flux (ngN/m ² /s)= 85 (mean) (Ref. Anderson & Levine,1987) N ₂ O emission rate : 7.9 TgN/y (global, microbial in soil) Rate of accumulation: 3.5 TgN/y
Hutchinson et al. 1992	well drained sub-tropical grassland	AS	N ₂ O emissions: 0.39%
Shepherd et al. 1991	Canada	AN	N ₂ O emissions: 5%
Benckiser, et al. 1996	Clayey loam, Germany. winter wheat, rye, and barley	pH6.2, AN winter N ₂ O measurement 5-15°C (Oct. to May). At 80 kgN/ha-yr., N ₂ O emission neg. correlated to OrgC(s), decreased when COD(s)/N>60. Highest emissions occur on topsoil.	N ₂ O emissions: 2.1% (w/ control, mixed crops)
Vermoesen et al. 1996	Four types of soil: sandy, sandy loam, clayey, heavy clay. no crop. Belgium.	Incubation experiment. ACI & PN. Fertilizer added: 100 and 150 mgN/kg soil. ANOVA analysis: N ₂ O emission depends 100% on soil; NO emission depends 97% on soil, 3% on quantity of N added. N ₂ O production best described by pH, sand content, and background NH ₄ . No differences on N ₂ O production between ACI and PN. Clayey soil had highest emission.	N ₂ O emissions: 0.09-3.1% mean: 0.95% (w/ control)
Skiba et al. 1996	Winter wheat. April. sandy clay loam. SE Scotland.	AN: 43kgNha ⁻¹ . 10 days. N ₂ O emissions became detectable after rainfall. Diurnal cycle observed. Differences between methods of measurement (chamber measurement, eddy covariance and conditional sampling).	N ₂ O emissions: 0.77% (w/o control)

Table A4 (Cont.)

Author	Sample source	Environment/key results	N ₂ O information
Christensen et al., 1996	poorly drained loam /clay loam. 2m below sea level. Wheat stubble. GW at 1m depth. Sealand, Denmark.	Intensive mineralization of organic matter. OrgC 9.5%. soil pH 7.7. Fertilizer not added. N ₂ O flux determined by the flux gradient/ FTIR method and chamber methods had ≤18% difference.	N ₂ O flux (mgN/m ² h): 162-202 (Chamber) 149-495 (Flux gradient)
Qian, et al. 1997	Corn system. Hard silt loam. Shelton, NE.	Soil pH 6.8. soil are underlain by sand and gravel at 0.5-1.2m. Fertilizer: AA, UAN. Also irrigated with GW containing 32mg/kg NO ₃ ⁻ -N. Total fertilizer applied: 234 and 153 kgN/ha for 1991 and 1992. N ₂ O was the major gaseous N product under dry soil conditions. Denitrification was predominant when soil water content >70% WFPS and N ₂ comprising 80-98% of the N ₂ +N ₂ O gases.	N ₂ O+N ₂ loss: (no control) 1.5% (dry season) 4.9% (normal season) N ₂ O emissions: (no control) 1.0% (dry season) 1.0% (normal season) Ratio of N ₂ O-N/(N ₂ O+N ₂)-N: 0.97 (dry season) 0.31 (normal season)
Thornton and Valente, 1996	Routon silt loam Corn . Tennessee	AN: 140 and 252 kgNha ⁻¹ . Soil NO ₃ ⁻ , NH ₄ ⁺ and WFPS were correlated with N ₂ O emissions.	N ₂ O emissions: 2.6-3.0% (w/ control)
Bremner et al. 1981b	Corn. Iowa. 31% sand, 29% clay.	AA, 180kgNha ⁻¹ . SOC 3.7%. Fertilizer applied in 1) Fall and 2) Spring. Fertilizer induced N ₂ O emissions reduced 63-87% by addition of nitrapyrin in Fall and Spring, respectively.	N ₂ O emissions: (control) Fall: 1.67% Spring: 0.52%
Seiler & Conrad 1981	Natural/not agricultural used soil. Eolian sand, Loess, Loess Loam. Mainz, Germany.	fertilizer: sodium N, ACl. 100 kgNha ⁻¹ . N ₂ O in soil was produced and consumed simultaneously in top layer. A considerable portion of N ₂ O was produced by nitrification process.	N ₂ O emissions (w/ control) SN: 0.01-0.05% ACl: 0.03-0.09% Flux: 0.5-16 mgN ₂ O-N/m ² -h. (unfertilized) 43 mgN ₂ O-N/m ² -h (fertilized)
Bremner et al. 1981a	Corn and Soybean rotate. Typical Haplaquolls soil. North central Iowa.	Experiment initiated 1 mo. after soybean planted. plant was removed. soil pH 6.0-7.9. SOC 2.7-4.6%. AA(aq) of 250kgN/ha injected at 20cm depth of soil.	N ₂ O emissions: (w/ control) 4-6.8%

Table A4 (Concl.)

Author	Sample source	Environment/key results	N ₂ O information
Aneja, et al 1997	Corn, Cotton, Soybean. Norfolk sandy loam. Clayton, NC.	Feb. to March. Winter fallow. non-irrigated. Remaining crop residue was incorporated into soil. Emission from crop residue is measured. NO emission increase with decrease of temp., probably due to NO consumption rate increase. N ₂ O deposition was observed.	flux of NO (ngN/m ² -s) NO: 9.2 (soybean) 6.1 (cotton) 4.7 (corn)
Bounman, et al. 1995	Global N ₂ O Model. Review data from Eichner (1990).	Independent of fertilizer types.	N ₂ O emissions from soil (w/ control): 1.25%

**Table A5 Estimation of Fertilizer Nitrogen Loss through Leaching
(Surface Runoff , Subsurface Drainage, and Groundwater) from Cornfields**

Author(s)	Sample source	Fertilizer/Key results	Loss (as N) (% of total N-fertilizer)	
			Run off	Drainage
Baker & Timmons 1994	Iowa, silt loam, continuous corn conducted 1984-86, field lysimeter	UAN, 5% N ¹⁵ labeled; four application methods PI(h&l),KI, SB 125-200 hgN/ha		16.1 (total) 4.8 (N ¹⁵)
Baker et al. 1975	Iowa, silt loam, corn /oats (soybean) rotation, conducted 1970-73.	unknown type, 112 kgN/ha no leaching into GW		21.8
Weed and Kanwar 1996	Iowa, fine loamy, continuous corn, corn/soybean, soybean/corn rotation, four tillage systems. conducted 1990-92	AA, KI 202kgN/ha, continuous corn; 168kg/ha rotation corn. Same treatment since 1977. Leaching to GW possible	rotation corn	15.3
Baker and Johnson 1981	Iowa, silt loam, rotation corn/soybean(oats). conducted 1974-78	Urea, 90, 100, 240 250kgN/ha rotation. corn. <50% pots is possible to leach into GW.		24.5

Table A5 (Cont.)

Author(s)	Sample source	Fertilizer/Application	Leaching Loss (% N of total N-fertilizer)
Johnson and Baker 1984	Iowa, rotation corn/soybean 1979-80 study. surface runoff from plots: 2.9 (2.6 kg/ha) were less than N input from precipitation (6.0 kg/ha).	unknown type 181-178kgN/ha corn	Total surface runoff & drainage: 20
Johnson, et al. 1979	Iowa, silt, continuous corn conducted 1973-75, three tillage systems.	AN at 1973-74 Urea at 1975. 168kg/ha	17.4
Stevens et al. 1997	IL, silt loam, continuous corn, conducted 1994-96.	AN, N ¹⁵ labeled 60,120,180,240 lb. N/acre. no GW leaching 64-95% of N remained in soil were in organic form.	Total N loss including soil N ₂ O emission. 20-44
Baker and Melvin 1994	Iowa, clay loam, corn (continuous, rotation) 1990-93 study	UAN, 0,50,100,150, 200 lb. N/acre	Rotation corn: 11.75
Torbert et al. 1993	IL, three sites: Cisne silt loam Drummer silty clay loam Plain field sand. Corn. Conducted 1985, 87-88.	AN, PN, 0, 100, 150, 200 lb. N/acre. N-loss by soil denitrification (loam); leaching into GW (sand); and surface runoff (loam and sand).	Total N loss: 17% silty clay loam, 20% silt loam, 83.5% sand. Ave. 40% .
Hoeft, Sept. 1997	IL soil	general	Rule of thumb: of total N loss, 2/3 by denitrification 1/3 by leaching.
Vömel and Ewert 1981	Germany	¹⁵ N experiment. Nitrate	fertilizer N loss via leaching 0.4-3.4% Fraction of N emitted as N ₂ O: NA

Table A5 (Concl.)

Author(s)	Sample source	Fertilizer/Application	Leaching Loss _____ (% N of total N-fertilizer)
Ronen, D. et al. 1988	Well, 30-m deep, sandy aquifer. Israel aqueous sample	D.O.C. from irrigation reached the water table Area where cultivated land was irrigated by sewage effluent for > 20 yrs. N ₂ O emission calc. based on Org-C in GW. N ₂ O from natural N cycle does not excluded.	80-400 mg/L N ₂ O/N _{loss} =6% 1.9% in water table flux: 3.4-7.8 kgN ₂ O-N/ha/yr. leaching: 0.4-1.0 x10 ⁶ ton N ₂ O-N/yr. (0.8-1.7)x10 ⁶ ton N ₂ O/yr.
	Well, 9m deep sandy aquifer under woodland. Veluwe, Netherlands	contaminated by acid rain, ammonia and animal waste.	10-30 mg/L
	karstic aquifer infiltrated by sewage effluent. Jerusalem	contaminated by sewage. anaerobic in ground water	6-20 mg/L

APPENDIX B

**FUEL ETHANOL PRODUCTION PROCESSES AND
THEIR THERMAL ENERGY CONSUMPTION**

FIGURE 1. PROCESS AND MAJOR ENERGY CONSUMPTION OF MOTOR FUEL GRADE ANHYDROUS ETHANOL PRODUCTION FROM CORN (DRY MILLING)

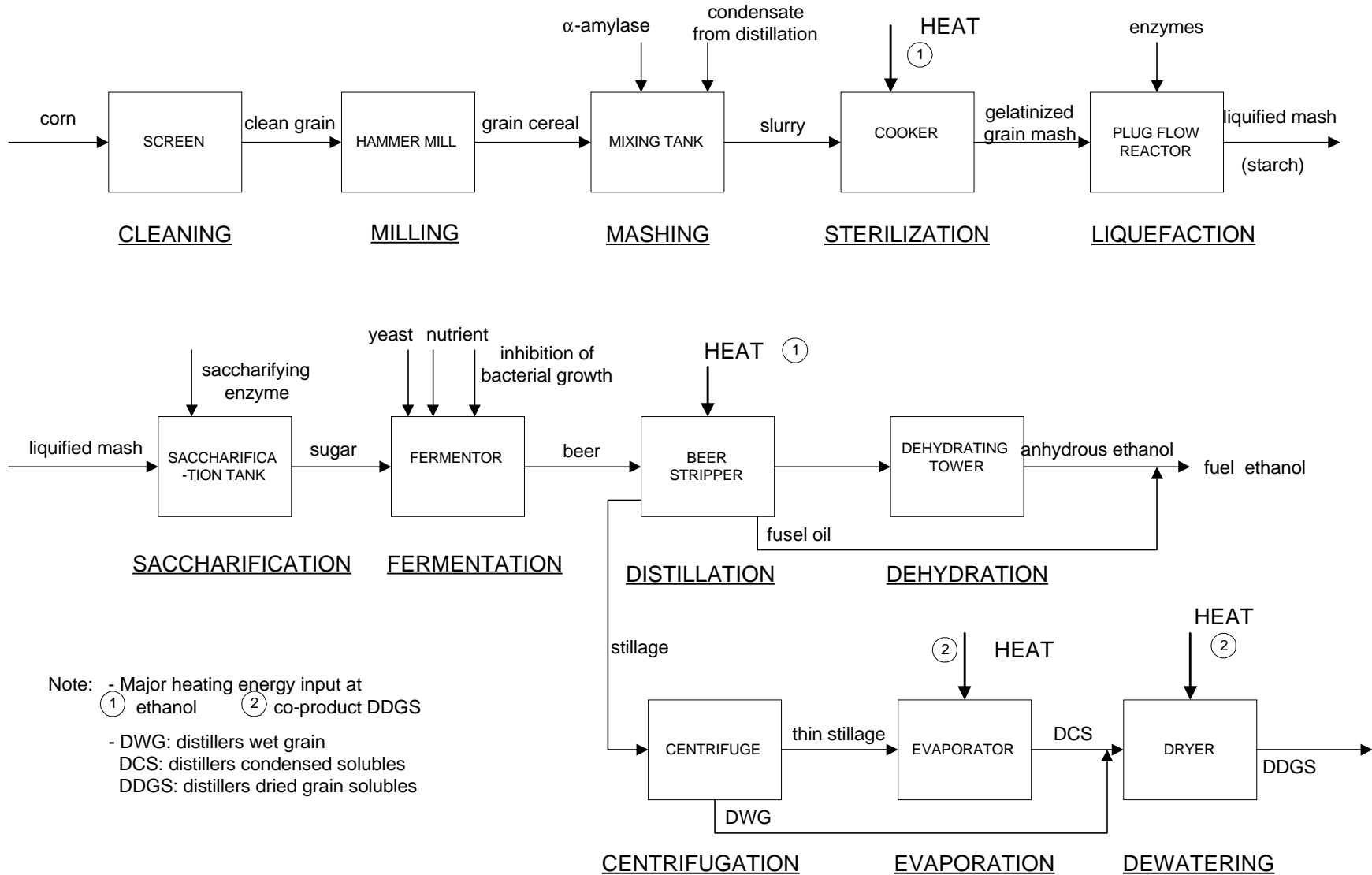
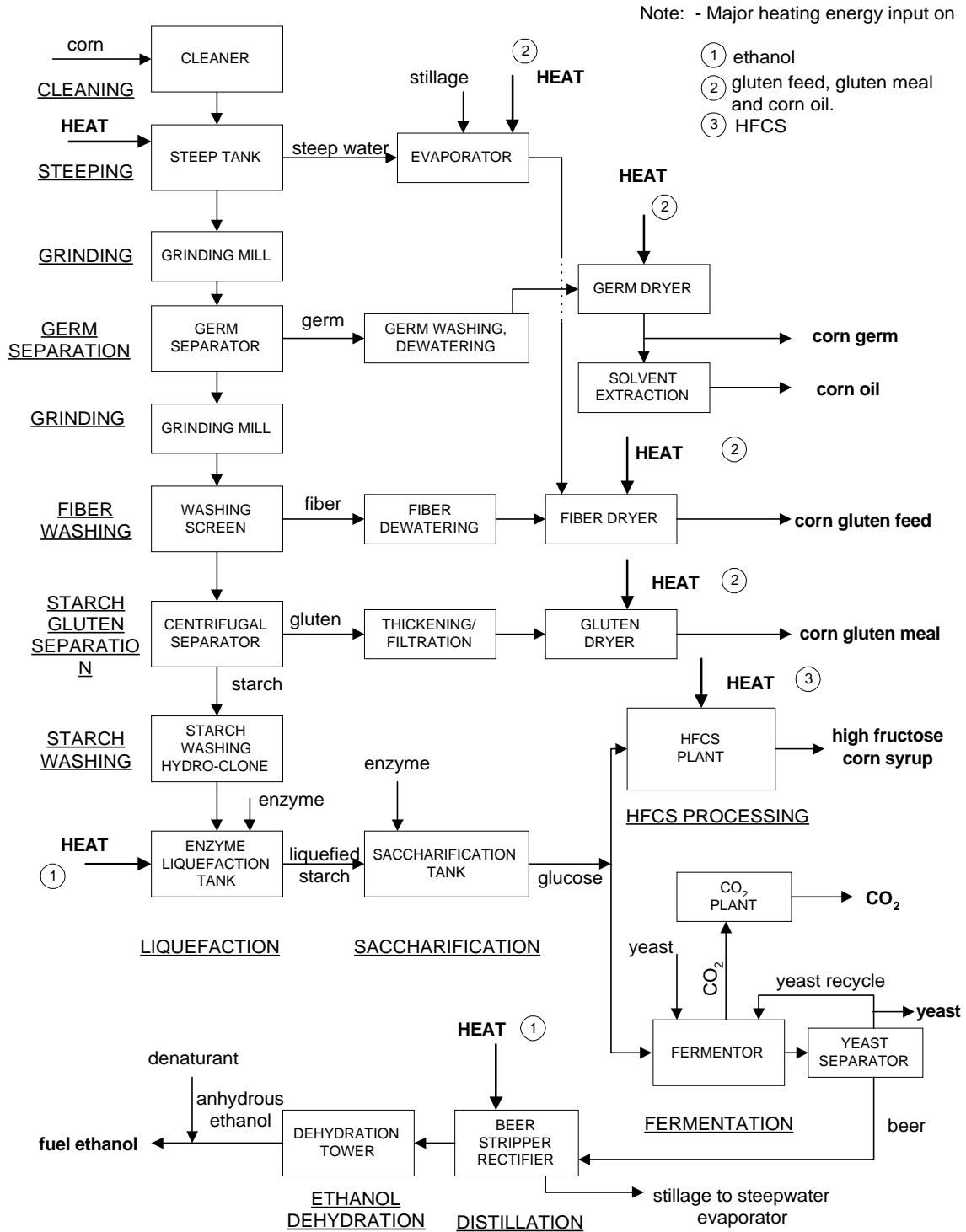


FIGURE 2. PROCESS AND MAJOR ENERGY CONSUMPTION OF FUEL ETHANOL PRODUCTION FROM CORN (WET MILLING)



ACKNOWLEDGMENTS

This study was funded by Illinois Department of Commerce and Community Affairs (DCCA). The authors thank DCCA project manager David Loos for his inputs and support. The authors wish to thank the following individuals for providing data and comments: Deborah Adler of US Environmental Protection Agency, James Baker of University of Iowa State University, Alfred Blackmer of University of Iowa State University, Michael Buckland of Delta-T Corporation, James Duffield of U.S. Department of Agriculture, Michael Graboski of Colorado School of Mines, Ed Harjehausen of Archer Daniels Midland Company, Robert Hoeft of University of Illinois at Urbana-Champaign, William Liegois of Stanley Consultants, Philip Madson of Raphael Katzen Associates International, Tristan Merediz of Process Systems, Inc., Carl Reeder of ADM Corn Processing, Philip Shane of Illinois Corn Growers Association, Hosein Shapouri of U.S. Department of Agriculture, B. Shroff of Raphael Katzen Associates International, Inc., Gary Welch of Pekin Energy Company, and Paul Wood of Process Systems, Inc. The authors are solely responsible for the contents of the report.

REFERENCES

- Ahmed, I. and D. Morris. 1994. *Ethanol, MTBE, and Greenhouse Gas Emissions*, Institute for Local Self-Reliance, Minneapolis, MN, June.
- Anderson, I.C. and J.S. Levine. 1987. "Simultaneous field measurements of biogenic emissions of nitric oxide and nitrous oxide", *J. Geophysical Res.*, **92**, **D1**: 965-975.
- Aulakh, M.S. et al. 1984. "Acetylene and N-serve effects upon N₂O emissions from NH₄⁺ and NO₃⁻ treated soils under aerobic and anaerobic conditions", *Soil Biol. Biochem.*, **16**, **4**: 351-356.
- Baker, J.L. and H.P. Johnson. 1981. "Nitrate-nitrogen in tile drainage as affected by fertilization", *J. Environ. Qual.*, **10**, **4**: 519-522.
- Baker, J.L. and S.W. Melvin. 1994. *Chemical Management in Agricultural drainage well research and demonstration project annual report*, Iowa Dept. Agriculture and Land Stewardship.
- Baker, J.L. and D.R. Timmons. 1994. "Fertilizer management effects on leaching of labeled nitrogen for no-till corn in field lysimeters", *J. Environ. Qual.*, **23**: 305-310.
- Baker, J.L. and H.P. Johnson. 1975. "Nitrate, phosphorus, and sulfate in subsurface drainage water", *J. Environ. Qual.*, **4**, **3**: 406-412.
- Benckiser, G., R. Eilts, A. Linn, H.J. Lorch, E. Sumer, A. Weiske, and F. Wenshofer. 1996. "N₂O emissions from different cropping systems and from aerated, nitrifying and denitrifying tanks of a municipal waste water treatment plant", *Biol. Fertil. Soils*, **23**: 257-265.
- Bounman, A.F., K.W. Van der Hoek, and J.G.J. Oliver. 1995. "Uncertainties in the global source distribution of nitrous oxide", *J. Geophysical Res.*, **100**, **D2**: 2785-2800.

- Bremmer, J.M., G.A. Breitenbeck, and A.M. Blackmer. 1981a. "Effect of anhydrous ammonia fertilization on emission of nitrous oxide from soils", *J. Environ. Qual.*, **10**, **1**: 77-80.
- Bremmer, J.M., G.A. Breitenbeck, and A.M. Blackmer. 1981b. "Effect of nitrapyrin on emission of nitrous oxide from soil fertilized with anhydrous ammonia", *Geophysical Res. Lett.*, **8**, **4**: 353-356.
- Buckland, M. 1997. Personal communication. Delta-T Corporation, Williamsburg, VA.
- Christensen, S., P. Ambus, J.R.M. Arah, H. Clayton, B. Gale, D.W.T. Griffith, K.J. Hargreaves, L. Klemetsson, A.M. Lind, M. Maag, A. Scott, U. Skiba, K.A. Smith, M. Welling, and F.G. Wienhold. 1996. "Nitrous oxide emission from an agricultural field: comparison between measurements by flux chamber and micrometeorological techniques", *Atmospheric Environ.*, **30**, **24**: 4183-4190.
- Conrad, R., W. Seiler, and G. Bunse. 1983. "Factors influencing the loss of fertilizer nitrogen into the atmosphere as N₂O", *J. Geophysical Res.*, **88**, **C11**: 6709-6718.
- Davis, S.C. and D.N. McFarlin. 1997. *Transportation Energy Data Book: Edition 17*, Center for Transportation Analysis, Oak Ridge National Laboratory, Oak Ridge, TN, Sept.
- Delucchi, M.A. 1993. *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity, Appendices A-S*, ANL/ESD/TM-22, Argonne National Laboratory, Center for Transportation Research, Nov.
- Delucchi, M.A. 1996. *Summary of Results from the Revised Model of Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*, Institute of Transportation Studies, University of California at Davis, Davis, CA, November.
- Eichner, M.J. 1990. "Nitrous oxide emissions from fertilized soils: summary of available data", *J. Environ. Qual.*, **19**: 272-280.
- Energy Information Administration. 1996. *Annual Energy Outlook 1997*, DOE/EIA-0383(97), Washington, DC, December.
- Graboski, M. 1997. Personal communication, Colorado School of Mine, Golden, CO.
- Green, M.B. 1987. "Energy in pesticide manufacture, distribution and use," Chapter 7 of *Energy in Plant Nutrition and Pest Control*, edited by Zane R. Helsel, Elsevier Science, New York, 1987.
- Ho, S.P. 1989. *Ethanol Process Energy and Cogeneration Efficiency*, Amoco Oil Company, Naperville, IL.
- Ho, S.P. and T.A. Renner. 1990. "The global warming impact of attainment strategies using alternative fuels," SAE technical paper 901489.

- Hoefl, R.G. 1997. Personal communication, University of Illinois at Urbana-Champaign.
- Hutchinson, G.L. and E.A. Brams. 1992. "NO versus N₂O emissions from an NH₄⁺-amended bermuda grass pasture", *J. Geophys. Res.*, **97**, **D9**: 9889-9896.
- Johnson, H.P. and J.L. Baker. 1979. "Tillage system effects on sediment and nutrients in runoff from small watersheds", *Transactions ASAE*, **22**, **5**: 1110-1114.
- Johnson, H.P. and J.L. Baker. 1984. *Field-to-Stream Transport of Agricultural Chemicals and Sediment in An Iowa Watershed: Part II. Data Base for Model Testing (1979-1980)*, report no. EPA-600/S3-84-055, Environmental Research Laboratory, Athens, GA.
- Stanley Consultants. 1996. *Comprehensive Assessment of the Ten Highest Priority Ethanol Research Areas*, Stanley Consultants, Muscatine, IA.
- Liegeois, W.A. 1997. Personal communication, Stanley Consultants, Muscatine, IA.
- Lin, B.H., M. Padgitt, L. Bull, H. Delvo, D. Shank, and H. Taylor. 1995. *Pesticide and Fertilizer Use and Trends in U.S. Agriculture*, Economic Research Service, U.S. Department of Agriculture, report No. 717, Washington, D.C., May.
- Madson, P.W. 1991. *Energy Utilization in Fuel Ethanol Production*, South Bend, IN.
- Marland, G. and A.F. Turhollow. 1991. "CO₂ emissions from the production and combustion of fuel ethanol from corn," *Energy*, **16**: 1307-1316.
- McAloon, A. 1978. *Grain Motor Fuel Alcohol Plant Simulation Table*, U.S. Department of Agriculture.
- Merediz, T.O. 1997. Personal Communication, Process Systems, Inc. (PSI), Memphis, TN.
- Minnesota Ethanol Commission. 1991. *Corn to Ethanol from a Net Energy Perspective*. Minnesota Department of Agriculture, St. Paul.
- Morris, D. and I. Ahmed. 1992. *How Much Energy Does It Take to Make a Gallon of Ethanol?*, Institute of Local Self-Reliance, Minneapolis, MN.
- Mosier, A.R. and G.L. Hutchinson. 1981. "Nitrous oxide emissions from cropped fields", *J. Environ. Qual.*, **10**, **2**: 169-173.
- Mosier, A.R., G.L. Hutchinson, B.R. Sabey, and J. Baxter. 1982. "Nitrous oxide emission from barley plots treated with ammonium nitrate or sewage sludge", *J. Environ. Qual.*, **11**, **1**: 78-81.
- Mosier, A.R., W.D. Guenzi, and E.E. Schweizer. 1986. "Soil losses of nitrogen and nitrous oxide from irrigated crops in northeastern Colorado", *Soil Sci. Soc. Am. J.*, **50**: 344-348.
- Perry, R. and D. Green. 1984. *Chemical Engineering Handbook*, 6th Edition.

- Qian, J.H., J.W. Doran, K.L. Weier, A.R. Mosier, T.A. Peterson, and J.F. Power. 1997. "Soil denitrification and nitrous oxide losses under corn irrigated with high-nitrate groundwater", *J. Environ. Qual.*, **26**: 348-360.
- Reeder, C. 1997. Personal communication, ADM Corn Processing, Decatur, IL.
- Ronen, D., M. Magaritz, and E. Almon. 1988. "Contaminated aquifers are a forgotten component of the global N₂O budget", *Nature*, **335**, **1**: 57-59.
- Seiler, W. and R. Conrad. 1981. "Field measurements of natural and fertilizer-induced N₂O release rates from soils", *J. Air Pollution Control Association*, **31**, **7**: 767-772.
- Shapouri, H., J.A. Duffield and M.S. Graboski. 1996. "Energy balance of corn ethanol revisited," paper presented at the 3rd Liquid Fuel Conference, Nashville, TN.
- Shapouri, H., J.A. Duffield and M.S. Graboski. 1995. *Estimating the Net Energy Balance of Corn Ethanol*, Agricultural Economic Report no. 721, U.S. Department of Agriculture, Economic Research Service, Washington, DC, July.
- Shepherd, M.F., S. Barzetti, and D.R. Hastie. 1991. "The production of atmospheric NO_x and N₂O from a fertilized agricultural soil", *Atmos. Environ.*, **25A**: 1961-1969.
- Shroff, B. 1997. Personal communication, Raphael Katzen International Associates, Cincinnati, OH.
- Skiba, U. et al. 1996. "Measurement of field scale N₂O emission fluxes from a wheat crop using micrometeorological techniques", *Plant and Soil*, **181**: 139-144.
- Stevens, W.B. et al. 1997. "Effect of fertilization on accumulation and release of readily-mineralizable organic N", *Proceedings of the Illinois fertilizer conference*, Peoria, IL.
- Thornton, F.C. and R.J. Valente. 1996. "Soil emissions of nitric oxide and nitrous oxide from no-till corn", *Soil Sci. Soc. Am. J.*, **60**: 1127-1133.
- Torbert, H.A. et al. 1993. "Short-term excess water impact on corn yield and nitrogen recovery", *J. Prod. Agric.*, **6**, **3**: 337-344.
- Tortoso, A.C. and G.L. Hutchinson. 1990. "Contributions of autotrophic and heterotrophic nitrifiers to soil NO and N₂O emissions", *Appl. Environ. Microbiol.*, **56**, **6**: 1799-1805.
- U.S. Department of Agriculture, National Agricultural Statistics Service, Economic Research Service (USDA/NASS/ERS). 1997. *Agricultural Chemical Usage 1996 Field Crops Summary*, publication no. AG Ch 1 (97), Washington, DC, September (available on Internet at URL <http://mann77.mannlib.cornell.edu/reports/>).

- U.S. Department of Agriculture, National Agricultural Statistics Service, Economic Research Service (USDA/NASS/ERS). 1997. *Crop Values: 1996 Summary*, publication no. Pr 2-1(97), Washington, DC, February.
- U.S. Department of Energy. 1996. *Model Year 1997 Fuel Economy Guide*, DOE/EE-0102, Washington, DC, October.
- U.S. EPA. 1990. *Analysis of the Economic and Environmental Effects of Ethanol as an Automotive Fuel*, special report of Office of Mobile Sources, U.S. EPA, April.
- U.S. EPA. 1991. *Compilation of Air Pollutant Emission Factors, Volume II: Mobile Sources*, U.S. EPA, Office of Mobile Sources, Ann Arbor, MI, Jan.
- Vömel, A. and Ewert, U. 1981. *Stickstoffdüngung und Stickstoffverluste auf ackerbaulich genutzten Böden*, Institut für Pflanzenbau und Pflanzenzüchtung der Universität Gießen, Versuchsstation Rauschholzhausen, 3357 Ebsdorfergrund 4.
- Vermosen, A. et al. 1996. "Effect of ammonium and nitrate application on the NO and N₂O emission out of different soils", *Plant and Soil*, **181**: 153-162.
- Wang, M. 1996. *GREET 1.0 – Transportation Fuel Cycles Model: Methodology and Use*, Center for Transportation Research, Argonne National Laboratory, ANL/ESD-33, Argonne, IL, June.
- Wang, M. 1997. "Greenhouse gas emission impacts of alternative-fueled vehicles: near-term vs. long-term technology options," paper presented at the 8th Global Warming International Conference, New York City, May 25-28.
- Watson, R.T., H. Rodhe, H. Oeschger, and U. Siegenthaler. 1990. "Greenhouse gases and aerosols", in *Climate Change 1995 -- Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analysis*, Edited by Houghton, J.T. et al., Cambridge University press, Cambridge, UK.
- Weed, D.A.J. and R.S. Kanwar. 1996. "Nitrate and water present in and flowing from root-zone soil", *J. Environ. Qual.*, **25**: 709-719.
- Welch, G. 1997. Personal communications, Pekin Energy Corporation, Pekin, IL.
- Williams, E.J., G.L. Hutchinson, and F.C. Fehsenfeld. 1992. "NO_x and N₂O emissions from soil", *Global Biogeochemical Cycles*, **6**, **4**: 351-388.
- Wood, P. 1993. "New ethanol process technology reduces capital and operating costs for ethanol producing facilities", *Fuel Reformulation*, **3**, **4**, July/August.
- Wood, P. 1997. Personal communication, Process Systems, Inc, Memphis, TN.



Permission to Use Copyrighted Material

Yes I give the National Renewable Energy Laboratory (NREL) of Golden, Colorado, irrevocable permission to post the following onto its site on the World Wide Web
 No

Name of Document, Report, Article, etc.:
Effects of Fuel Ethanol Use on Fuel-Cycle Energy and Greenhouse Gas Emissions,
by M. Wang, C. Sanicks, and D. Santini, January, 1999, AUL/ESD-38

Yes In addition to posting on the Web, I give NREL permission to distribute hard copies of the document through its National Alternative Fuels Hotline in response to requests.
 No

When posting on the Web, NREL will credit the copyright holder thus: ~~"Posted on this site with permission from _____"~~ ~~When distributing hard copies, NREL will label the document "Reprinted with permission from _____"~~ *This contribution was created under a contract between the U.S. Department of Energy and the Univ. of Chicago and is subject to the following government license.*

I deny permission to post the document on the Web or to distribute hard copies, but for the document to be abstracted and cited in NREL's database, along with info obtained directly from the copyright holder. The document can be written:

The submitted manuscript has been created by the University of Chicago as Operator of Argonne National Laboratory ("Argonne") under Contract No. W-31-109-ENG-38 with the U.S. Department of Energy. The U.S. Government retains for itself, and others acting on its behalf, a paid-up, nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

I represent and warrant that I have the full right and authority to grant the rights herein granted and that no one else's permission is required.

UNIVERSITY OF CHICAGO as Operator of Argonne National Laboratory *by*

Printed name
Mary R. Hale
Signed name

Title and company
July 20, 2001
Date

Mary R. Hale
Technical Publications Associate
Publications & Record Services

Created February 1997

Argonne National Laboratory



PHONE: 630-252-2140
 FAX: 630-252-5886
 Information and Publishing Division,
 Publications and Record Services (PRS)
 BLDG. 203-C110
 9700 S. Cass Avenue
 Argonne, IL 60439

TELEFAX COVER SHEET

THIS TRANSMISSION CONSISTS OF 1 PAGE(S) EXCLUDING THIS COVER SHEET.

DATE: July 20, 2001

TIME: 9:23 AM

TO: Howard Brown

FROM: Mary Hale *Mary Hale*

RE: ANL/ESD-38, "Effects of fuel ethanol use on fuel-cycle energy and greenhouse gas emissions"

MESSAGE: Here is the permission you requested. If you have any questions, you can reach me at mhale@anl.gov.

C: M. Wang, ES
Permissions