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Environmental Sciences Division
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ENVIRONMENTAL SCIENCES DIVISION

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ABSTRACT

MARLAND, G. and A. TURHOLLOW. 1990. CO_2 Emissions from Production and Combustion of Fuel Ethanol from Corn. ORNL/TM-11180. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 27 pp.

In searching for ways to avoid a climatic change driven by the increasing atmospheric concentration of carbon dioxide, we need to inquire into the possibility of reducing the rate of CO_2 emissions to the atmosphere. Are there fuels that emit less CO_2 into the atmosphere than do conventional fuels? In particular, does the use of biomass fuels reduce net CO_2 emissions to the atmosphere? We consider the case of ethanol from corn.

If ethanol production from corn were completed in an essentially closed cycle whereby the growing plant removed CO_2 from the atmosphere, some parts of the plant were consumed to provide energy for conversion of other parts of the plant to ethanol, and the resultant ethanol was burned to provide useful energy and return CO_2 to the atmosphere, there would be no net emission of CO_2. In fact, in the U.S. economy today, fossil fuels are oxidized at a number of process steps and the use of ethanol fuel is not CO_2 free. Fossil fuels are used to produce fertilizer, to fuel farm and transport equipment, and to run the conversion process. The amount of CO_2 attributable to ethanol is highly variable because of (1) geographic variability in corn yield and agricultural practice, (2) temporal variability in corn yield, due largely to differences in weather, and (3) temporal changes in process and process efficiency. We must also decide how to allocate CO_2 emissions when the process yields multiple products; ethanol, corn oil, and animal feeds.

Because of the wide variability in process and process yields and because of the approximations necessary to complete the calculation, these results should be used with caution. In fact, extensive circulation of this manuscript in draft form has elicited many comments, including a suggestion for an alternate way to attribute process CO_2 to ethanol while taking a CO_2 credit for process by-products. Although there is no "correct" way to allocate by-product credits, the choice does have a large impact on the numerical result and we have used a lengthy Addendum to describe what seems to be the most appropriate (and most conservative) approach. Our baseline calculation then suggests that for the production and consumption of ethanol from corn at the margin of the current U.S. energy system, the CO_2 emissions are 79 percent of the comparable value for gasoline. This is on an energy content basis and does not take credit for octane enhancement or other performance gains often attributed to ethanol.

PREFACE

Since the initial preparation and distribution (e.g., appendix to Segal 1989) of our calculations on CO_2 emissions related to the production and combustion of fuel ethanol from corn, increasing interest in alternative transportation fuels has focussed attention and review on this topic and on our calculations. Especially since the review of S. P. Ho (1989) appeared with such uncompromisingly critical phrasing, we felt it was necessary to reexamine our calculations in the light of this new discussion and to react to Ho's specific criticisms.

Our initial manuscript represented a quick, first-cut calculation and tried to point out the many sources of uncertainty and the subsequent dangers of trying to take the results too quantitatively, and it should not be surprising that others have chosen alternate assumptions and/or taken exception to ours. The important challenge is to ascertain if reviewers have discovered defects in our analysis, if they have been able to obtain better data or improved insight over our initial analysis, or if they have come to conclusions that are qualitatively different from ours--given the inescapable uncertainties.

Of the several published and unpublished responses to our calculations, all have accepted our basic philosophy and approach. The major qualitative difference with the numbers and uncertainties presented in our original manuscript is in how one chooses to assign CO_2 emissions among the multiple products of the ethanol production process - i.e., the "by-product credits." We have reexamined our text in the light of specific criticisms that have been expressed to us.

Because our original manuscript was so widely circulated and so frequently discussed in what was essentially a draft format, we felt that for most readers the most useful approach to follow in formal publication would be to publish what is essentially the draft document and to respond to both internal and external criticisms in an Addendum. This should allow readers to discern both the evolution and range of thinking. The text published here differs from that circulated as the September 1988 draft only to the extent that systematic conversion to SI units has been completed and a rounding error in Table 1 has been corrected. The text is followed by an Addendum which addresses specific criticisms that were raised. Those who would use our numerical results should rely on the summary table from the Addendum.

CO_2 EMISSIONS FROM PRODUCTION AND COMBUSTION OF FUEL ETHANOL FROM CORN

INTRODUCTION

How much CO_2 is released to the atmosphere as a consequence of burning ethanol from corn? The basic combustion question is very straightforward and reveals simply that burning ethanol releases 17.53 kg C/10^9 J as CO_2. This compares with 13.78 kg C/10^9 J for the combustion of natural gas, 19.94 kg C/10^9 J for petroleum liquids, and 24.12 kg C/10^9 J for bituminous coal (Marland 1983).

This answer is not particularly useful, however, for it fails to acknowledge that the carbon from fossil fuels is being released to the atmosphere from long term storage and results in a net increase in atmospheric CO_2, whereas the carbon in ethanol has been very recently removed from the atmosphere by the corn plant and is being recycled only to provide energy useful to man--with the aid of a solar energy input. If the ethanol production and consumption were truly a closed cycle, we could note that there is no net CO_2 release associated with its use. Two questions arise however: whether there is net storage of carbon somewhere in the system and whether there is a net supplement of carbon-based fossil fuels somewhere in the system.

In answer to the first question, it is observed that virtually all parts of the corn plant are oxidized in one way or another within a relatively short period of time and that there is no net carbon storage. In general, long-term corn production does result in a net continuing oxidation of soil carbon, but the flux is generally small and will not be considered further.

Before considering energy subsidies for ethanol, we should note that refined petroleum products at the point of end-use burning should be charged for energy subsidies as well. Energy is consumed in petroleum production and refining, so that useful petroleum products have an energy subsidy of approximately 12% (Marland 1983), and the CO_2 emission actually attributable to burning 10^9 J of refined petroleum products is estimated at 22.29 kg C.

Similarly, if fossil fuels are oxidized and CO_2 released during the production of ethanol, these CO_2 releases should be attributed to the ethanol production and consumption process. In essence, ethanol does not appear for use without the consumption of some energy (and release of CO_2) for its production. Energy subsidies from fossil fuels occur both in the agricultural enterprise (primarily in machinery fuel and fertilizer production) and in the conversion process (milling, fermentation, distillation).

The question, then, is how much energy (especially from fossil fuels) is consumed to make ethanol available for use? The answer to this question is highly variable for at least three principal reasons: (1) geographic variability in corn yield and agricultural practice, (2) temporal variability in corn yield, due largely to differences in weather, and (3) temporal changes due to changes in process and process efficiency. Differences in process yield and energy input over space and time can be very large. Acknowledging this variability, we have tried to calculate a conservative, yet typical, value for current production. Improvements are certainly possible, and it is possible to envision changes, such as the substitution of nuclear process heat or the development of a nitrogen-fixing corn plant, that would make a major difference in total CO_2 emissions. In the text that follows, we summarize the carbon flows involved in the production and consumption of ethanol. The energy flows on which the carbon numbers are based are detailed in the Appendix.

THE AGRICULTURAL ENTERPRISE

Corn production in the U.S. required 19.61 x 10^6 kJ/ha in 1978 (see Appendix for details). Although this is 21.3% higher than comparable requirements in Wisconsin, data from Wisconsin (Weinblatt et al. 1982) illustrate how this energy was allocated: field operations and farm vehicles, 35.4% (mostly as diesel fuel and gasoline); grain handling and drying, 5.8% (mostly liquified petroleum [LP] gas with some electricity); fertilizer, 52.2% (88.5% natural gas and 11.5% electricity); and other, 6.5% (including irrigation, pesticides, and miscellaneous). By 1987 fertilizer use had increased, but liquid fuel consumption had decreased an estimated 29.4%. In 1987 an average hectare of U.S. corn required 5.73 x 10^6 kJ of direct fuel expenditures, 12.52 x 10^6 kJ of energy embodied in fertilizer, and another 1.25 x 10^6 kJ of miscellaneous energy inputs as pesticides, etc. This hectare yielded, on average, 7.49 metric tons of corn (119.4 bu/acre), which could be converted to ethanol at a volumetric rate of 372 L/metric ton (2.5 gal/bu). The total energy input to corn in 1987 was thus 19.51 x 10^6 kJ/ha or 8.85 x 10^6 J/kg of ethanol (25.1 x 10^3 Btu/gal). Of this, approximately 2.60 x 10^6 J/kg was liquid fuels, 5.03 x 10^6 J/kg was natural gas, 0.67 x 10^6 J/kg was coal, 0.22 x 10^6 J/kg was from non-fossil-based electricity, and 0.33 x 10^6 J/kg was "other" (see Table 1). This breakdown assumes that 75% of the electricity was derived from coal burning at a heat rate of 10,960 Kj/kWh (10,400 Btu/kWh) and 25% was from non-fossil sources (e.g., hydro, nuclear), also based on this heat rate. We have used fertilizer-use data from the U.S. Department of Agriculture (1988a) and have assumed (after Weinblatt et al., 1982) that the energy invested in fertilizer is 72,265, 12,920, and 9945 kJ/kg of N, P_2O_5, and K_2O, respectively. Both higher and lower values have been published for the energy content of fertilizer, and lower values have been projected for the future, but these values seem to be near the consensus for current production.

ETHANOL CONVERSION PROCESS

The largest energy consumption during the conversion of corn to ethanol is in electric power for milling and direct heat for distillation. Average data are difficult to obtain and the technology has improved with time. A variety of published sources suggest total energy consumption for the conversion process in the range of 11,130 to 16,700 kJ/L (40,000 to 60,000 Btu/gal) (see Appendix) and our information from a major local producer (P. Herman, personal communication, 1988) falls in this range as well. Values at the local facility fall short of the minimum possible because the plant is optimized for production of corn syrup and ethanol is treated as a swing product, i.e., production varies as the demand for corn syrup changes. It is probably true in most operating plants that production is optimized for multiple or alternate products. The energy for the conversion process includes approximately 0.32 kWh of electricity per liter and the remainder is process heat from fossil fuel burning--assumed here to be coal (see Table 1). We use a total of 11,130 kJ/L but recognize that the current value could often be 50% larger. (Carbon dioxide generated during fermentation is often captured for use but ends up in the atmosphere during product [e.g. soft drink] consumption.)

CO_2 EMISSIONS

All of the energy detailed in Table 1 is consumed to produce fuel ethanol. Even if there is no net CO_2 release from the ethanol itself, all of the CO_2 released during ethanol production is properly attributed to the use of ethanol fuel. These fuel-use numbers can be converted to carbon releases using conversion factors that recognize all of the energy embodied in the fuels: 13.78 kg C/10^9 J for natural gas, 24.65 kg C/10^9 J for coal, 22.29 kg C/10^9 J for liquid fuels (Marland 1983). Since electricity in the United States is now approximately 75% from thermal electric stations that burn fossil fuels, we assume that electricity is 75% from coal and 25% from non-fossil sources (e.g. hydro, nuclear). These conversion factors include consideration of the energy subsidies in primary fuel production. We assume that "other" in Table 1 means liquid fuels. Table 1 shows that the emission of CO_2 from ethanol is thus 0.471 kg C/kg ethanol or 15.86 kg C/10^9 J of ethanol. This number should be taken as approximate only, because of the wide variability observed, the approximations necessary to complete the estimate, and the items omitted from the accounting (e.g., transporting corn to the ethanol plant). Perhaps the largest variables are the corn yield and the energy use in conversion. If corn yield were 4.52 metric tons/ha (72 bu/acre) (as it was in 1974), the CO_2 production rate in kg C per 10^9 J would be approximately 25% higher than with the 7.49 metric tons/ha (119.4 bu/acre) yielded in 1987. Using 16,700 kJ/L for milling and distillation would have raised the CO_2 emissions number on the order of 30%.

BY-PRODUCTS

The final, and very important, question to be raised concerns the allocation of resources to final product when the process yields multiple products. The process scheme described yields animal feeds (distiller's grain, gluten meal, gluten feed) and corn oil in addition to ethanol. How much of the CO_2 released should be charged to the ethanol production and how much to the by-products?

One possible way to estimate this allocation is based on product value. According to the U.S. Department of Agriculture (1988b), for the six-year average (1981-1986), in the wet milling process the by-products recouped 48.9% of the cost of corn. If we can assume that energy inputs can be allocated on the same basis of 48.9% by the by-products and 51.1% by ethanol, the net CO_2 release attributable to burning ethanol from corn is estimated at 8.14 kg C/10^9 J. We urge again that this number be used with great care. This analysis, however, establishes clearly that ethanol from corn is not now a CO_2-free source of energy and that the net CO_2 contribution is a significant fraction of that associated with refined petroleum products. If ethanol production were to be undertaken at a much larger scale, it is likely that by-product yield would become a smaller fraction of the total and that supplemental fossil-fuel use would decline as the corn plant was used to supply part of the process energy. This could significantly alter the CO_2 emissions coefficient.

Table 1. Energy consumption and CO_2 emissions in ethanol production (10^6 J per kg ethanol unless shown otherwise)

	Total energy	Liquid fuel	Natural gas	Coal[a]	Non-fossil-generated electricity[a]	Other[b]
			Energy consumption			
Agriculture						
Direct uses	2.60	2.60				
Fertilizer	5.68		5.03	0.49	0.16	
Other	0.57			0.18	0.06	0.33
Subtotal	8.85	2.60	5.03	0.67	0.22	0.33
Milling and Conversion	14.11			3.30[c] 9.71[d]	1.10	
Total Energy	22.96	2.60	5.03	3.97[c] 9.71[d]	1.32	0.33
			CO_2 Emissions			
C (as CO_2) (kg C/kg ethanol)	0.471	0.058	0.069	0.098[c]		0.007 0.239[d]
C (as CO_2) (kg C/10^9 J ethanol)	15.86 (8.10 allocated to ethanol)[e] (7.76 allocated to co-products)[e]					

[a]Assuming that 75% of electricity is from coal-fired generating plants and the other 25% is from non-fossil generating plants (e.g., hydro, nuclear).

[b]Energy embodied in pesticides and for irrigation and miscellaneous uses.

[c]Coal-fired electricity.

[d]Coal-generated process heat.

[e]Allocation based on product value.

APPENDIX

INTRODUCTION

To determine the net contribution of CO_2 to the atmosphere that results from the production and use of ethanol from corn grain, one must examine the energy inputs used for the production of corn and for the process of converting corn into ethanol. Energy used in the conversion process is estimated to be 1.6 to 2.5 times greater than that used for the production of corn. About 2.6×10^6 kJ are used, on average, to produce a metric ton of corn (63,000 Btu/bu[1]), and 4.1×10^6 to 6.2×10^6 kJ are used in the conversion process. (These estimates are based on 1987 data; with 1988 data the estimate would be considerably higher because of the drought-induced reduction in corn yields.) A liter of ethanol contains about 23,450 kJ, so the energy input to produce a liter of ethanol plus by-products is about 77 to 101% of the energy contained in a liter of ethanol (Table A-1.). Most of the energy input is from coal (60 to 69%, assuming that 75% of the electricity is generated with coal).

[1]A bushel of corn is 56 pounds.

Table A-1. Energy inputs to produce ethanol (kJ/L)[a]

	Total	Liquid fuel	Natural gas	Coal	Electricity	Other[b]
Corn production	6990	2060	3980		700	250
Conversion	11130 to 16700			7650 to 13220	3480	
Total	18120 to 23690	2060	3980	7650 to 13220	4180	250

[a]Assumes 372 liters of ethanol/metric ton of corn (2.5 gal of ethanol/bu of corn).
[b]Energy embodied in pesticides, irrigation, and miscellaneous.

Corn can be run through either a dry or wet milling process to produce ethanol. (It is also possible to use a whole-grain milling process.) About 7.5×10^6 metric tons of corn were used to produce ethanol in the 12 month period beginning September 1, 1986, of which about 40% was dry milled and 60% wet milled (USDA 1988c). Energy consumption in the two milling processes is quite similar and for this analysis they are assumed to be the same (Weinblatt et al. 1982). (Other recent reports have not distinguished between energy consumption in the two processes [National Advisory Panel on Cost-Effectiveness of Fuel Ethanol Production, 1987; U.S. Department of Agriculture 1988b].)

ASSUMPTIONS

In this study it is assumed that whenever electricity is used, 10,960 kJ of primary energy were required to produce 1 kWh of electricity (10,400 Btu/kWh). Ethanol contains 23,450 kJ/L; diesel fuel, 38,955 kJ/L; gasoline, 34,780 kJ/L; LP gas 26,430 kJ/L; and natural gas, 38,020 kJ/m^3.

CORN PRODUCTION

The energy consumption figures for corn are estimated for an average unit of land in the United States. There are wide regional differences in the consumption of energy per unit of corn produced, primarily a result of the amount of energy that is used for irrigation. Most corn is produced without irrigation. It was estimated that in 1978 it required almost three times as much energy to produce a unit of corn in Kansas as it did in Wisconsin (Weinblatt et al. 1982). Energy consumed also depends on the crop rotation sequence. In the Corn Belt, where the majority of corn is produced in the United States, if corn follows soybeans, then machinery requirements and use of insecticides and nitrogen fertilizer are reduced. For example, in Iowa about 34 kg less nitrogen fertilizer per hectare is required (Duffy 1987).

Two comprehensive studies on energy use in U.S. agriculture were made in the 1970s for the years 1974 and 1978 (U.S. Department of Agriculture 1980, Federal Energy Administration and U.S. Department of Agriculture 1976). Since these studies were done, crop production has changed, becoming more energy-efficient and more cost-efficient. Output has increased and energy consumption has decreased. Corn yields averaged 4.5, 6.3, and 7.5 metric tons/ha (72, 101, and 119 bu/acre) in 1974, 1978, and 1987, respectively (USDA 1988d). Total energy consumption for crop production was 1.89×10^{18} J (1.79 quads) in 1974 and 1.92×10^{18} J (1.82 quads) in 1978.

In the report by Weinblatt et al. (1982), energy consumption per unit area for Wisconsin is estimated for 1978. We assume that, except for irrigation, the distribution of energy used for corn production in Wisconsin is typical for the United States. Field operations and farm vehicles (using diesel, gasoline, and a small amount of LP gas) accounted for 35.4% of total energy consumption; grain handling and drying (using LP gas and a small amount, 5%, of electricity) accounted for 5.8%; fertilizers accounted for 52.2%, and others (irrigation, pesticides, and miscellaneous) accounted for 6.4%. Liquid fuels accounted for about 41% of total energy consumption. Fertilizers and liquid fuels together accounted for 93.6% of total energy consumption for corn in Wisconsin. Irrigation accounted for only 14%

of total energy consumption in crop production in 1978. Therefore, fertilizers and liquid fuels will be the primary focus in updating the estimate of energy consumption for corn production.

The 1974 USDA study indicates that corn used 27.9% of total energy used for crop production in the United States. Adjusting this to reflect the change in corn acreage in the U.S. relative to other crops, we estimate that corn used 29.7% of total energy consumed in 1978. On a per-hectare basis, this represents 19.60×10^6 kJ. This is 21.3% higher than the value for Wisconsin for 1978. Values taken from the Wisconsin data will thus be adjusted upward by 21.3% to reflect that the Wisconsin values are below the national average. Between 1978 and 1987 liquid-fuel use in agriculture fell dramatically (Table A-2.). When calculated on an energy basis, liquid-fuel use fell 31.7% between 1978 and 1987. When adjusted for the change in the area planted, use fell 29.4%. Liquid-fuel use was 6.69×10^6 kJ/ha (2.57×10^6 Btu/acre) in Wisconsin in 1978. Adjusting this number upward by 21.3% to reflect the U.S. average and downward by 29.4% to reflect the decrease in fuel use between 1978 and 1987, liquid fuel consumption is calculated to be 5.73×10^6 kJ/ha. "Other" use is estimated at 6.4% of 19.60×10^6 kJ or 1.25×10^6 kJ/ha.

Table A-2. Liquid fuel use in agriculture (billions of liters)

	Year	
Fuel	1978	1987
Gasoline	13.6	6.8
Diesel	12.1	11.0
LP gas	4.9	2.6

Source: U.S. Department of Agriculture, 1987.

Fertilizer data are available that give average per-area use in 1987 for corn (U.S. Department of Agriculture 1988a). Nitrogen, P_2O_5, and K_2O were applied at rates of 153, 72, and 95 kg/ha (137, 64, and 85 lbs/acre), respectively. Energy invested in these fertilizers is assumed to be 72,265, 12,920 and 9945 kJ/kg (31,100, 5,560, and 4,280 Btu/lb) of N, P_2O_5, and K_2O, respectively (Weinblatt et al. 1982). Weinblatt et al. (1982) indicate that these figures were used in the comprehensive 1974 and 1978 studies previously referred to. Data from The Fertilizer Handbook (Fertilizer Institute 1982) indicate that energy invested in a kg of nitrogen in ammonia is about 55,750 kJ and in urea (a nitrogen fertilizer) about 78,980 kJ. A report by Dvoskin et al. (1978) uses a figure of about 60,400 kJ/kg of nitrogen. The Office of Technology Assessment indicates that the escalation in energy prices in the 1970s spurred efforts to design new energy-efficient fertilizer plants and to retrofit existing plants to make them more energy efficient (U.S. Congress, Office of Technology Assessment 1986). The report also indicates that new urea processes can provide production-energy savings of

25 to 50% and that a new phosphoric acid process promises energy savings. For this report we used the data from Weinblatt et al. (1982). Energy data also need to be divided into the various fuel sources. Although Weinblatt et al. do not provide a breakdown between natural gas and electricity use for fertilizers, Dvoskin et al. (1978) do. Their data indicate that 2.65, 64.66, and 61.23% of the energy for N, P_2O_5, and K_2O is from electricity and the remainder is from natural gas. Fertilizer used on the average hectare of corn contains 12.52 x 10^6 kJ of energy, of which 11.09 x 10^6 kJ (88.5%) is from natural gas and 1.43 x 10^6 kJ (11.5%) is to produce electricity. About 85% of the energy for fertilizers is for nitrogen fertilizers.

The amount and type of energy used for the production of corn is summarized in Table A-3. The total is 19.51 x 10^6 kJ/ha (7.49 x 10^6 Btu/acre), only slightly less than the 19.87 and 19.61 x 10^6 kJ/ha used in 1974 and 1978, respectively. The mix of energy sources has changed, however, with more natural gas and less liquid fuels being consumed. In 1987 corn yields averaged 7.49 metric tons/ha (119.4 bu/acre). Energy use therefore averaged 2.60 x 10^6 kJ/metric ton.

Table A-3. Energy consumption for the production of corn (millions of kJ/ha hectare)

	Total energy	Liquid fuel	Natural gas	Electricity	Other
Liquid Fuel	5.73	5.73			
Fertilizers	12.52		11.09	1.43	
Other[a]	1.25			0.52	0.73
Total	19.51	5.73	11.09	1.95	0.73

[a]Energy embodied in pesticides and for irrigation and miscellaneous uses.

THE CONVERSION PROCESS

Estimates made for the amount of energy consumed during the conversion of corn grain into ethanol include energy consumption for all the necessary steps from grinding through drying the feed by-products and distillation. Estimates made for the amount of energy consumed in the process of converting corn into ethanol have varied widely. Data are difficult to obtain, the technology has improved over time, and energy use has decreased over time. Some estimates of total energy consumption are listed. They include electricity, which is assumed to require 10,960 kJ/kWh (10,400 Btu/kWh). The Office of Technology

Assessment lists energy consumption at 15,320 kJ/L (55,000 Btu/gal) of ethanol, including 0.34 kWh of electricity/L (U.S. Congress, Office of Technology Assessment 1980). Weinblatt et al. (1982) list energy consumption at 17,125 kJ/L (61,500 Btu/gal) for dry milling and 16,650 kJ/L (59,800 Btu/gal) for wet milling, including 0.34 kWh for either milling process. Donaldson and Culberson (1983) indicate energy consumption at approximately 8,350 kJ/L (30,000 Btu/gal). Data provided from a report by Chem Systems (1983) indicate energy consumption of 18,800 kJ/L (67,500 Btu/gal), including 0.16 kWh of electricity, for a whole-grain milling process. Data from Keim (1983) indicate energy consumption of 15,320 to 17,820 kJ/L (55,000 to 64,000 Btu/gal), including 0.24 kWh of electricity, for a whole-grain milling process and 10,580 to 13,370 kJ/L (38,000 to 48,000 Btu/gal), including 0.32 kWh of electricity, for a wet milling process. More recently a report by the National Advisory Panel on Cost-Effectiveness of Fuel Ethanol Production (1987) states that between 11,130 and 16,700 kilojoules of energy are required per liter of ethanol (40,000 to 60,000 Btu per gallon). A report by the U.S. Department of Agriculture (1988b) compares an average milling plant to a state-of-the-art plant that uses the best available commercial components. The current average plant has energy costs of $0.045/L ($0.17/gal), while the state-of-the-art plant has energy costs of only $0.029/L ($0.11/gal). In this study, it is assumed that between 11,130 and 16,700 kJ/L, including 7,650 to 13,220 kJ of steam and 0.32 kWh of electricity, are required and that all of the steam required is produced with coal.

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ADDENDUM

In a paper presented at the 1989 National Conference on "Clear Air Issues and America's Motor Fuel Business" S. P. Ho of Amoco Oil Company (Ho 1989) reported that he had reviewed our paper and "found a number of errors and questionable assumptions which lead to erroneous conclusions." According to Ho, the major errors are five: (1) misrepresenting corn yield, (2) misrepresenting process energy for the corn-to-ethanol conversion, (3) giving "very large and erroneous CO_2 credits" for ethanol by-products, (4) inconsistent use of higher and lower fuel heating values, and (5) assuming that CO_2 emissions from electric power generation are at 75% of the rate that would prevail if all electric power were generated by coal combustion. Although we wrote in opening that the energy input to ethanol from corn "is highly variable for at least three principal reasons: (1) geographic variability in corn yield and agricultural practice, (2) temporal variability in corn yield, due largely to differences in weather, and (3) temporal changes due to changes in process and process efficiency;" and in closing that "we urge again that this number be used with great care;" and in between provided a wide range of values for corn yield and process energy and their impact on our calculation; it is worth examining Ho's comments in detail (if not in order).

Ho notes that our corn yield was based on the 1987 peak of 7.49 metric tons per "harvested" hectare (119.4 bushels per "harvested" acre) whereas he would choose a 5-year mean yield of 5.65 metric tons per "planted" hectare (90 bushels per "planted" acre). At the time of our calculation we chose data for the most recently completed year, 1987, recognizing that 1986 and 1987 were peak years but that mean yields had been increasing with time. Data from 1968 to 1989 reveal a linear increase with time of 0.10 metric tons per hectare per year (1.6 bushels per acre per year) with the best fit line passing through 7.10 metric tons per harvested hectare (113.3 bushels per harvested acre) in 1989. The 5-year mean for 1985-1989 is 7.00 metric tons per harvested hectare (111.6 bushels per harvested acre) (including the very poor drought year of 1988). Ho's insistence on using "planted" area does not acknowledge that over the last five years only 89.4% of planted area has been harvested for grain. Of the remaining area, 9.8% was for silage and forage (1.0% was abandoned) and it does not seem appropriate to average these in at zero yield. Although 7.49 metric tons per hectare (119 bushels per acre) is admittedly a high yield for corn, four of the last five years have exceeded 7.31, and 7.49 does not seem inappropriate for the near future. The point of Ho and others is well taken that if corn planting were to be dramatically expanded for ethanol production, that decreasing land quality at the margin could result in some decrease in mean yield. Although the breakdown does not seem to match perfectly, the total energy input to corn production (on a basis of energy input per unit volume of ethanol) for Ho's calculations and for ours match very well once adjusted for differences in corn yield.

Ho envisions that we have used higher and lower heating values (HHV and LHV, respectively) inconsistently in order to make CO_2 emissions from ethanol appear lower with respect to gasoline. In fact, we have used higher heating values throughout our calculations. Whether higher or lower heating values are used in these calculations is merely a matter of accounting convention and the only important consideration is consistency. If one inventories energy inputs according to the higher heating values of the fuels, it is appropriate that these be converted to CO_2 emissions using factors for CO_2 per unit energy on a HHV basis. Whether or not the difference between HHV and LHV is accessible to motor vehicles, the use of CO_2-per-unit-energy conversion factors based on LHV will exaggerate CO_2 emissions if the fuel input inventory was based on fuel HHV. Although the difference is small, even using Ho's statement (p. 6) "on an energy content basis alone, each gallon of ethanol requires slightly more energy (80 MBtu) to produce than the amount it generates (76 MBtu)" is incorrect if the energy inputs to ethanol were based on HHV and the output on LHV. Although we can not tell for certain from his circulated manuscript, Ho appears to have committed this error. Ho's confusion with our numbers results from his focus on ethanol as currently used as a fuel supplement in gasoline engines. Our calculation stopped at the point of liquid fuel production and compared ethanol with a mean for "refined petroleum products" (e.g., the calculation was based on crude oil) without implying how the fuel would be used. Ho correctly asserts that if the comparison is to be with gasoline in current engines then the value for gasoline should be used (20.40 kg C/10^9 J on a HHV basis) and we should consider giving ethanol additional credits for improved combustion efficiency and for octane enhancement. This is certainly the comparison of primary current interest and Ho's extension of the calculation through end-use is a valuable addition. Ho's text suggests that even minor adjustments in fuel blending practice and carburetor adjustment could yield CO_2-emissions benefits if optimized for ethanol-blended motor fuels. Neither we nor Ho have explored the longer-term potential CO_2 implications of ethanol as a transportation fuel in an optimal engine. (Likewise, neither we nor Ho have tried to evaluate fugitive emissions of other greenhouse gases related to either gasoline or ethanol production and consumption).

The Congressional Research Service (Segal 1989) used our numbers to construct a direct comparison between ethanol and gasoline as motor fuels. The unfortunate step is that we did not communicate sufficiently with the Congressional Research Service staff and their calculation--based on lower heating values--did not convert our number for production inputs to ethanol to an LHV basis. Had they done so, their conclusion that "ethanol yields 24 percent as much CO_2 as gasoline on a volume basis, or 37 percent as much CO_2 as gasoline on an energy content basis" would have read 27% and 41% respectively, and the reduction of CO_2 emissions for a 10% ethanol blend with respect to 100% gasoline would have read 3.9% rather than 4.2%, on an energy content basis. Considering the other uncertainties in these calculations, this becomes an important, but not numerically significant, distinction.

Ho objects, also, to our converting electricity to CO_2 at 75% the rate that would characterize electricity from coal. Data from the Energy Information Administration of DOE (U.S. DOE 1989) show that for the 5-year period 1984 through 1988, electricity was generated in the U.S. as follows: coal=56.4%, petroleum=4.9%, natural gas=10.8% (total fossil=72.1%), hydroelectric=10.8%, nuclear=16.7%, other=0.4%. There is no question that some CO_2 is emitted during nuclear fuel mining and processing but this is on the order of 3 percent of emissions from a coal-fired plant (Mortimer 1989). It is also true that all energy technologies have energy and CO_2 emissions embodied in physical plant, but this is a factor for which we have charged none of the energy technologies. On balance, it appears that charging total electricity at 75% of the CO_2 rate of coal-fired plants probably results in a small exaggeration of the CO_2 attributable to ethanol in the U.S. For countries more dependent on nuclear- or hydro-electricity, the CO_2 attributable to ethanol would be less.

Ho asserts that we have used unreasonably low numbers for energy consumed in the corn-to-ethanol conversion process. Our text cites seven earlier analyses and then focuses on a range published by the National Advisory Panel on Cost-Effectiveness of Fuel Ethanol Production which covers most of the values from the other studies. In our calculations "we use 14,110 kJ/kg (40,000 Btu/gal) (the low end of this range), but recognize that the current value could often be 50% larger." One of our citations is to a U.S. Department of

Agriculture study which suggests that current state-of-the-art plants have only 65% of the energy cost per kg of ethanol as does the current average plant. It seems likely to us that an expanding ethanol industry would more nearly resemble current state-of-the-art than current average plants. Our tour of a modern ethanol facility suggests that great strides have already been achieved toward maximizing energy-use efficiency but the plant we visited is optimized for production of corn syrup and ethanol is treated as a swing product as the demand for corn syrup fluctuates. Ho's statement is that "conversion of corn to ethanol requires 57 MBtu (20,110 kJ/kg) energy equivalent...for process energy..." a value which is within, although near the high side, of the range we cited.

Telephone interviews with a number of individuals and corporations involved in the ethanol fuel business find that energy consumption numbers for existing plants are most often held as proprietary information. Virtually all we have talked to acknowledge that energy consumption would be reduced significantly if state-of-the-art technology were fully employed. We believe that 14,110 kJ/kg (40,000 Btu/gal) ethanol--including full finishing of by-products--is not being achieved in existing, operating plants but is within design limits for an energy-efficient, current plant with superior maintenance, and is an achievable target for a growing industry. The top end of our cited range, 21,165 kJ/kg (60,000 Btu/gal), is clearly an upper limit and should be considered a worst-case for energy-conscious future plants.

In responding to the difference between the value we chose to use for energy use in conversion and that chosen by Ho, the U.S. Renewable Fuels Association (1989) has declined to release proprietary data but has chosen to carry out their calculations using the average of Ho's value and ours, i.e., 17,110 kJ/kg (48,500 Btu/gal). Based on qualitative discussions with other industry sources, we believe this is a reasonable value to represent the best of current practice in the United States. In retrospect, we feel that we would have done better in our original calculations if we had used a range of values rather than selecting an optimum value and trying to verbalize the uncertainty involved. With this perspective we have revised our calculations below to show 17,110 $\pm$ 3,000 kJ/kg (48,500 $\pm$ 8,500 Btu/gal) as the energy requirement for conversion of corn to ethanol. It should be noted that if this efficient facility depends on a power plant that co-generates steam and electricity then, in the current situation, this probably means a higher fraction of coal-fired electricity--although a gas-fired system would mean somewhat lower CO_2 emissions.

The final question posed by Ho, and one raised in our original text and by other readers as well, is how best to assign energy inputs (and CO_2 emissions) among the various products which emerge from an ethanol production plant. Our initial suggestion was that this could be done on the basis of product value, and since 51.1% of the cost of corn (1981-1986 average) was born by ethanol, we assigned 51.1% of process CO_2 emissions to the ethanol stream. Our cited reference had observed that "much controversy over the cost of ethanol production is due to its dependence on highly variable corn and by-product prices" (U.S. Department of Agriculture 1988b, p.5), and it is clear that how one chooses to assign by-product credits will greatly affect assigned CO_2 emissions. Ho gives the ethanol conversion process two credits, one of 1060 kJ/kg (3000 Btu/gal) of ethanol for the energy content of fusel oil and aldehydes produced, and one of 2470 kJ/kg (7000 Btu/gal) of ethanol for the energy that would be required in the production of soybean meal to provide protein equivalent to that of the DDGS (distiller's dried grain plus solubles) produced as an ethanol by-product.

For 25.4 kg (1 bushel) of corn the principal by-products from the wet milling process are gluten meal, (60% protein) 1.13 kg at \$260/metric ton (2.5 pounds at \$236/ton)=\$0.30; gluten feed (21% protein), 5.67 kg at \$113.50/metric ton (12.5 pounds at \$103/ton)=\$0.64;

and corn oil, 0.73 kg at \$0.54/kg (1.6 pounds at \$0.245/pound)=\$0.39; where the values are the 1981-1986 averages from the U.S. Department of Agriculture (1988b) and the by-products cover 48.9% of the cost of the corn. The Archers Daniels Midland Annual Report for 1989 lists 18 additional products from corn processing but these three (plus food grade CO_2) dominate the economics and the mass flows. Although ethanol by-product feeds serve primarily as a livestock protein supplement and displace soybean meal, they substitute for some corn as well. The analysis of the U.S. Department of Agriculture (1988b) concluded that (p.36) "The primary effects of changes in ethanol production are played out in the adjustments between the production and use of corn and soybeans and the raising of livestock." They suggest that a large ethanol program would reduce by-product credits and increase ethanol production costs.

Whereas our initial calculation of by-product credits was based on cash flows, on reflection, for this calculation, it does seem appropriate to keep CO_2 as the common currency. The question then focuses on the CO_2 implications of alternate means of meeting the by-product market rather than on the financial credits, and the answer does not imply a relationship between dollar and CO_2 costs. In short, we recognize the merits of the approach suggested by Ho and by D. Bartus at the EPA. The important consideration is to insure full and complete CO_2 accounting for all processing of all by-product substitutes. This calculation results in a by-product credit which is considerably less than we had calculated on economic considerations. This, too, is not a fully satisfactory calculation because it does not actually allocate CO_2 emissions among products but assumes instead that ethanol production is the primary objective and then gives a CO_2 credit for the CO_2-minimum way of producing by-product substitutes; but it does seem to be an appropriate approach for the current purpose.

Recognizing that it would require a full programming model to evaluate the complete replacement of ethanol by-products, for this calculation we take the simplifying assumption that ethanol by-products substitute only for soybean meal and on a protein basis alone. There are some counterbalancing effects since, for example, producing soybean meal yields an excess of vegetable oil while, in the opposite direction, we are taking no credit for the feed value of ethanol by-products in excess of their protein content. This is expected to produce a minimum by-product credit.

Taking the same approach as used earlier for corn, along with fertilizer-use values of 3.36, 13.17 and 23.53 kg/ha (3, 11.75, and 21 pounds/acre) for nitrogen, P_2O_5 and K_2O, respectively, produces the energy-use values shown in Table B-1. If the yield for soybeans is taken as 2.27 metric tons/hectare (33.7 bu/acre) (1985-1987 average U.S. Department of Agriculture 1989b), the farming energy inputs per kg of soybeans will be 1/2270 times the values in Table B-1. Processing of soybeans to meal and vegetable oil requires 1597 kJ/kg (41,240 Btu/bushel) of which 524 kJ are to produce electricity and 1074 kJ are to produce steam. If a kg of soybeans yields 0.792 kg (47.5 lb/bu) of soybean meal with 44% protein content then it takes 0.721 kg of soybeans to produce feed protein to replace the by-products from one kg of ethanol, and the by-product credit, per kg of ethanol, amounts to 2606 kJ (7390 Btu/gal). This is allocated as 1046 kJ from liquid fuels, 154 kJ from natural gas, 772 kJ from coal for steam, 388 kJ from electricity from coal, 129 kJ from electricity from other (non-fossil) sources, and 116 kJ other (assumed to be liquids) sources.

Table B-1. Energy consumption for the production of soybeans (millions of kJ/ha)

	Total energy	Liquid fuel	Natural gas	Electricity	Other
Liquid Fuel	3.26	3.26			
Fertilizer	0.65		0.39	0.26	
Other	0.67	0.03	0.10	0.18	0.36
Total	4.58	3.29	0.49	0.44	0.36

This 2606 kJ/kg ethanol is equivalent to 0.057 kg C/kg ethanol or 1.90 kg C/10^9 J ethanol and represents the ethanol by-product credit.

Calculations sent to us by David Bartus of the U.S. Environmental Protection Agency led us to discover a typographical error in reporting application rates for fertilizers in our original draft. On page 10, text line 6, the application rates of nitrogen, P_2O_5 and K_2O should have been shown as 148 kg/ha (132lb/acre), 68 kg/ha (61lb/acre), and 95 kg/ha (85 lbs/acre) respectively. All subsequent calculations in the original text were based on these values. In rechecking these values we were reminded that these are mean application rates for areas over which fertilizer was applied and do not include consideration of the fraction of corn planting which received no fertilizer at all. In fact, only 96% of the area planted in corn receives nitrogen fertilizer, 83% receives phosphorous, and 75% receives potassium (U.S. Department of Agriculture 1988a). Table B-2 shows reduced values for energy use for fertilizer because it is now based on fertilizer use for all harvested acres, not just for those areas that were actually fertilized.

Note that values used for liquid fuel use in agriculture during 1987 (Table A-2) were originally estimated from 1986 and earlier data. Now that 1987 data are available, (U.S. Department of Agriculture 1989a) the values are in fact 4.7% less than we had estimated and the numbers in Table B-2 reflect this change also.

With these lengthy reconsiderations, we have recalculated our original Table 1 and present the results in Table B-2. The net CO_2 emissions from the production and consumption of ethanol fuels are shown to be 18.08 ± 2.47 kg C/10^9 J, prior to assignment of by-product credits. This is 14% higher than originally reported but is still marginally lower than the comparable value for gasoline, even without by-product or performance credits. The upper bound of this calculation is nearly identical to the net CO_2 emissions value for gasoline. Our earlier comments about uncertainty and variability are no less applicable now and these numbers should not be used without that awareness. We point out again, that these calculations are based at the margin of the current energy system and that the 18.08 kg C/10^9 J could be reduced to 12.74 Kg C/10^9 J if natural gas were used to fire a steam/electric co-generation facility for conversion of corn to ethanol, or to near 5 Kg C/10^9 J if that facility were fueled with uranium, wood, or other biomass grown on a sustained-yield basis.

With conservative CO_2 credits for ethanol by-products, based on CO_2 emissions from production and processing of alternate livestock protein, the CO_2 emissions attributable to the production and combustion of ethanol fuels at the margin of the current energy system sum to an estimated 16.18 kg C/10^9 J. Without evaluating how the fuels will be used, this is 73 percent of the comparable value for an average slate of refined liquid products from crude oil or 79 percent of the comparable value for gasoline.

To conclude, we reiterate from our original text "that ethanol from corn is not now a CO_2-free source of energy and that the net CO_2 contribution is a significant fraction of that associated with refined petroleum products". Despite numerical revisions based on reviewers responses to our initial computation, we continue to believe that, even at the margin of current practice, the use of ethanol as a replacement or supplemental fuel does result in a net decrease in CO_2 emissions. If ethanol is viewed alternatively as merely an energy carrier, it provides a low-CO_2 path for deriving a liquid transportation fuel from coal. To look further from current practice, net CO_2 emissions attributable to ethanol could be reduced significantly if process heat and electricity were obtained from natural gas rather than from coal burning, and even further if nuclear or biomass fuels were used in the conversion process.

Table B-2. Energy Consumption and CO_2 Emissions in ethanol production (10^6 J per kg Ethanol Unless Shown Otherwise)

	Total energy	Liquid fuel	Natural gas	Coal[a]	Non-fossil-generated electricity[a]	Other[b]
			Energy Consumption			
Agriculture						
Direct uses	2.49	2.49				
Fertilizer	5.33		4.79	0.41	0.13	
Other	0.57			0.18	0.06	0.33
Subtotal	8.38	2.49	4.79	0.58	0.19	0.33
Milling and Conversion	17.11 ± 3.00[e]			3.30[c] 12.71[d]	1.10	
Total Energy	25.49 ± 3.00	2.49	4.79	3.88[c] 12.71[d]	1.29	0.33
			CO_2 Emissions			
C (as CO_2) (kg C/kg ethanol)	0.538 ± .073	0.056	0.066	0.096[c] 0.313[d]		0.007
C (as CO_2) (kg C/10^9 J)	18.08 ± 2.47					
By-product credit (kg C/10^9 J)	1.90					
Total net carbon emission attributable to ethanol (kg C/10^9 J)	16.18 ± 2.47					

[a]Assuming that 75% of electricity is from coal-fired generating plants and the other 25% is from non-fossil generating plants (e.g., hydro, nuclear).

[b]Energy embodied in pesticides and for irrigation and miscellaneous uses.

[c]Coal-fired electricity.

[d]Coal-generated process heat.

[e]We do not imply that this is the only source of uncertainty in these calculations, but rather that this number alone cannot be attributed to generally accepted, published sources.

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