Ethanol Fuels: Energy Security, Economics, and the Environment

DAVID PIMENTEL

Department of Entomology
College of Agriculture and Life Sciences
Cornell University
Ithaca, NY 14853-0999 USA

Abstract *Problems of fuel ethanol production have been the subject of numerous reports, including this analysis. The conclusions are that ethanol: does not improve U.S. energy security; is uneconomical; is not a renewable energy source; and increases environmental degradation. Ethanol production is wasteful of energy resources and does not increase energy security. Considerably more energy, much of it high-grade fossil fuels, is required to produce ethanol than is available in the energy output. About 72% more energy is used to 'produce a gallon of ethanol than the energy in a gallon of ethanol. Ethanol production from corn is not renewable energy. Its production uses more non-renewable fossil energy resources in growing the corn and in the fermentation/distillation process than is produced as ethanol energy. Ethanol produced from corn and other food crops is also an unreliable and therefore a non-secure source of energy, because of the likelihood of uncontrollable climatic fluctuations, particularly droughts which reduce crop yields. The expected priority for corn and other food crops would be for food and feed. Increasing ethanol production would increase degradation of agricultural land and water and pollute the environment. In U.S. corn production, soil erodes some 18-times faster than soil is reformed, and, where irrigated, corn production mines water faster than recharge of aquifers. Increasing the cost of food and diverting human food resources to the costly and inefficient production of ethanol fuel raise major ethical questions. These occur at a time when more food is needed to meet the basic needs of a rapidly growing world population.*

Keywords: ethanol, food, energy, environment, pollution.

Introduction

Numerous reports have concluded that ethanol production does not provide energy security, is not a renewable energy source, is uneconomical, and causes environmental degradation (ERAB, 1980, 1981; USDA, 1986; Dovring, 1988; Pimentel et al., 1989; Walls et al., 1989; Kane et al., 1989; Sparks Commodities, 1990). Related to these findings, a recent report by the U.S. General Accounting Office (GAO) (1990) analysed tax costs and federal farm program expenditures associated with projected increased ethanol production. The GAO (1990) report concluded that: (1) increasing ethanol production would greatly increase tax-subsidy expenditures; (2) no projections could be made concerning any net federal budget savings from increasing ethanol production; and (3) an estimate of any overall federal budget impact was precluded because of the uncertainties about production economics for both ethanol and gasoline (GAO, 1990: 25).[1] Also, the report indicated that it was not possible to calculate how much higher the subsidies might have to be increased to encourage expansion of ethanol production.

Clearly, conclusions drawn about the benefits and costs of ethanol production will be incomplete or misleading if only a part of the total system is assessed. The objective of this analysis is to update and assess all the recognized factors that operate in ethanol production. These include the direct costs in terms of energy and dollars of producing the corn feedstock as well as in the fermentation/distillation processes. Additional costs accrue from federal and state subsidies, plus costs associated with environmental degradation that occur during the entire production system. Decisions about the practicality of ethanol production in the United States will affect the nation's energy security, its agricultural system, economy, and the environment, as well as government and consumer expenditures. Ethical questions involved in converting human food into fuel also deserve serious consideration.

Energy Balance

Ethanol production is energy inefficient, requiring considerably more energy input than is contained in the ethanol produced.

The conversion of corn and some other food/feed crops into ethanol by fermentation is a well-known and established technology. The yield from a bushel of corn in a large plant is about 2.5 gallons of ethanol.

The production of corn in the United States requires significant energy and dollar inputs. Indeed, growing corn is a major energy and dollar cost of producing ethanol (Tables 1 and 2). For example, to produce an average of 110 bu./acre of corn using conventional production technology requires about 137 gallons of gasoline equivalents (Table 1) and costs about $280 (USDA, 1989a; Pimentel, 1989). Most of the energy inputs in corn production are oil, natural gas, and/or other high grade fuels. Fertilizers and mechanization account for about two-thirds of the energy inputs for corn production (Table 1). The 2.8 million BTU input shown in Table 1 for only partial irrigation is an additional factor, but is a relatively small input. However, when corn is produced under complete irrigation, the energy input for irrigation is more than three-fold all the energy inputs for producing rainfed corn (Batty and Keller, 1980; Pimentel and Burgess, 1980). About 16% of U.S. corn is grown under irrigation (FEA, 1976; USDA, 1989a) and this is reflected in Table 1.

Table 1
Energy inputs for corn production in the United States (modified after Pimentel and Wen, 1990).

Inputs	Quantity/Acre	BTU/A x 10^3
Labour	4 hr	0
Machinery	50 lb	1,630
Gasoline	4.3 gal.	520
Diesel	8.0 gal.	1,080
Irrigation	2,840 x 10^3 BTU	2,840
Electricity	14 kwh	144
Nitrogen	136 lb	5,107
Phosphorus	67 lb	757
Potassium	86 lb	384
Lime	380 lb	214
Seeds	19 lb	832
Insecticides	1 lb	160
Herbicides	3.6 lb	640
Drying	100 bu.	1,970
Transport	280 lb	145
Total		16,423

Corn yield = 110 bu./A

Table 2
Inputs per gallon of ethanol.

Inputs	Pounds	BTU	Dollars
Corn	22.4	56,720[a]	$1.02[f]
Transport	22.4	610[b]	0.12
Stain. Steel	0.05[c]	1,348[c]	0.04
Steel	0.10[c]	2,106[c]	0.04
Cement	0.27[c]	909[c]	0.04
Plant, other	--	2,800[d]	0.28[g]
Water	1,279.00[c]	1,364[c]	0.08
Electricity	0.5 kWh[c]	5,160	0.05[h]
Fuel	--	60,000[e]	0.15[i]
Operating, other	--	--	0.12[j]
Total		131,017	$1.94

Output: 1 gallon of ethanol = 76,000 BTU.
[a] = Table 1.
[b] = Estimated transport.
[c] = Slesser and Lewis (1979).
[d] = Doering, (1980).
[e] = ERAB (1980); NAP (1987).
[f] = Bushel of corn = $2.55 (USDA, 1989a).
[g] = Portion of capital costs based on $0.40/gal. (Walls et al., 1989).
[h] = NAP (1987).
[i] = Using natural gas or fuel oil would raise this price to $0.35/gal. (NAP, 1987).
[j] = Portion of operating costs based on $0.40/gal. (Walls et al., 1989).

Once corn is harvested three additional energy expenditures contribute to the total costs of the conversion process. These include transport to the ethanol plant, energy expended relating to capital equipment requirements, and plant operations (Table 2).

The average costs in terms of energy and dollars for a large (60–70 million gallon/yr.) modern ethanol plant are listed in Table 2. The largest energy inputs are for corn production and fuel energy used in the fermentation/distillation process. The total energy input to produce one gallon of ethanol is 131,017 BTU. However, one gallon of ethanol has an energy value of only 76,000 BTU. Thus, a net energy loss of 55,017 BTU occurs for each gallon of ethanol produced. Put another way, about 72% more energy is required to produce a gallon of ethanol than the energy that is in a gallon of ethanol (OTA, 1990).[2]

About 53% of the cost of producing ethanol ($1.94/gal.) in a large plant is for the corn feedstock itself (Table 2). This cost is offset in part by the by-products produced, including dry distillers' grains (DDG) made from dry-milling that can be fed primarily to cattle (NAS, 1981). Wet-milling ethanol plants produce such products as corn gluten meal, gluten feed, and oil. Sales of the by-products offset the costs of ethanol production an average of $0.50/gal. for dry-milling and $0.61/gal. for wet-milling (Walls et al., 1989). However, these price values for the by-products would most likely decline as the by-products saturate the market. Moreover, the protein produced in ethanol by-products is expensive compared with alternate sources of protein, like soybeans. The price of protein per pound in DDG for livestock feed ranges between $0.33 and $0.41, compared with soybean protein at only $0.25 per pound (Glaze et al., 1982; USDA, 1989a).

The energy credit for the dry distillers' grain which can be fed to cattle ranges from 11,000 BTU/gal. (ERAB, 1980) to 32,000 BTU/gal. (calculated based on protein value as livestock feed). Thus, the total energy inputs in Table 2 for producing ethanol can be partially offset by 11,000 to 32,000 BTUs. The resulting energy input-output comparison, however, is still negative. Even when the BTUs in by-products are included, the energy output from ethanol production ranges from only 87,000 BTUs to 108,000 BTUs, compared with over 131,000 BTUs required to produce the ethanol.

Furthermore, most of the cost contributions from by-products are negated by the environmental pollution costs that are estimated to be $0.36/gal.[3] In U.S. corn production, soil erodes about 18-times faster than soil can be reformed (Lal and Stewart, 1990). In irrigated acreage, groundwater is being mined 25% faster than the recharge rate (USWRC, 1979). This shows that the environmental system in which corn is being produced is being rapidly degraded. Further it substantiates the finding that the U.S. corn production system is not sustainable for the future, unless major changes are made in the cultivation of this important food/feed crop. Hence, corn can not be considered a renewable resource.

About 850 million gallons of ethanol are currently produced in the United States each year (USDA, 1989b). This amount of ethanol provides less than 1% of the fuel utilized by U.S. automobiles (USBC, 1989). Therefore, even a major effort to more than double ethanol production from corn to 2 billion gallons would supply less than

2% of U.S. automobile fuel.

A vital factor, when considering the advisability of producing ethanol for automobiles, is the amount of cropland that is required to grow corn to fuel each automobile. To clarify this, the amount of cropland that is needed to fuel one automobile with ethanol was calculated. An average U.S. car travels about 10,000 miles/yr. and uses about 515 gallons of fuel (USBC, 1989). Although 110 bushels/acre of corn yield 275 gallons of ethanol, the equivalent in gasoline energy is only 174 gallons because ethanol has a much lower BTU content (76,000 BTU versus 120,000 BTU for gasoline). As shown above, there is a significant net energy loss in producing ethanol. However, even assuming *zero* or no energy charge for the fermentation and distillation process and charging *only* for the energy required to produce corn (Tables 1 and 2), the net fuel energy yield from one acre of corn is only 37 gallons (174 gal. minus 137 gal.). Thus to provide the 515 gal./car, about 14 acres of corn must be grown to fuel one car with ethanol for one year. In comparison, only 1.5 acres of crop land is currently used to feed each American (USDA, 1989a). Therefore, nearly nine-times more cropland would be required to fuel one car than is needed to feed one American.

Assuming a net production of 37 gallons of fuel per acre and if all cars in the United States were fuelled with ethanol, then a total of nearly 2 billion acres of cropland would be required to provide the corn feedstock. This amount of acreage totals more than four-times all the cropland that is actually and potentially available for all crops in the United States (USDA, 1989a).

Currently, to produce 850 million gallons of ethanol about 3 million acres or 5% of U.S. corn land is devoted to producing corn for ethanol (USDA, 1989a). If ethanol production were more than doubled to 2 billion gallons or tripled to 3 billion gallons, then the corn land required would be 7.3 million acres (13%) or 10.9 million acres (19%), respectively. Possibly this added cropland could be obtained from cropland that is currently idle (USDA, 1989a). However, this type of land is considered to be of marginal quality for crop production (Batie, 1983), increasing both the cost of producing corn and the cost of environmental degradation that occurs on marginal land.

Increasing the use of marginal land also increases the susceptibility of the corn crop to climate fluctuations, particularly droughts. For example, during 1988 a drought reduced the corn crop by about 30% (USDA, 1989a). These severe fluctuations in corn production occur periodically every four to five years. The major fluctuations in corn production clearly raise questions about relying on a corn/ethanol system for U.S. energy security. When there is a shortage of corn due to a drought, the expected priority for corn would be for food and feed.

Ethanol Economics

Ethanol costs substantially more to produce than it is worth in the market and its production has been sustained by large government subsidies.

The data in Table 2 and numerous other studies confirm that the dominant cost (53%) in ethanol production is the price of the corn feedstock. In this analysis, a value of $2.55/bu. corn was used (USDA, 1989a). However on average, corn costs more than $3.00/bu. to produce, when the farmers' fair wage is included (USDA, 1989a; Garst, 1990). The fermentation/distillation costs are relatively small compared with that of the corn feedstock (Table 2).

Based on current production technology and recent oil prices, ethanol costs substantially more to produce than it is worth in the market (USDA, 1986). Clearly, without subsidy, U.S. ethanol production would be reduced or cease, confirming the fact that basically ethanol production is uneconomical (Pimentel et al., 1989). Specifically, federal subsidies average $0.60/gal. and state subsidies average $0.19/gal. (EPA, 1990). When a credit of $0.61/gal. is given for by-products and the pollution costs of $0.36/gal. are taken into account, the total cost of a gallon of ethanol comes to $1.70. Because of the relatively low energy content of ethanol, 1.5 gallons of ethanol are the energy equivalent of a gallon of gasoline. This means a comparable cost for ethanol is $2.55/gal. Compared with the recent cost of producing gasoline which was about $0.60/gal., the $2.55/gal. is significantly higher.

At present federal and state subsidies for ethanol production total about $0.7 billion/yr. (EPA, 1990). More than doubling ethanol production to 2 billion gallons will require $1.6 billion/yr. in subsidies. If, however, ethanol production was more than doubled, corn prices would rise and price supports for corn production would decrease. According to GAO (1990) data, more than doubling ethanol production would reduce federal price supports (subsidies) to farmers by about $0.93 billion/yr. (or less if price supports decline faster or over a longer period of time than the GAO study assumed). Still the taxpayers would have to pay the remaining federal and state subsidies for ethanol that total about $0.7 billion/yr. On the other hand, subsidies might have to be increased to encourage the expansion of ethanol production (GAO, 1990). This would be expected because increased ethanol production will increase the price of the corn feedstock and other raw materials. Also, it should be noted that corn subsidies have been declining during the past three years and are projected to continue to decline (USDA, 1989a). Therefore, any reduction in price support payments would probably not be as large as some models have projected.

Actually, the real costs to the consumer would be greater than the conservative $0.7 billion/yr. needed to subsidize ethanol production because of increased corn prices. Higher corn prices translate into higher meat, milk, and egg prices (Sparks Commodities, 1990) because currently about 70% of the corn grain is fed to U.S. livestock (USDA, 1989a). Doubling ethanol production could be expected to inflate corn prices about 9% (GAO, 1990). Therefore consumers, in addition to paying tax dollars for ethanol subsidies, would be paying significantly higher food prices in the market place.

Environmental Impacts

Ethanol produced from corn causes environmental degradation from increased soil erosion and aquifer mining, from soil, water, and air pollution, and from increased emissions of global-warming gases.

Ethanol production, including both the growing of the corn and fermentation/distillation, adversely affects the quality of the environment in many ways. All these environmental problems cost the consumer and the nation and diminish the sustainability of U.S. agriculture for the future.

Corn is one of the major row crops that is causing serious soil erosion in the United States. Estimates are that about nine tons/acre of soil are eroded per year by rain and wind in corn production areas (Follett and Stewart, 1985; NAS, 1989a; Paoletti et al., 1989; Lal and Pierce, 1991). As mentioned, this rate of soil loss is 18-times faster than soil reformation (Lal and Stewart, 1990). To replace even a portion of the total soil nutrients and water that are lost as soil erodes, large amounts of fertilizers and water must be applied to maintain crop yields.

If the corn ethanol program were to be expanded, more marginal land would have to be put into production. Such land is more susceptible to soil erosion (Follett and Stewart, 1985), making it less productive than most other cropland. The result would be the expenditure of more fossil fuel-based inputs. Overall, the use of such land would be considerably more costly for corn production than corn produced on highly productive land.

At present more than 16% of corn grain production is irrigated and irrigation requires enormous amounts of energy. About 20% of the total energy expended in U.S. agriculture is for irrigation (FEA, 1976). Producing an acre of corn using irrigation requires more than three-times the energy as when the same corn yield is produced under rain-fed conditions (Batty and Keller, 1980; Pimentel and Burgess, 1980). Further, use of marginal lands often requires irrigation and other increased production costs. Another major problem associated with irrigation is the overdraft of water from aquifers, which are being mined about 25% faster than recharge rates (USWRC, 1979). The current level of irrigation used on corn is contributing to the water overdraft problem as well as other water quality problems, such as the salinization of land and rivers (NAS, 1989b).

In addition to being the largest user of fertilizers among all crops, corn production also is the largest user of insecticides and herbicides in the United States (USDA, 1989a). Unfortunately, substantial amounts of pesticides are washed and/or drift from the target area to contaminate adjoining terrestrial and aquatic ecosystems (Pimentel and Levitan, 1986). Monitoring for fertilizer and pesticide pollution in U.S. well water and groundwater costs the nation $2 billion/yr. ($1.2 billion just for pesticides) (Nielsen and Lee, 1987). Other environmental damage caused by pesticides is estimated to cost the nation about $3 billion/yr. (Pimentel et al., 1990). Although these may be necessary expenditures for food production, their impact must be considered when comparing the environmental effects of producing alternate fuels.

As expected, major pollution problems also are associated with the production of ethanol in the chemical plant. For each gallon of ethanol produced using corn, about 160 gallons of waste water are produced. This waste water has a biological oxygen demand (BOD) of 18,000–37,000 mg/litre depending on the type of plant (Kuby et al., 1984). The cost of processing this sewage was not included in the pollution cost of $0.36/gal., but if included would add another $0.06/gal. to the cost (Pimentel et al., 1989).

Ethanol burns cleanly in the automobile if measurements are made only at the exhaust pipe, and therefore partially reduces air pollution. However, when all air pollutants associated with the entire ethanol system are measured, then ethanol production is found to contribute to major air pollution problems. The 135,812 BTU of fossil fuel, including coal, oil, and natural gas, which are burned in corn production and burned in the ethanol plant, release significant amounts of pollutants into the atmosphere. Also, the carbon dioxide emissions released from burning these fossil fuels contribute to global warming (Schneider, 1989). This becomes a very serious concern when coal is used as the fuel for the fermentation/distillation process. Overall pollution and its associated costs would increase if ethanol production is expanded.

Food versus Fuel Issues

Ethanol produced from corn is not a renewable energy source. Its production adds to the depletion of agricultural resources and raises ethical questions at a time when food supplies must increase to meet the basic needs of the rapidly growing world population.

Burning a human food resource (corn) for fuel, as happens when ethanol is produced, raises important ethical and moral issues. Today malnourished people in the world number 1.6 billion or about 30% of the world population (Kates et al., 1989). This number is larger than ever before in human history and is growing. Coupled with this problem is the escalating rate of growth in the human population. More than a quarter of a million people are added each day to the world population, and each of these human beings requires adequate food.

Present food shortages throughout the world call attention to the importance of continuing U.S. exports of corn and other grain for human food. During the past three years, U.S. corn grain exports have nearly doubled, increasing U.S. export trade by some $5.2 billion/yr. (USBC, 1989). Increased corn exports increase the market for corn, improve our balance of payments and most importantly help feed people who need additional food for survival. Clearly, using corn for food serves ethical purposes not served by burning corn as ethanol.

At present agricultural land supplies 98% of all world food, while the aquatic ecosystem supplies only 2% (Waggoner, 1984). Expanding ethanol production could entail diverting valuable cropland from producing corn needed to sustain human life to producing corn for ethanol factories. This would create serious practical as well as ethical problems. Already worldwide, including the United States, per capita supplies of cropland and freshwater are declining, while soil erosion, deforestation, and food losses to pests are increasing. All these factors are contributing to present food shortages throughout the world (Durning, 1989). Therefore, the practical aspects, as well as the moral and ethical issues, must be seriously considered before steps are taken to convert more corn into ethanol (Pimentel et al., 1989). Clearly, the ethical issue of burning corn will become more intense as food supplies must be increased to meet the basic needs of the rapidly growing world population (Kates, et al., 1989).

Conclusion

The foregoing analysis, for which all major factors operating in ethanol production were assessed, confirms that ethanol production does not contribute to national energy security, is not a renewable energy source, is an uneconomical fuel, and its overall production system causes serious environmental degradation. This analysis generally substantiates the findings of ERAB (1980; 1981), GAO (1980), OTA (1980), USDA (1986), Dovring (1988), Pimentel et al. (1989), Walls et al. (1989), and Sparks Commodities (1990). Further, it agrees with the latest GAO (1990) report that indicates there are numerous uncertainties concerning any supposed budgetary or other benefits of ethanol production for the nation.

At present the total cost to produce a gallon of ethanol from corn is $1.94. Although the by-products produced in ethanol production may reduce the cost of ethanol from $0.50 to $0.61/gal., partial pollution costs of about $0.36/gal., resulting from ethanol production, offset a major portion of any by-product benefits.

Certainly, ethanol would not be produced at present without the high federal and state subsidies which average $0.79/gal. or total $0.7 billion/yr. More than doubling ethanol production to 2 billion gals./yr. would result in an increased subsidy of $1.6 billion/yr. However, because such an increase in ethanol production would increase corn prices, the government might be able to reduce price support payments to farmers. Under these circumstances, the net cost to federal and state budgets would remain at about $0.7 billion/yr., plus any additional subsidies that might be needed to offset the increase in costs of the corn-feedstock and other raw materials.

The real costs to the consumer, however, would be considerably greater than even these substantial amounts. Not only do subsidies increase taxes, but higher corn prices translate into higher meat, milk, and egg prices in the market, because about 70% of U.S. corn is fed to livestock.

Land use is a major factor involved in the ethanol equation. Assuming *zero* energy input for fermentation/distillation in ethanol production and charging only for the high grade fuel used in producing corn, 14 acres of corn cropland are required to fuel one U.S. automobile for one year. This land area is nine-times the amount of land currently required to feed one American.

In addition to heavy cropland use, ethanol production causes serious environmental problems. These include: soil erosion; rapid water runoff; aquifer overdraft; fertilizer and pesticide pollution; and air pollution. Also, ethanol production contributes to the global warming problem because of the enormous amounts of fossil energy burned to produce ethanol.

Corn exports are now valued at $5.2 billion and doubling corn exports would raise the total to $10.4 billion. This would help purchase fuel, increase the market for corn, improve the U.S. balance of payments and, most important, help to feed people who need added food for survival.

On balance, ethanol production would increase U.S. need for fossil fuels, rather than decrease U.S. dependence on fossil fuels. Thus, to more than double ethanol production to 2 billion gallons will require a significant increase in the expenditure of fossil fuels which would be needed both for corn production and for the fermentation and distillation process.

When all of the factors involved in ethanol production are evaluated, the conclusion emerges that ethanol production from corn is an unproductive process, and one that also raises ethical questions about the use of valuable food resources. Certainly ethanol production is a very expensive and energy-inefficient way to produce motor fuel.

Acknowledgements

I thank the following specialists for reading earlier drafts of the manuscript and for their many helpful suggestions: R.A. Lewis and R. Lewis, American Methanol Institute; P. Weisz, University of Pennsylvania; D.J. Reinemann, University of Wisconsin; R. Baer, Cornell University; and two reviewers of the Journal.

Notes

1. The GAO (1990) report provided a limited assessment that acknowledged it was not considering all the relevant factors and inputs involved in ethanol production. For example, the report recognized that as ethanol production is increased, corn feedstock costs increase and by-product values decline, yet it did not adjust anticipated subsidy levels to take these changes into account. The report also appeared not to take into account the prospect of declining price supports for corn after 1995 or increasing corn exports in the absence of an ethanol-subsidy program. These factors would greatly affect the analysis and would significantly influence, eliminate or reverse any hypothetical budget-outlay decrease. Other major factors that influence any expanded ethanol program in the future include the global warming effects and especially the more frequent droughts and other major climatic changes caused by the warming (Schneider, 1989).
2. All extracted and manufactured fuels require energy inputs to make them available for use. For transportation fuels like gasoline, production requires relatively little energy input compared with output. For example, about 0.1 gallon of gasoline energy equivalents is required to transport, refine, and deliver 1 gallon of gasoline. However, with ethanol about 1.7 gallons of ethanol energy equivalents are required to produce 1 gallon of ethanol. Clearly, ethanol is not a renewable fuel in terms of energy, economics, and the environment. This is explained in the text.
3. Cropland erosion results in the loss of $18 billion/yr. in lost fertilizer nutrients (Troeh et al., 1980). In addition, there is an estimated $6 billion/yr. in offsite environmental damages from soil erosion (Clark, 1985). This amounts to a loss of about $0.23/gal. of ethanol produced. Because the fertilizer applied to corn is estimated to offset about 10% of the nutrients lost by erosion annually, the net loss is estimated to be $0.21/gal. for erosion. The heavy use of insecticides and herbicides on corn results in an estimated environmental impact of $0.15/gal. (Pimentel et al., 1989).

References

Batie, S. 1983. *Soil Erosion: Crisis in America's Cropland?* Washington, DC: The Conservation Foundation.

Batty, J.C., and J. Keller. 1980. Energy requirements for irrigation. In *Handbook of Energy Utilization in Agriculture,* edited by D. Pimentel, pp. 35–44. Boca Raton, FL: CRC Press.

Clark, E.H. 1985. The off-site costs of soil erosion. *J. Soil Water Conserv.* 40: 19–22.

Doering, O.C. 1980. Accounting for energy in farm machinery and buildings. In *Handbook on Energy Utilization in Agriculture,* edited by David Pimentel, pp. 9–14. Boca Raton, FL: CRC Press.

Dovring, F. 1988. *Farming for Fuel.* New York: Praeger.

Durning, A.B. 1989. *Poverty and the environment: reversing the downward spiral.* Worldwatch Paper 92. Washington, DC: Worldwatch Institute.

Energy Research Advisory Board (ERAB). 1980. *Gasohol.* Washington, DC: Energy Research Advisory Board, U.S. Dept. of Energy.

——. 1981. *Biomass Energy.* Washington, DC: Energy Research Advisory Board, U.S. Dept. of Energy.

Environmental Protection Agency (EPA). 1990. *Analysis of the Economic and Environmental Effects of Ethanol as an Automotive Fuel.* Washington, DC: U.S. Environmental Protection Agency.

Federal Energy Administration (FEA). 1976. *Energy and U.S. Agriculture: 1974 data base.* Vol. 1. Washington DC: Federal Energy Administration, U.S. Government Printing Office.

Follett, R.F., and B.A. Stewart. 1985. *Soil Erosion and Crop Productivity.* Madison, WI: Amer. Soc. Agron., Inc., Crop Sci. Soc. of Amer., Inc., Soil Sci. Soc. of Amer., Inc., Pub.

General Accounting Office (GAO). 1980. *Conduct of DOE's Gasohol Study Group.* Washington, DC: United States General Accounting Office. GAO/EMD-80-128.

——. 1990. *Alcohol Fuels.* Washington, DC: United States General Accounting Office, GAO/RCED-90-156.

Garst, D. 1990. *What farmers want.* Washington, DC: Talk to the Agri-Business Council.

Glaze, D.H., S.E. Miller, and C.S. Thompson. 1982. The demand for distillers dried grains in South Carolina. *Bull. SC Agric. Exp. Stn.*, Clemson, SC The Station, Aug. issue 642.

Kane, S., J. Reilly, M.R. LeBlanc, and J. Hrubovcak. 1989. Ethanol's role: an economic assessment. *Agribusiness* 5: 505–22.

Kates, R.W., R.S. Chen, T.E. Downing, J.X. Kasperson, E. Messer, and S.R. Millman. 1989. *The Hunger Report Update 1989.* Providence, RI: Alan Shawn Feinstein World Hunger Program, Brown University.

Kuby, W., R. Markoja, and S. Nackford. 1984. *Testing and evaluation of on-farm alcohol production facilities.* Cincinnati, OH: Acurex Corporation. Industrial Environmental Research Laboratory. Office of Research and Development. U.S. EPA.

Lal, R., and F.J. Pierce. 1991. *Soil management for sustainability.* Ankeny, IA: Soil and Water Conservation Society.

Lal, R., and B.A. Stewart. 1990. *Soil Degradation. Advances in Soil Science. Vol. 11.* New York: Springer-Verlag.

National Academy Sciences (NAS). 1981. *Feeding Value of Ethanol Production By-Products.* Washington, DC: National Academy of Sciences.

——. 1989a. *Alternative Agriculture.* Washington, DC: National Academy of Sciences.

——. 1989b. *Irrigation-Induced Water Quality Problems.* Washington, DC: National Academy of Sciences.

National Advisory Panel (NAP). 1987. *Fuel ethanol cost-effectiveness study. Final Report.* Washington, DC: National Advisory Panel on Cost-Effectiveness of Fuel Ethanol Production.

Nielsen, E.G., and L.K. Lee. 1987. *The magnitude and costs of groundwater contamination from agricultural chemicals.* U.S. Dept. of Agr., Econ. Res. Ser., Nat. Res. Econ. Div., Staff Re., AGES 870318.

Office of Technology (OTA). 1980. *Energy from Biological Processes. Vols. I, II.* Washington, DC: United States Office of Technology Assessment.

——. 1990. *Replacing gasoline: alternative fuels for light-duty vehicles.* Washington, DC: United States Office of Technology Assessment.

Paoletti, M.G., B.R. Stinner, and G.G. Lorenzoni. 1989. Agricultural Ecology and Environment. *Agriculture Ecosystems and the Environment* 27: 1–4.

Pimentel, D. 1989. Agriculture and ecotechnology. In *Ecological Engineering: An Introduction to Ecotechnology,* edited by W.J. Mitsch and S.E. Jorgensen, pp. 103–25. New York: John Wiley & Sons.

Pimentel, D., and M. Burgess. 1980. Energy inputs in corn production. In *Handbook on Energy Utilization in Agriculture*, edited by D. Pimentel, pp. 67–84. Boca Raton, FL: CRC Press.

Pimentel, D., and L. Levitan. 1986. Pesticides: Amounts applied and amounts reaching pests. *BioScience* 36: 86–91.

Pimentel, D., and D. Wen. 1990. Technological changes in energy use in U.S. agricultural production. In *Agroecology*, edited by C.R. Carroll, J.H. Vandermeer, and P.M. Rosset, pp. 147–67. New York: McGraw Hill.

Pimentel, D., L. McLaughlin, A. Zepp, B. Lakitan, T. Kraus, P. Kleinman, F. Vancini, W.J. Roach, E. Graap, W.S. Keeton, and G. Selig. 1990. Environmental and economic impacts of reducing U.S. agricultural pesticide use (in press). In *Handbook of Pest Management in Agriculture*, edited by D. Pimentel. Boca Raton, FL: CRC Press.

Pimentel, D., A.F. Warneke, W.S. Teel, K.A. Schwab, N.J. Simcox, D.M. Ebert, K.D. Baenisch, and M.R. Aaron. 1989. Food versus biomass fuel: Socioeconomic and environmental impacts in the United States, Brazil, India, and Kenya. *Advances in Food Research* 32: 185–238.

Schneider, S.H. 1989. *Global Warming: Entering the Greenhouse Century.* San Francisco: Sierra Club Books.

Slesser, M. and C. Lewis. 1979. *Biological Energy Resources.* New York: Halsted.

Sparks Commodities. 1990. *Impacts of the Richardson Amendment to H.R. 3030 on the U.S. Agricultural Sector.* McLean, VA: Sparks Commodities, Inc., Washington Division.

Troeh, F.R., J.A. Hobbs, and R.L. Donahue. 1980. *Soil and Water Conservation for Productivity and Environmental Protection.* Englewood Cliffs, NJ: Prentice-Hall.

USBC. 1989. *Statistical Abstracts of the United States.* Washington, DC: U.S. Dept. of Commerce, Bureau of Census.

USDA. 1986. *Fuel Ethanol and Agriculture: An Economic Assessment.* U.S. Dept. of Agr., Office of Energy, Agricultural Econ. Report Number 562.

——. 1989a. *Agricultural Statistics.* Washington, DC: U.S. Government Printing Office.

——. 1989b. *Economics of Ethanol Production in the United States.* U.S. Dept. of Agr. USDA-AER-607.
USWRC. 1979. *The Nation's Water Resources. 1975–2000. Vols. 1–4. Second National Water Assessment.* Washington DC: United States Water Resources Council. U.S. Government Printing Office.
Waggoner, P.E. 1984. Agriculture and carbon dioxide. *Am. Sci.* 72: 179–84.
Walls, M.A., A.J. Krupnick, and M.A. Toman. 1989. Ethanol Fuel and Non-market Benefits: Is a Subsidy Justified? Discussion Paper ENR89-07. Washington, DC: Energy and Natural Resources Division, Resources for the Future.