Ethanol as Fuel: Energy, Carbon Dioxide Balances, and Ecological Footprint

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The major contributor to global warming is considered to be the high levels of greenhouse gas emissions, especially carbon dioxide (CO_2), caused by the burning of fossil fuel. Thus, to mitigate CO_2 emissions, renewable energy sources such as ethanol have been seen as a promising alternative to fossil fuel consumption. Brazil was the world's first nation to run a large-scale program for using ethanol as fuel. Eventually, the United States also developed large-scale production of ethanol. In this study, we compare the benefits and environmental impacts of ethanol fuel, in Brazil and in the United States, using the ecological footprint tool developed by Wackernagel and Rees. We applied the STELLA model to gauge possible outcomes as a function of variations in the ethanol production scenario.

Keywords: ecological footprint, fuel ethanol, CO_2 balance, energy balance, environmental impacts

As concern about global warming and dependence on fossil fuels grows, the search for renewable energy sources that reduce carbon dioxide (CO_2) emissions becomes a matter of widespread attention. Among the renewable sources is the use of ethanol as fuel. Ethanol fuel is often associated with a concept of "green" energy (i.e., with efficient sources of energy that contribute to the reduction of greenhouse gas emissions and other environmental impacts). However, when seeking an alternative source of energy, one must evaluate the whole production and usage cycle to correctly evaluate potential environmental benefits and disadvantages.

Overview of Brazilian ethanol production

In Brazil, ethanol for fuel is derived from sugarcane and is used pure or blended with gasoline in a mixture called gasohol (24% ethanol, 76% gasoline). According to Oliveira (2002), a conjunction of factors in the mid-1970s led Brazil to adopt a large-scale ethanol program: heavy Brazilian dependence on fossil fuels at that time; the military government's concerns about national sovereignty; decreases in oil production by the Organization of the Petroleum Exporting Countries; and low prices of sugar, with the consequent possibility of bankruptcy by sugar industrialists. The series of measures adopted by the Brazilian government included subsides and protection from alcohol imports (Oliveira 2002).

Overview of US ethanol production

The 1990 Clean Air Act Amendments were the first US legislation to consider fuel, along with vehicle technology, as a potential source of emission reductions. The provisions of the amendments include, among others, (a) the control of carbon monoxide and (b) reformulated gasoline. The first of these involves increasing the oxygen content of gasoline sold during the winter in cities that exceed national air quality standards for carbon monoxide pollution. The second requires that gasoline sold in the country's worst ozone areas contain a minimum oxygen content. Ethanol and methyl tertiary-butyl ether, or MTBE, have been used as oxygenates of gasoline (i.e., as additives that increase oxygen content). Besides its use as an oxygenate, ethanol has also been used as a major fuel component.

In the United States, 90% of ethanol is derived from corn. Its production has increased significantly, from 76×10^6 liters in 1979 to 6.4×10^9 liters in 2001 (Shapouri et al. 2002a). In 2003, ethanol-blended gasoline accounted for more than 10% of gasoline sales in the United States (see *www.epa.gov/orcdizux/consumer/fuels/altfuels/420f00035.pdf*). Pure ethanol, however, is rarely used as fuel for transportation purposes. It is usually mixed with gasoline. The most popular blend for light-duty vehicles is known as E85, and contains 85% ethanol and 15% gasoline.

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Table 1. Energy for constituent inputs used in the production of sugarcane in Brazil and corn in the United States.

Constituent	Quantity per hectare	Energy equivalent (GJ)	Energy per hectare (GJ)
Sugarcane (Brazil)			
Nitrogen	65.0 kg[a]	57.50 per Mg[b]	3.74
Phosphate (P_2O_5)	52.0 kg[a]	7.03 per Mg[b]	0.36
Potassium oxide (K_2O)	100.0 kg[a]	6.85 per Mg[b]	0.68
Lime	616.0 kg[a]	1.71 per Mg[b]	1.05
Seed	215.0 kg[a]	15.60 per Mg[a]	3.35
Herbicides	3.0 kg[a]	266.56 per Mg[b]	0.80
Insecticides	0.5 kg[a]	284.82 per Mg[b]	0.14
Labor	26 workers[a]	0.11 per worker[c]	2.86
Diesel fuel[c]	600 L[d]	38.30 per m^3[e]	23.00
Total			35.98
Corn (United States)			
Nitrogen	146 kg[f]	57.50 per Mg[b]	8.40
P_2O_5	64 kg[f]	7.03 per Mg[b]	0.45
K_2O	88 kg[f]	6.85 per Mg[b]	0.60
Lime	275 kg[f]	1.71 per Mg[b]	0.47
Seed	21 kg[a]	103.00 per Mg[g]	2.16
Herbicides	3 kg[f]	266.56 per Mg[b]	0.80
Insecticides	1 kg[f]	284.82 per Mg[b]	0.28
Diesel fuel	80 L[g]	38.30 per m^3[g]	3.06
Gasoline	29 L[g]	34.90 per m^3[g]	1.01
Liquefied petroleum gas	59 L[g]	28.50 per m^3[g]	1.68
Electricity	191 kWh[g]	3.60 per MWh[g]	0.69
Natural gas	14 m^3[g]	0.04 per m^3[g]	0.56
Total			20.16

a. Pimentel and Pimentel 1996.
b. West and Marland 2002.
c. Ortega et al. 2003.
d. Amount of diesel fuel used by machinery and trucks for the processes of planting, harvesting, and transportating sugarcane from fields to industry (Ortega et al. 2003).
e. Lorenz and Morris 1995.
f. Based on average use from 1994–1997, according to the US Department of Agriculture (USDA 1999).
g. Shapouri et al. 2002b.

Energy balance for Brazilian ethanol production

Approximately 73% of Brazilian sugarcane production is concentrated in the state of São Paulo (Braunbeck et al. 1999). Average sugarcane production in Brazil reached approximately 69 megagrams (Mg) per hectare (ha) in 2001; however, in land cultivated in São Paulo, the average yield is about 80 Mg per ha (Braunbeck et al. 1999). For this reason, the data for Brazilian ethanol production used in this study for calculations of energy and CO_2 balances correspond to average values for the state of São Paulo. The amount of energy required for the agricultural production of 80 Mg per ha of sugarcane totaled approximately 36 gigajoules (GJ) per ha (table 1). Macedo (1998) calculated a smaller energy input for sugarcane production, namely 15.2 GJ per ha. However, no further information is given by Macedo, making it difficult to analyze the origin of the difference between that value and the one calculated here.

In the ethanol conversion process, the distilleries are self-sufficient in terms of production and consumption of energy. For all operations, the energy is supplied by the burning of bagasse, which is the sugarcane waste left after the juice is extracted. In a visit to Usina São Martinho on 3 October 2003, the first author observed that the burning of bagasse was generating approximately 18.0 kilowatt-hours (kWh), or 64.7 megajoules (MJ), per Mg of sugarcane crushed. For distillery operations, approximately 45.4 MJ (912.6 kWh) was required, resulting in a surplus of 19.3 MJ (5.4 kWh). These conditions are representative of Brazilian distilleries, according to Goldemberg and Moreira (1999), but a study conducted by Beeharry (1996) indicates that they represent a low thermodynamic efficiency. Under these conditions, hourly data on production and consumption resulted in an electricity energy surplus of only 1.54 GJ per ha (box 1).

For ethanol, diesel, and gasoline, the higher heating values, adopted for comparison purposes, were, respectively, 23.5 GJ per cubic meter (m^3) (Lorenz and Morris 1995), 38.3 GJ per m^3, and 34.9 GJ per m^3 (Shapouri et al. 2002b). Energy balance calculations were based on a productivity of 80 Mg per ha of sugarcane (Braunbeck et al. 1999), and a production of 80 liters of ethanol per Mg of sugarcane milled (Goldemberg and Moreira 1999). Considering these conditions, 1 ha of sugarcane harvested will result in 6.4 m^3 of ethanol, which represents 150.40 GJ of fuel energy. Burning the bagasse that resulted from crushing the harvested sugarcane generates 5.17 GJ. For distillery operations, 3.63 GJ are required; consequently, the electricity energy surplus is 1.54 GJ.

For distribution of ethanol, Shapouri and colleagues (2002b) calculated an energy requirement value of 0.44 GJ per m^3, adopted in this study for distribution of ethanol as well

Box 1. Electricity energy balance in one hour of distillery production at Usina São Martinho, Brazil.

Sugarcane milled: 1196 megagrams (Mg)
Electricity produced: 77.4 gigajoules (GJ) (21.5 megawatt-hours [MWh])
Electricity used for distillery operations: 54.4 GJ (15.1 MWh)
Surplus electricity: 23.0 GJ (6.4 MWh)
Surplus per Mg of sugarcane: 19.3 MJ (5.35 kWh)
Surplus per hectare: 1.54 GJ (428 kWH)

as for distribution of gasoline and diesel. The 6.4 m^3 of ethanol requires 2.82 GJ for its distribution. Based on these estimates, the energy output–input ratio for production and distribution of ethanol is approximately 3.7 (table 2).

Comparing the 9.2 energy output–input ratio calculated by Macedo (1998) with our ratio of 3.7 (table 2), it is possible to see that the main reason for the discrepancy is the amount of energy considered to be required for agricultural production. This amount seems to have been underestimated in Macedo's work.

Energy balance for US ethanol production

To estimate energy inputs for US ethanol production, one must account for the variations in kinds of energy resources used by the different states, the unpredictable effects that weather has on these energy resources, and other aspects of agricultural production (Shapouri et al. 2002b). Weather conditions, irrigation, and moisture content of corn are some of the factors that influence the amount of energy used in growing corn for ethanol production.

Regarding the industrial process, current technology allows for production of 372 to 402 liters of ethanol per Mg of corn (see *www.ars.usda.gov*). Pimentel and Pimentel (1996) considered the yield from 1 Mg of corn in a large processing plant to be about 372 liters of ethanol. In this study, an intermediate value of 387 liters per Mg of corn was adopted. The agricultural energy input for corn production in US fields amounts to 20.2 GJ per ha (table 1); however, Pimentel (2003) calculated a value of 35.6 GJ per ha. The difference is due to the inclusion of machinery manufacture and corn transportation inputs. In our study, corn transportation inputs were included in the agricultural sector; the inputs for machinery manufacture were not. Nevertheless, energy for the use (not the manufacture) of machinery is embedded as diesel and gasoline inputs. Some authors, such as Pimentel (2003), include manufacturing data in their inputs; however, since there is little explanation about how those values were obtained, we considered these data intractable.

We assumed a crop yield of 7.85 Mg per ha, which according to Shapouri and colleagues (2002a, 2002b) represents the average for the years 1995–1997 in the nine major corn-producing states of the United States (Illinois, Indiana, Iowa, Minnesota, Nebraska, Ohio, Michigan, South Dakota, and Wisconsin). From this value, we determined the total volume of ethanol from 1 ha of corn to be approximately 3.04 m^3.

Table 2. Energy balance of ethanol production from sugarcane in Brazil and from corn in the United States.

Production sector	Energy required (GJ)	Energy generated (GJ)
Sugarcane (Brazil)		
Agricultural sector	35.98	–
Industrial sector	3.63	155.57
Distribution	2.82	–
Total	42.43	155.57
Corn (United States)		
Agricultural sector	22.08	–
Industrial sector	41.60	71.44
Distribution	1.34	–
Total	65.02	71.44

Note: Values correspond to ethanol production derived from 1 hectare of sugarcane or corn plantation.

In our estimates of energy for constituent inputs used in US corn production (table 1), human labor as an energy input consideration was neglected. It represents a relatively negligible factor, considering the highly mechanized harvesting characteristic of corn production in the United States; however, it is important in the far more labor-intensive harvesting of sugarcane in Brazil (table 1).

Considering that corn transportation to distilleries requires 0.63 GJ per m^3 of ethanol produced, and that ethanol conversion consumes 13.7 GJ of energy per m^3 of ethanol produced (Shapouri et al. 2002b), the resulting energy output–input ratio for US ethanol production is 1.1, which is significantly lower than the ratio of 3.7 for Brazilian ethanol from sugarcane (table 2).

Pimentel (2003) calculated an output–input ratio of approximately 0.78 for US corn ethanol production; the result for Wang and colleagues (1999) was an output–input ratio of 0.96. Differences among these studies are related to various assumptions about corn production and ethanol conversion technologies, fertilizer manufacturing efficiency, fertilizer application rates, and other factors (Shapouri et al. 2002b). Hence, we used the STELLA model (Richmond 2001) to examine the effects of varying some of these input assumptions.

Summary of STELLA findings: Input data sensitivity analyses

Comprehensive STELLA models were adapted specifically to the Brazilian and to the US production situations (De Oliveira 2004). Both the agricultural and the industrial submodels were integrated into the comprehensive models as was appropriate to each country. We applied the models to determine how significantly net energy output–input balance might be affected by the differences in harvest production variables, as found in the literature and discussed above. To illustrate the impact that some aspects of ethanol production have on energy balances and CO_2 emissions, we analyzed a set of different variables. The values of such variables were defined within a reasonable range, based on literature consulted during the development of this study.

The most significant variation between best- and worst-case scenarios of current ethanol production conditions was found in the case of Brazilian ethanol production. Assuming a scenario with a sugarcane yield of 69 Mg per ha, rather than 80 Mg per ha, an ethanol conversion rate of 80 liters per Mg of sugarcane instead of 85 liters, and an energy requirement of 75.6 GJ to produce 1 Mg of N instead of 57.5 GJ, the difference in energy balance is about 23% (table 3).

When analyzed individually, the variables for ethanol derived from sugarcane showed significant variations of about 15% when agricultural productivity changed, and variations of 13% for ethanol conversion rates. Possible values for sugarcane yield varied from 68 to 80 Mg per ha, with a resulting energy balance range of 3.23 to 3.66. Energy per Mg of nitrogen varied from 57.5 to 75.6 GJ, with a resulting energy balance range of 3.57 to 3.66. Ethanol conversion ranged from 80 to 85 liters per Mg, resulting in an energy balance range of 3.66 to 3.87.

Less significant variations were observed for variables in corn ethanol production in the United States. For example, the difference in energy balance between best- and worst-case scenarios was only about 9% for corn ethanol production (table 3). Individually, the variables also showed little influence on energy balance results (table 4).

Carbon dioxide balances

For CO_2 balances, the items considered were as follows:

- Emissions from fuel burning in motor vehicles
- Emissions from manufacture, transport, and application of herbicides, fertilizers, and insecticides
- Emissions from conversion and transport of ethanol
- Emissions from production, combustion, and distribution of gasoline
- Increase in soil organic carbon

For purposes of simplification, a light-duty automobile model was chosen as representative for each country. For the United States, the model was a 2001 Ford Taurus flexible-fueled vehicle, with a kilometerage of 8.94 kilometers (km) per liter with gasoline or 6.82 km per liter with E85 (see the US Department of Energy [USDOE] fuel economy site, *www.fueleconomy.gov*). For Brazil, the model was a 2003 Volkswagen Golf 1.6, with a kilometerage of 10.2 km per liter with pure ethanol or 13.97 km per liter with gasohol (see *www.volkswagen.com.br*). In both cases, the distance traveled in one year is considered as 24,150 km per year (i.e., the same distance used by USDOE in calculating annual fuel cost and greenhouse gas emissions).

Carbon dioxide balance for Brazilian ethanol production

The agricultural inputs required for sugarcane production result in the release of approximately 2. 27 Mg of CO_2 per ha (table 5). Calculations based on work by West and Marland (2002) and Shapouri and colleagues (2002b) show that distribution of ethanol emits approximately 35.4 kilograms (kg) of CO_2 per m^3 transported. Emissions from methane (CH_4) and nitrous oxide (N_2O) also result from the agricultural sector in the amounts of 26.90 kg per ha and 1.33 kg per ha, respectively, according to Lima and colleagues (1999). According to calculations based on Schlesinger (1997), and Weir (1998), such emissions represent greenhouse gas equivalents amounting to, respectively, 161 kg and 465 kg of CO_2.

Carbon emitted through the combustion of ethanol in the vehicle motor is reabsorbed by the sugarcane, rendering the balance practically zero (Rosa and Ribeiro 1998), and consequently is not accounted for in the CO_2 balance. Other sources of CO_2 emissions from ethanol production result from the preharvest burning of sugarcane and from the decomposition of vinasse, a by-product of ethanol production

Table 3. Best- and worst-case scenarios for ethanol energy balances and carbon dioxide (CO_2) emissions in Brazil (where ethanol is produced from sugarcane) and in the United States (where ethanol is produced from corn).

Scenario	Yield (Mg per ha)	Energy (GJ) per Mg nitrogen	Ethanol conversion (L per Mg)	Energy balance	CO_2 emissions (kg per m^3 ethanol)
Sugarcane (Brazil)					
Best-case scenario	80	57.5	85	3.87	461
Worst-case scenario	69	75.6	80	3.14	572
Corn (United States)					
Best-case scenario	8.16	57.5	402	1.12	1392
Worst-case scenario	7.60	75.6	372	1.03	1459

Table 4. Energy balance ranges for ethanol resulting from different assumptions for three variables: yield, energy used to produce one megagram of nitrogen, and ethanol conversion.

Variable	Range of possible values	Resulting energy balance range
Yield	7.60–8.16 Mg per ha	1.09–1.11
Energy per Mg nitrogen	57.5–75.6 GJ per Mg	1.05–1.10
Ethanol conversion	372–402 L per Mg	1.08–1.11

Table 5. Carbon dioxide (CO_2) emissions from the manufacture and distribution of agricultural constituents used as inputs for Brazilian sugarcane production and for US corn production.

Crop (broken down by constituent)	Quantity of constituent per ha	CO_2 released (kg) per unit of constituent	CO_2 released (kg) per ha
Sugarcane (Brazil)			
Nitrogen	65.0 kg	3.14 per kg[a]	204.10
Phosphorus pentoxide (P_2O_5)	52.0 kg	0.61 per kg[a]	31.72
Potassium oxide (K_2O)	100.0 kg	0.44 per kg[a]	44.00
Lime	616.0 kg	0.13 per kg[a]	80.08
Herbicides	3.0 kg	17.24 per kg[a]	51.72
Insecticides	0.5 kg	18.08 per kg[a]	9.04
Diesel fuel	600 L	3.08 per L[b]	1848.00
Total			2268.66
Corn (United States)			
Nitrogen	146 kg	3.14 per kg[b]	458.44
P_2O_5	64 kg	0.61 per kg[b]	39.04
K_2O	88 kg	0.44 per kg[b]	38.72
Lime	275 kg	0.13 per kg[b]	35.75
Herbicides	3 L	17.24 per L	51.72
Insecticides	1 L	18.08 per L[b]	18.08
Diesel fuel	80 L	3.08 per L[b]	246.40
Gasoline	29 L	2.71 per L[b]	78.59
Liquefied petroleum gas	59 L	1.96 per L[b]	115.64
Electricity	191 kWh	0.66 per kWh[b]	126.06
Natural gas	14 m^3	2.02 per m^3[b]	28.28
Total			1236.72

a. West and Marland (2002).
b. Calculated on the basis of Shapouri and colleagues (2002b) and West and Marland (2002); includes emissions from production, distribution, and combustion of the fossil fuel.

Table 6. Carbon dioxide (CO_2) emissions from ethanol production from sugarcane in Brazil.

Process	CO_2 equivalent emissions (kg per ha)
Agriculture[a]	2269
Methane (CH_4)	161
Nitrous oxide (N_2O)	465
Ethanol distribution	227
Total	3122

a. See table 5 for breakdown of CO_2 emissions from agriculture.

Table 7. Carbon dioxide (CO_2) balance of corn ethanol (E85).

Process	Total CO_2 released (kg per ha)
Agricultural inputs	1237
Increase in soil organic carbon	–660[a]
Corn transportation	154
Ethanol conversion	2721
Ethanol distribution	108
Gasoline production and distribution	203
Gasoline combustion[b]	1267
Balance	5030

Note: Negative and positive values indicate reductions in and additions to the atmospheric CO_2 pool, respectively.
a. Based on West and Post (2002).
b. Combustion of gasoline added to the E85 mixture.

applied as fertilizer in sugarcane fields. Because these CO_2 emissions are also reabsorbed by sugarcane, they are also not accounted for on the CO_2 balance. Hence, the net contribution of CO_2 from the sugarcane agroindustry to the atmosphere is 3.12 Mg per ha (table 6).

Carbon dioxide balances for US ethanol production

The 3.04 m^3 of ethanol converted from 1 ha of corn harvested and processed will result in 3.58 m^3 of E85. After gasoline is added to form the mixture, this amount of E85 will allow the reference vehicle for the United States to run for approximately 24,400 km. We calculated, on the basis of West and Marland (2002) and Shapouri and colleagues (2002b), that the production and distribution of gasoline result in emissions of 375 kg of CO_2 per m^3 produced. Consequently, 203 kg of CO_2 are emitted from the production and distribution of the 0.54 m^3 of gasoline added to 3.04 m^3 of ethanol to form the E85 mixture. Combustion of this gasoline emits 1.26 Mg of CO_2. For CO_2-balance purposes, when the 3.85 m^3 of E85 is burned, only the emissions that correspond to the gasoline fraction of the mixture will be accounted for, because CO_2 emissions from the ethanol fraction will ultimately be reabsorbed. In this way, combustion of 3.85 m^3 of E85 will emit 1.27 Mg of CO_2. The CO_2 balance for corn ethanol production, distribution, and combustion is summarized in table 7.

Factors affecting carbon dioxide emissions

Like energy balances, CO_2 emissions are affected by several variables, particularly conversion efficiency and crop yield. Different assumptions for such values will result in different values of CO_2 emissions. For ethanol derived from sugarcane, the agricultural inputs are responsible for the larger amount of emissions; for ethanol derived from corn, most emissions result from conversion.

STELLA software summary of findings for carbon dioxide emission

Running STELLA software for diverse assumptions of sugarcane and corn yield per ha and of ethanol conversion efficiency, we observed some variation in the amounts of CO_2 released. The difference in CO_2 released between the best- and worst-case scenarios for current parameters for corn production was only about 5% per m^3 of ethanol produced (table 3). For sugarcane production, this difference was much bigger, at about 25% per m^3 (table 3).

Analyzing the different variables separately, we found that the largest variation between best- and worst-case assumptions occurred with the sugarcane yield. For example, reducing sugarcane yield to Brazilian average production of 69 Mg per ha resulted in an increase in emissions of about 15%. About the same percentage change was observed when we reduced the conversion efficiency to 80 liters per Mg of sugarcane (table 8). For corn ethanol conversion, the difference between the best- and worst-case assumptions (402 and 372 liters per Mg of corn) was only 1% of CO_2 emissions (table 8).

For comparative purposes, we calculated the amount of CO_2 emissions resulting from the use of the amount of gasoline equivalent to ethanol produced in 1 ha of sugarcane or corn.

Brazil. As noted before, the 6.4 m^3 of ethanol produced from 1 ha of sugarcane harvested will allow the reference vehicle to run for 65,280 km. To run the same 65,280 km with gasohol, 4.67 m^3 of gasohol would be required. The total CO_2 emission owing to production, distribution, and combustion of this volume of gasohol is 10.2 Mg of CO_2.

United States. For the reference automobile model running on gasoline, and assuming the same 24,400 km that the car can travel with 3.58 m^3 of E85, 2.73 m^3 of gasoline would be required, resulting in 7.43 Mg of CO_2 emitted from the production, distribution, and combustion of such a volume of gasoline.

Cost of ethanol production and subsidies

From the beginning of the Brazilian program, ethanol production received subsidies, and prices at the pump were determined by the federal government. This support is no longer needed, and prices were liberalized in 1999 (Goldemberg et al. 2004). However, corn ethanol in the United States is heavily subsidized. According to Shapouri and colleagues (2002a), the federal excise tax exemption is \$0.53 per gallon of ethanol blend. The tax exemption approximately equalizes the price of ethanol and conventional gasoline, and thus encourages its use as a gasoline extender (Shapouri et al. 2002a).

Environmental impacts of ethanol production

Although using ethanol fuel has some environmental benefits, there are also drawbacks. Some of these are described below for Brazilian and US ethanol production.

Brazil: Major impacts. Aloisi and colleagues (1994) report erosion values of 12.4 Mg of soil per ha of sugarcane planted. This can be compared with the 2.4-Mg-per-ha rate of soil formation as cited by Sparovek and Schnug (2001), showing net soil losses of 10 Mg per ha. Thus, the rate of erosion is approximately 5.2 times larger than the rate of soil formation.

Water use is another issue in ethanol production; an enormous quantity of water is used to clean sugarcane, because of the large amounts of soil attached to its stalks. Cortez and Rosillo-Calle (1998) report values between 500 and 2500 liters of water used in this process per Mg of sugarcane milled. During the first author's visit to the distillery, approximately 3.89 m^3 of water per Mg of sugarcane were being used. Considering the average Brazilian ethanol production in the last 5 years of 12.4×10^9 liters (see *www.ibge.gov.br*), total water consumption owing to ethanol production is enough to supply for 1 year approximately 13,800 people in Brazil. After being used to clean sugarcane, this water has high biological oxygen demand (BOD) values, above 100 mg per liter. In most cases, it is not properly treated before returning to the rivers.

Preharvest burning of sugarcane is related to increased levels of carbon monoxide and ozone in the agricultural region and cities where sugarcane is produced (Kirchoff 1991). Besides creating air-quality problems that will directly affect the human population in these cities (Godoi et al. 2004), this preharvest burning very often reaches native forest fragments located nearby or in the middle of plantations, as the senior author of this paper has observed every year since 1980.

Vinasse, a liquid residue from ethanol production, is applied on soils in Brazil at high volumes per ha. Its consequent infiltration is responsible for the alteration of the

Table 8. Individual analyses of variables and carbon dioxide (CO_2) emissions for ethanol in Brazil (made from sugarcane) and in the United States (made from corn).

Crop (broken down by variable)	Range of possible values for variable	Resulting CO_2 emissions range (kg per m^3)
Sugarcane (Brazil)		
Yield (Mg per ha)	69–80	488–560
Energy (GJ) per Mg nitrogen	57.5–75.6	488–498
Ethanol conversion (L per Mg)	80–85	461–488
Corn (United States)		
Yield (Mg per ha)	7.6–8.16	1396–1408
Energy (GJ) per Mg nitrogen	57.5–75.6	1396–1437
Ethanol conversion (L per Mg)	372–402	1392–1404

physicochemical characteristics of groundwater, with resulting high concentrations of magnesium, aluminum, iron, manganese, and chloride (Gloeden 1994). The high BOD values of vinasse might be also affecting groundwater and rivers.

Giampietro and colleagues (1997) estimate that the energy required to clean up BOD from distillery wastes is 10.5 GJ per m^3 of ethanol produced. Considering this additional requirement, ethanol energy balances would be reduced by 61% and 31% for sugarcane ethanol and corn ethanol, respectively, as calculated by STELLA software. Regarding CO_2 emissions, that scenario would not affect CO_2 balances for production of ethanol in Brazil, since about 90% of electrical energy in the country is provided by hydroelectric plants. In the United States, owing to the large-scale use of fossil fuels for energy generation, cleaning up BOD would increase CO_2 emissions by 112%, as calculated by the STELLA model, using West and Marland's (2002) values for CO_2 emissions from electricity generation.

It is also important to remember that in Brazil, distillery wastes are applied as fertilizer on soils. Thus, at least theoretically, no additional energy would be required to clean up such waste. However, some residual amount of BOD will undoubtedly reach groundwater and rivers; this amount is currently impossible to determine.

United States: Major impacts. Pimentel and Pimentel (1996) point out that corn causes serious soil erosion in the United States, amounting to values of approximately 22.2 Mg per ha, which is 18 times faster than the rate of soil formation. Pimentel (2003) also reports that in some western irrigated corn acreage, groundwater is being mined at a rate 25% faster than the natural recharge of its aquifer. According to Donahue and colleagues (1990), as cited by Pimentel (1997), 1 ha of corn transpires approximately 4 million liters of water during its growing season, and an additional 2 million liters per ha evaporates concurrently from the soil.

Loss of biodiversity

With large extensions of monoculture, native habitat loses space to agriculture. As a consequence, fauna and flora are lost, thereby reducing biological diversity. Odum, cited by Wackernagel and Rees (1995), suggests that one-third of every ecosystem type should be preserved to secure biodiversity. Moreover, large-scale production of energy crops will undoubtedly result in an expansion of energy crop monocultures, which could ultimately reduce yields because of increased pest problems, diseases, and soil degradation (Giampietro et al. 1997).

Electricity cogeneration from sugarcane distilleries

The energy surplus of electricity obtained during the process of ethanol conversion from sugarcane in Brazil is sometimes used as an argument for the advantages resulting from the use of ethanol as fuel. However, hydroelectricity generation in Brazil, which accounts for approximately 90% of the total according to the Brazilian national electricity energy agency (ANEEL 2002), yields a much larger amount of energy per unit area when compared with sugarcane distilleries. The Brazilian hydroelectric power plant, Itaipu Binacional, is capable of producing approximately 2000 GJ of electricity per ha of impoundment, while distilleries offer a surplus of approximately 1.54 GJ per ha of sugarcane milled. Even considering the total electricity generated by the distillery, the amount would represent only 0.23% of hydroelectric generation, based on data provided by Itaipu Binacional (see *www.itaipu.gov.br*). Considering the scenario in which the 16 million automobiles in Brazil were all using ethanol as fuel, the surplus of electricity resulting from the production of ethanol required for the fleet would be only enough to supply approximately 1.4 million people in Brazil. Since the total Brazilian population is approximately 180 million people (see *www.ibge.gov.br*), the contribution of the distilleries for the Brazilian energy matrix is negligible.

Pollutant emissions

Although the use of ethanol reduces emissions of carbon monoxide, there is some evidence that its use may lead to increased ambient levels of other air pollutants, specifically aldehydes and peroxyacyl nitrates, which are toxic and possibly carcinogenic in animals (Gaffney and Marley 1997). The environmental regulatory agency of the State of São Paulo, Companhia de Tecnologia de Saneamento Ambiental, or CETESB (1990), compared the use of ethanol in a gasohol mixture with the use of ethanol alone, and reported that the gasohol mixture resulted in lower levels of aldehyde emissions, especially acetaldehydes, but higher nitrogen oxide (NO_X) emissions than when ethanol alone was used. However, Hodge (2002) states that the use of ethanol as an oxygenate in reformulated gasoline in the United States contributed to the increase of ozone through higher levels of volatile organic compounds and NO_X emissions.

Ecological footprint

The ecological footprint, as described by Wackernagel and Rees (1995), is an accounting tool based on two fundamental concepts, sustainability and carrying capacity. It makes it possible to estimate the resource consumption and waste assimilation requirements of a defined human population or economy sector in terms of corresponding productive land area. In theory, the ecological footprint of a population is estimated by calculating how much land and water area is required on a continuous basis to produce all the goods consumed and to assimilate all the wastes generated by that population or economy sector.

To calculate the ecological footprint in this study, we used data for the forest area required to sequester CO_2 emitted by gasoline or ethanol production, distribution, and combustion processes, as well as the area required for growing crops of sugarcane or corn for ethanol production. The water necessary for Brazilian distilleries normally is encountered within the basin where sugarcane is planted, so for purposes of

Table 9. Ecological footprint for Brazilian and US automobiles at present ethanol production capacity.

Country/fuel	Area for CO_2 assimilation (ha)	Area harvested (ha)	Total ecological footprint (ha)
Brazil (gasohol)	0.57	0.06	0.63
Brazil (ethanol)	0.19	0.37	0.56
United States (gasoline)	1.11	–	1.11
United States (E85)	0.75	0.99	1.74

Note: Ecological footprint values are expressed for one automobile per year.

calculating the ecological footprint, it is already accounted for in the area required for growing sugarcane. In a scaled-up scenario, to the extent that additional water might be needed to reduce the additional BOD required for assimilation of distillery effluents, the ecological footprint might require upward adjustment. This adjustment was considered negligible for the present scale of operation.

There is considerable uncertainty about the potential of forests to sequester CO_2. For example, Moffat (1997) reported studies showing values of as much as 200 metric tons of CO_2 sequestered per ha of tropical forest, with about half of this forest capacity located at mid and high latitudes. On the other hand, Wackernagel and Rees (1995) consider average values of 6.6 metric tons of CO_2 sequestered by forests in the world. Assuming a value of 6.6 Mg per ha for CO_2 sequestration, as suggested by Wackernagel and Rees (1995), the ecological footprint values for the different fuel options are summarized in table 9.

Choosing different values for CO_2 sequestration might result in different values for the ecological footprint; however, the primary objective of this study is to compare the options available, and any changes in the assumptions of carbon sequestration will affect the ecological footprint equally for all fuel options considered.

When we considered possible variations in energy balances and CO_2 emissions for the best- and worst-case scenarios, only the Brazilian ethanol example led to any significant difference (about 28%) in calculated ecological footprint. However, this difference is minor compared to the overall conclusions of this study.

Table 10. Carbon dioxide (CO_2) emissions from the industrial phase of ethanol production in the United States.

Process	Energy required (GJ)	Fuel type	CO_2 emitted (kg)
Corn transportation	1.92	Diesel	154
Ethanol conversion	41.60	–	2721[a]
Ethanol distribution	1.34	Diesel	108
Total			2983

Note: Values correspond to 1 hectare of corn plantation.
a. Based on West and Marland (2002) and Shapouri et al. (2002b).

Adjusting Brazilian ecological footprint values for counterbalancing erosion rates and loss of biodiversity, the resulting values were as follows: for gasohol, 0.57 ha for CO_2 sequestration plus 0.41 ha harvested, for a total ecological footprint of 0.98 ha; for ethanol alone, 0.17 ha for CO_2 sequestration plus 2.56 ha harvested, for a total ecological footprint of 2.73 ha.

Ecological footprint: Comparison of benefits and disadvantages

When using the ecological footprint to compare benefits and disadvantages of the use of ethanol as fuel, we considered a scenario that substituted ethanol (in Brazil) or E85 (in the United States) for gasohol or gasoline, respectively, in all automobiles. In the Brazilian case (table 9), the forest area required as a sink for CO_2 emission from one automobile is 0.38 ha smaller if this automobile uses ethanol instead of gasohol as fuel. Consequently, if the whole Brazilian automobile fleet used ethanol, the area required to absorb CO_2 would be 6.08 million ha smaller than if the same fleet used gasohol.

The energy surplus generated by distilleries, considering the scenario above, would be 9.44 million GJ. According to Wackernagel and Rees (1995), the area, or footprint, required to produce such energy by hydroelectric dams is 9400 ha of impoundment. Therefore, the benefit in terms of CO_2 emissions and energy generated by substituting gasohol for ethanol, expressed in terms of ecological footprint area required, is approximately 6.09 million ha. In a scenario in which the whole Brazilian automobile fleet uses only ethanol, the amount of additional area required to counterbalance erosion and secure biodiversity would be 34.40 million ha. This amount is 5.65 times larger than the ecological footprint of 6.09 million ha, which represents the benefits in terms of ecological footprint for ethanol production, when erosion and diversity are neglected as factors affecting ecological footprint.

For the US production of ethanol, even without considering the environmental impacts, the results show that this option is not a realistic alternative. The major constraint is the amount of land area required for corn plantations. Running the STELLA model using current ethanol production conditions, and assuming an annual increase of 4% in the US automobile fleet, we determined that by the year 2012, all the available cropland area of the United States would be required for corn production. This scenario assumed that the whole automobile fleet would use E85 as fuel. In the same scenario, by the year 2036, not only the entire US cropland area but also the entire land area now used for range and pasture would be required. Finally, by 2048, virtually the whole country, with the exception of cities, would be covered by corn plantations.

Supplying the 16 million passenger automobiles in Brazil with ethanol would require an area of approximately 6 million ha planted with sugarcane. Such an area corresponds to 10% of Brazilian cropland area. In Brazil, unlike the United States, this is a possible scenario for the next 30 years, because of the relatively small Brazilian automobile fleet and the higher ethanol productivity from sugarcane when compared with corn. Actually, by 1984, 94.4% of the Brazilian automobile fleet used ethanol as fuel (Cortez and Rosillo-Calle 1998), and the current area planted with sugarcane in the country corresponds to 5 million ha, according to the Brazilian Institute of Geography and Statistics (IBGE 2003), since sugarcane is raw material not only for ethanol but for sugar as well.

Conclusions

The use of ethanol as a substitute for gasoline proved to be neither a sustainable nor an environmentally friendly option, considering ecological footprint values, and both net energy and CO_2 offset considerations seemed relatively unimportant compared to the ecological footprint. As revealed by the ecological footprint approach, the direct and indirect environmental impacts of growing, harvesting, and converting biomass to ethanol far exceed any value in developing this alternative energy resource on a large scale.

In the Brazilian case, for carbon sequestration, it seems to be more effective to reduce the rate of deforestation than to plant sugarcane. According to Fearnside and colleagues (2001), the amount of CO_2 released to the atmosphere because of forest burning in the Amazon is about 187 Mg per ha. The current Brazilian energy scenario contrasts with that of the 1970s. Currently, Brazil produces 90% of the oil it consumes, and so the national security argument for substituting ethanol no longer applies. Furthermore, the argument for electricity cogeneration is meaningless, since the energy surplus is minimal.

In the US case, the use of ethanol would require enormous areas of corn agriculture, and the accompanying environmental impacts outweigh its benefits. Ethanol cannot alleviate the United States' dependence on petroleum.

However, the ethanol option probably should not be wholly disregarded. The use of a fuel that emits lower levels of pollutants when burned can be important in regions or cities with critical pollution problems. Also, in agricultural situations where biomass residues would otherwise be burned to prepare for the next planting cycle, there would be some advantage in using the residues for alcohol production. However, further research should be done to improve the conversion process. Considering that, eventually, petroleum may no longer be available in the amounts currently consumed, one must conclude that substitution of alternatives to fossil fuel cannot be done using one option alone. It will prove more prudent to have numerous options (e.g., ethanol, fuel cells, solar energy), each participating with fractional contributions to the overall national and global need for fuel energy. Finally, it is important to notice that no option comes free from significant environmental problems.

References cited

Aloisi RR, Geraldi Filho L, Correa WJ, Henrique JLP, Sparovek G. 1994. O uso de canais ecoadouros como pratica de controle de erosão. STAB 12: 20–26.

[ANEEL] Agencia Nacional de Energia Elétrica. 2002. Atlas de energia elétrica do Brasil. Brasília (Brazil): ANEEL.

Beeharry RP. 1996. Extended sugarcane biomass utilization for exportable electricity production in Mauritius. Biomass and Bioenergy 11: 441–449.

Braunbeck O, Bauen A, Rosillo-Calle F, Cortez L. 1999. Prospects for green cane harvesting and cane residue use in Brazil. Biomass and Bioenergy 17: 495–506.

Bruce D, Nancy N, Michael C. 2002. The US corn ethanol industry: An overview of current technology and future prospects. International Sugar Journal 104: 204–211.

[CETESB] Companhia de Tecnologia de Saneamento Ambiental. 1990. Impacto ambiental da mistura combustível etanol–metanol–gasolina. São Paulo (Brazil): Departamento de Tecnologia de Emissões de Veículos.

Cortez LAB, Rosillo-Calle F. 1998. Towards Proalcohol II—Review of the Brazilian bioethanol programme. Biomass and Bioenergy 14: 115–124.

De Oliveira MED. 2004. Ethanol as fuel, CO_2 balances, and environmental impacts. Master's thesis. Washington State University, Pullman.

Donahue RL, Follett RH, Tulloch RW. 1990. Our Soils and Their Management. Danville (IL): Interstate Printers and Publishers.

Fearnside PM, Graça PMLA, Rodrigues FJA. 2001. Burning of Amazonian rainforests: Burning efficiency and charcoal formation in forest cleared for cattle pasture near Manaus, Brazil. Forest Ecology and Management 146: 115–128.

Gaffney JS, Marley NA. 1997. Potential air quality effects of using ethanol–gasoline fuel blends: A field study in Albuquerque, New Mexico. Environmental Science and Technology 31: 3053–3061.

Giampietro M, Ulgiati S, Pimentel D. 1997. Feasibility of large-scale biofuel production. BioScience 47: 587–600.

Gloeden E. 1994. Monitoramento da qualidade das águas das zonas não saturadas em área de fertilização de vinhaça. Master's thesis. Universidade de São Paulo, São Paulo, Brazil.

Godoi AFL, Ravindra K, Godoi RHM, Andrade SJ, Santiago-Silva M, Vaeck LV, Grieken RN. 2004. Fast chromatographic determination of polycyclic aromatic hydrocarbons in aerosol samples from sugar cane burning. Journal of Chromatography A 1027: 49–53.

Goldemberg J, Moreira JR. 1999. The alcohol program. Energy Policy 27: 229–245.

Goldemberg J, Coelho ST, Nastari PM, Lucon O. 2004. Ethanol learning curve—the Brazilian experience. Biomass and Bioenergy 26: 301–304.

Hodge C. 2002. Ethanol use in US gasoline should be banned, not expanded. Oil and Gas Journal 100: 20–27.

[IBGE] Instituto Brasileiro de Geografia e Estatística. 2003. Levantamento sistematico da producao agricola. Brasília (Brazil): IBGE.

Kirchoff WMJH. 1991. Enhancements of CO and O_3 from burning in sugar cane fields. Journal of Atmospheric Chemistry 12: 87–102.

Lima MA, Ligo MAV, Cabral OMR, Boeira RC, Pessoa MCPY, Neves MC. 1999. Emissao de gases de efeito estufa provenientes da queima de residuos agricolas no Brazil. São Paulo (Brazil): Embrapa Meio Ambiente.

Lorenz D, Morris D. 1995. How Much Energy Does It Take to Make a Gallon of Ethanol? Washington (DC): Institute of Local Self-Reliance.

Macedo IC. 1998. Greenhouse gas emissions and energy balances in bio-ethanol production and utilization in Brazil. Biomass and Bioenergy 14: 77–81.

Moffat AS. 1997. Resurgent forests can be greenhouse gas sponges. Science 277: 315–316.

Oliveira JAP. 2002. The policymaking process for creating competitive assets for the use of biomass energy: The Brazilian alcohol programme. Renewable and Sustainable Energy Reviews 6: 129–140.

Ortega E, Ometto AR, Ramos PAR, Anami MH, Lombardi G, Coelho OF. 2003. Energy Comparison of Ethanol Production in Brazil: Traditional versus Small Distillery with Food and Electricity Production. Campinas (Brazil): Universidade de Campinas.

Pimentel D. 1997. Water resources: Agriculture, the environment and society. BioScience 47: 97–106.

———. 2003. Ethanol fuels: Energy balance, economics and environmental impacts are negative. Natural Resources Research 12: 127–134.

Pimentel D, Pimentel M. 1996. Food, Energy, and Society. Niwot: University Press of Colorado.

Richmond B. 2001. An Introduction to Systems Thinking. Hanover (NH): High Performance Systems.

Rosa LP, Ribeiro SK. 1998. Avoiding emissions of carbon dioxide through the use of fuels derived from sugarcane. Ambio 27: 465–470.

Schlesinger WH. 1997. Biogeochemistry: An Analysis of Global Change. San Diego (CA): Academic Press.

Shapouri H, Gallagher P, Graboski MS. 2002a. USDA's 1998 US Ethanol Cost-of-Production Survey. Washington (DC): Office of Energy Policy and New Uses. Agricultural Economic Report no. 808.

Shapouri H, Duffield JA, Wang N. 2002b. The Energy Balance of Corn Ethanol: An Update. Washington (DC): Office of Energy Policy and New Uses. Agricultural Economic Report no. 814.

Sparovek G, Schnug E. 2001. Temporal erosion-induced soil degradation and yield loss. Soil Science Society of America Journal 65: 1479–1486.

[USDA] US Department of Agriculture. 1999. Agricultural Statistics 1999. Washington (DC): National Agriculture Statistics Service.

Wackernagel M, Rees W. 1995. Our Ecological Footprint: Reducing Human Impact on the Earth. Gabriola Island (Canada): New Society.

Wang MC, Saricks C. Santini D. 1999. Effects of fuel ethanol use on fuel-cycle energy and greenhouse gas emissions. Argonne (IL): Argonne National Laboratory.

Weir KL. 1998. Sugarcane fields: Sources or sinks for greenhouse emissions? Australian Journal of Agricultural Research 49: 1–10.

West TO, Marland G. 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. Agriculture, Ecosystems and Environment 91: 217–232.

West TO, Post WM. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. Soil Science Society of America Journal 66: 1930–1946.