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

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CO_2 concentration

- Today's concentration - 360 ppm.
- Relatively stable at 280 ppm until industrial revolution.
- Increase of 31% in the past 200 years.
- Range of concentrations **never** before experienced during evolution of modern human social and economic systems

Major cause of CO_2 increase

- Combustion of fossil fuels.

In such scenario alternative fuels gains attention

from scientists, government, and population in general

Arguments for ethanol production

- "Green energy"
- Reduction of CO_2 emissions
- Positive energy balance (output/input)

Focus

- Energy Balance
- Carbon dioxide balances
- Environmental Impacts
- Ecological Footprint

Overview - Brazil

Brazil – First country to develop a large-scale program for fuel ethanol production

- Heavy dependence on fossil fuels at the time
- Concerns with national sovereignty (military government)
- Decrease in oil production (OPEC) – 1974
- Low prices or sugar, possibility of bankruptcy by sugar industrialists

1970 – 1 billion liters
2003 – 12 billion liters

Overview - USA

1990 Clean Air Act Amendments:
- First US legislation to consider fuel, along with vehicle technology as potential sources of emissions reduction

Provisions include:
(a)Control of carbon monoxide
Increasing the oxygen content of gasoline sold during the winter in cities that exceed national air quality standards for CO
(a) Reformulated gasoline
Gasoline sold in the country's worst ozone areas must contain a minimum oxygen content and a maximum ozone content

1979 – 76 million liters
2001 – 6.4 billion liters

Basic differences

- USA ethanol derived from Corn and Brazilian derived from Sugarcane
- USA uses mixture E85, Brazil uses pure ethanol
- Gasohol: mixture in Brazil (76% gasoline, 24%) ethanol.

Energy Inputs - Agriculture

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 Balances

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.

Ethanol Conversion -USA

Conversion process use electricity and thermal energy (Natural Gas).

354 kWh (1.27 GJ) per cubic meter and 12.4 GJ of thermal energy

Total - 13.7 GJ per cubic meter of ethanol produced

Industrial Sector

All energy used to operate the distilleries comes from burning bagasse.

Industrial Sector

CO_2 Balances

- Production and transport and application of fertilizers, herbicides and insecticides
- Production and distribution of fuels
- Soil Organic Carbon (SOC)
- Emissions from automobiles

CO_2 Balances

Reference automobiles*

USA :

Ford Taurus Flex Fuel

Mileage - 8.94 km l^{-1} (gasoline), 6.82 km^{-1} (E85)

Source: USDOE – www.fueleconomy.gov

Brazil:

Volkswagen Gol 1.6

Mileage - 10.2 km l^{-1}(ethanol), 13.9 km l^{-1} (gasohol)

Source: Volkswagen do Brasil – www.volkswagen.com.br

* Considering the distance traveled per year as 24150 km

CO_2 emissions - Brazil

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

CO_2 emissions - USA

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.

CO_2 Emissions from Use of Gasoline as Fuel USA

1 ha corn – **3.04** m^3 ethanol (378 – 402 liters per Mg of corn)
1 ha corn – 7.6 – 8.16 Mg

3.58 m^3 of E85→ 24.4 thousand km (reference car)

Using gasoline:
2.73 m^3 of gasoline.

Production and distribution - 1024 kg of CO_2
Combustion - 6409 kg of CO_2

Total emissions: 7433 kg CO_2

1 Mg - 2205 lb.
1 ha - 2.47 acres
1galllon - 3.78 l

difference = 2.4Mg

CO_2 Emissions from Gasoline as fuel - Brazil

Brazilian cars - Gasohol (76% gasoline, 24% ethanol)
1 ha – 80 Mg of sugarcane (69 – 85)
1 Mg sugarcane – 80 liters ethanol (80 – 85)
6.4 m^3 ethanol → 65.3 thousand km

Using Gasohol:
4.67 m^3 of gasohol
(1.12 m^3 ethanol; 3.55 m^3 gasoline)
Production, distribution and combustion of gasoline
9.66 Mg CO_2
Production and distribution of ethanol
586 kg CO_2

Total emissions: 10.2 Mg of CO_2

Difference : 7.1 Mg

Sensitivity Analyses

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

Ecological Footprint

(Wackernagel and Rees, 1995)

- Based on sustainability and carrying capacity concepts
- estimates the resource consumption and waste assimilation requirements of a defined human population or economy in terms of corresponding productive land area
- How much land and area are required on a continuous basis to produce all the goods consumed and assimilate all the wastes generated

Ecological Footprint (EF) Calculation

- Area used to grow sugarcane or corn
- Area for CO_2 assimilation - 6.6 Mg ha^{-1}
- Electricity Generation - 1000 GJ ha^{-1} ($278 x 10^3$ kWh)
- Water Use - Sugarcane Brazil - not considered (water encountered within the basin were sugarcane is planted); data collection.

EF Automobile Results (1 automobile, 1 year) Brazil

Ethanol

- 2368 liters
- Production and Distribution of ethanol

→ 1236 kg of CO_2

Area to sequester CO_2 = 1236/6600 = **0.19 ha**

- Sugarcane area planted

→ 0.37 **ha**

Total EF = 0.19 +0.37 = **0.56 ha**

EF Results (1 automobile, 1 year) Brazil

Gasohol

- 1729 liters (1314 gasoline, 415 ethanol)

- Production, distribution and combustion of gasoline

→ 3577 Kg of CO_2

- Production and distribution of Ethanol

→ 217 kg of CO_2

Total Emissions = 3794 kg of CO_2

- Area to Sequester CO_2 = 3794/6600 = **0.57 ha**

- Sugarcane area planted = **0.06 ha**

Total EF = 0.57 + 0.06 = **0.63 ha**

EF Results
USA

Gasoline

- 2701 liters
- Production, distribution and combustion of gasoline

$\rightarrow$ 7532 kg of CO_2

- Area required for sequestering CO_2

7352/6600 = **1.11 ha**

EF = **1.11 ha**

EF Results
USA

E85

- 3541 liters

- Production, distribution and combustion of E85

→ 4967 kg of CO_2

- Area sequester CO_2 = 4967/6600 = **0.75 ha**

- Area to plant corn

→ **0.99 ha**

Total EF = 0.99 +0.75 = **1.74 ha**

EF summary

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.

Advantages in terms of EF - Brazil

Each ton sugarcane milled - 0.02 GJ (5.35 kWh) of electricity surplus

Automobile using ethanol - area to sequester CO_2 is 0.38 ha smaller

The whole Brazilian fleet using ethanol

Area required to absorb CO_2 - 6.09 million ha smaller

Energy generation - 9.44 million GJ, that corresponds to 9440 ha of impoundment (hydro-electric dams)

Benefits in terms of EF - 6.10 million ha

Disadvantages

Erosion - 5.4 times soil formation rate

Secure biodiversity - 1/3 area set aside

Comparison benefits and disadvantages

Additional area required to secure biodiversity and counterbalance erosion = 35.8×10^6 ha

Benefits in terms of EF area = 6.10×10^6 ha

Ratio = 5.86

EF uncertainties

- CO_2 sequestration rates
- Water Impact

Other environmental impacts

- Water Use
- Water contamination.
- Soil compaction
- Atmospheric pollution by pre-harvest burning of sugarcane
- Vinasse decomposition

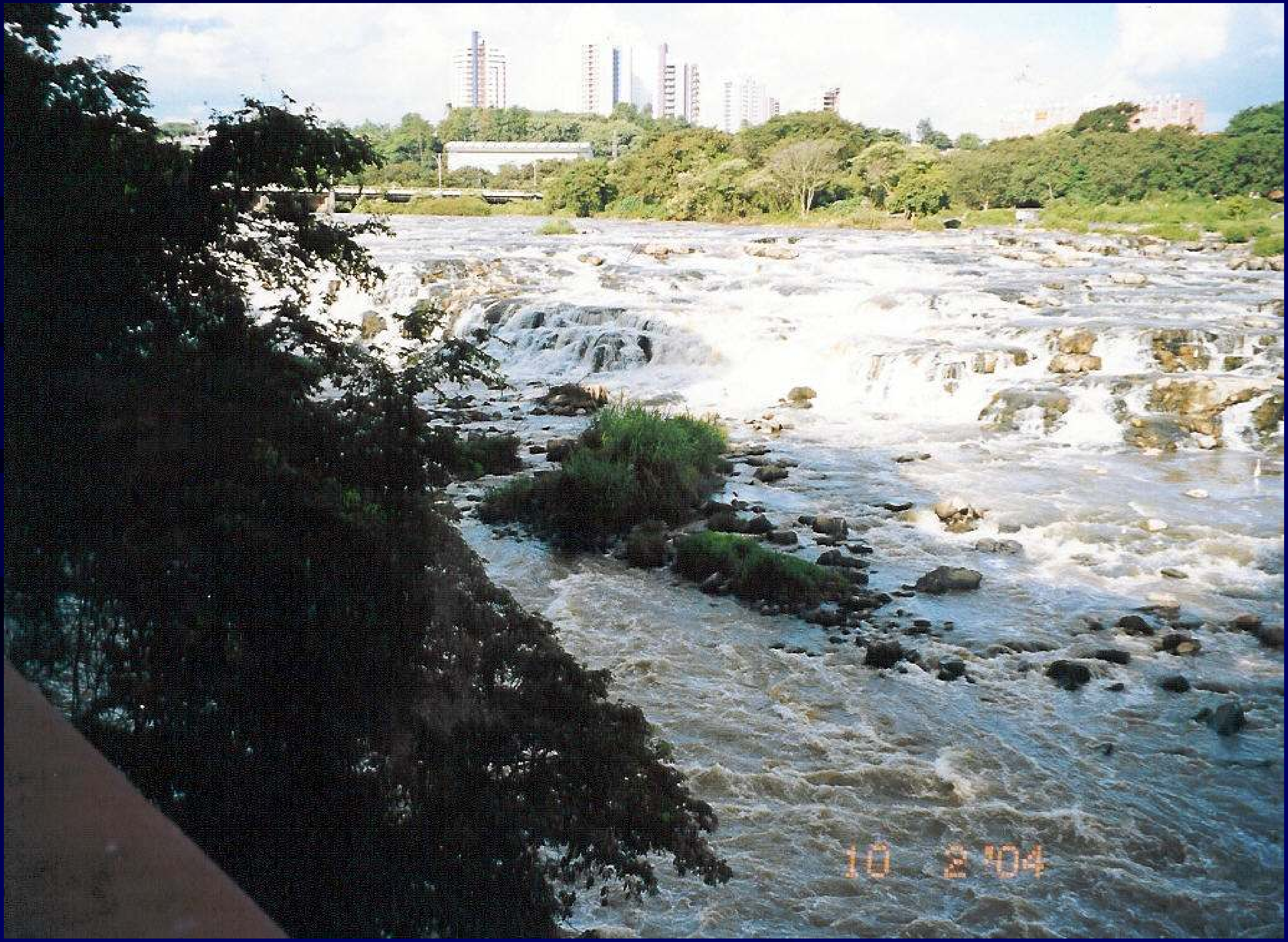
Water Use

- Considering average production of the last five years in Brazil, the water used was enough to supply a population 13.8 million people per year in Brazil.

- Withdraw in the most critical period of the year (dry season)

Piracicaba River-September (dry season)

Piracicaba River - February (wet season)



Pre-harvest burning

Release at a rapid rate of about 19.4 Mg of CO_2 per hectare in the most critical period of the year in terms of air quality.

Forest fragments

- Piracicaba River basin characterized by irregular forest fragments - smaller than 5ha.
- Susceptibility to edge effect
- Lack of internal structure for breeding typical species
- Besides small areas of fragments, there is lack of connectivity among them.

Pre-harvesting burning reaching forest fragment

Forest Fragments - Brazil

Vinasse decomposition

Vinasse decomposition can release about 13 Mg of CO_2 in a relatively short period of 30 days.

Vinasse being used as fertilizer

Water - Corn USA

Growing corn requires large amounts of water

One hectare of corn transpires 4 million liters of water during its growing season and additional 2 million liters ha^{-1} evaporate concurrently from the soil.

Environmental impacts - Corn ethanol

- Ground water being mined 25% faster than natural aquifer recharge
- 12 liters of waste per liter of ethanol produced (high BOD)
- Erosion rates 18 times faster than soil formation
- Use of marginal land in case of production increase

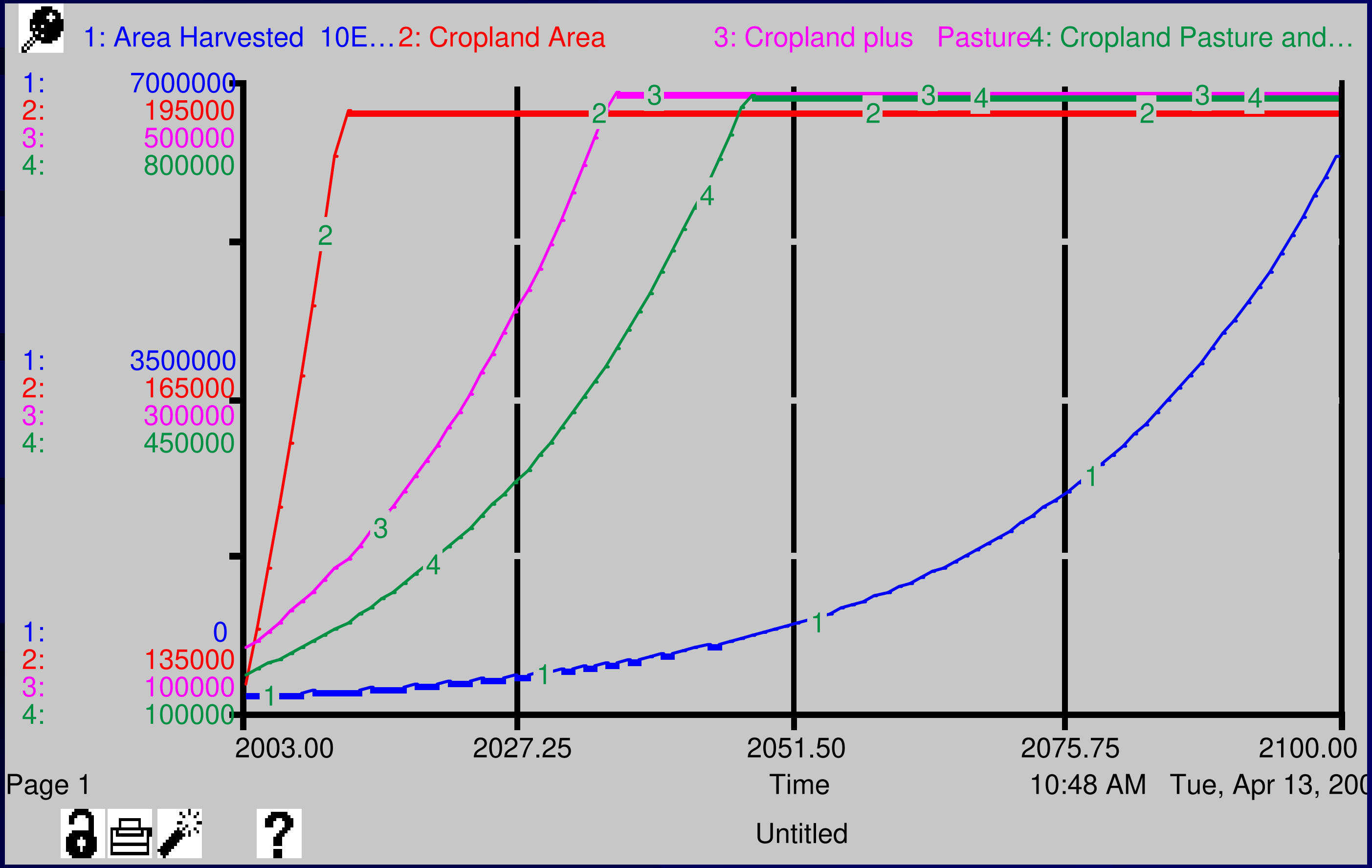
Transportation Sector

- Responsible for about 23-26% of energy consumption in the USA

-If only passenger cars were to use ethanol as fuel (the whole fleet)* – 60% of country's crop land area would be required to grow corn.

* 138 million automobiles

Area required for growing corn

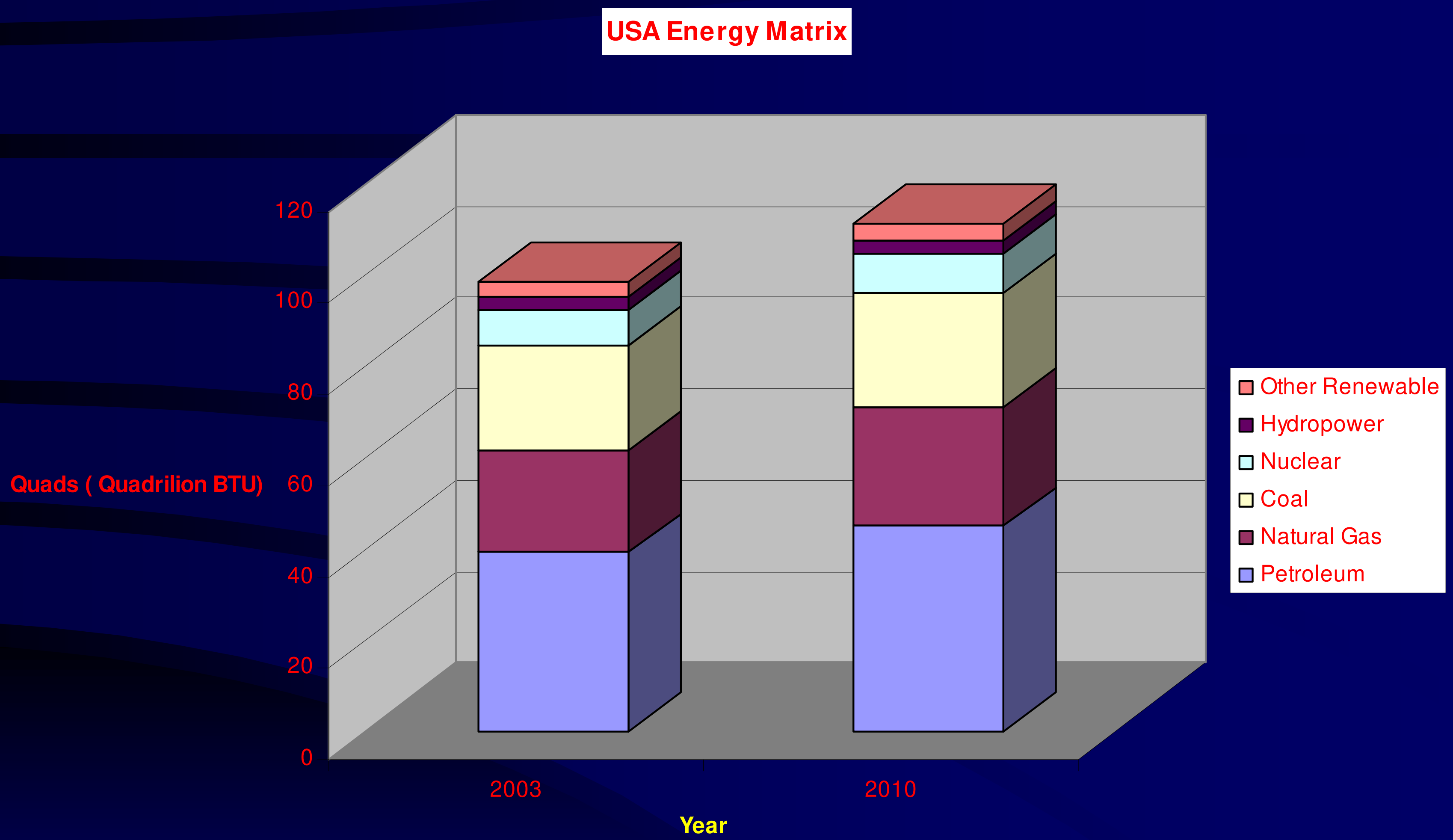


Cropland area - 2012
Cropland and pasture - 2036
Cropland, pasture and forest - 2048

Energy Matrix .cont

- Fossil fuels – 85 % of energy matrix*

*USDOE


USA Energy Matrix
Quads (Quadrilion BTU)
0
20
40
60
80
100
120
2003
2010
Year
Other Renewable
Hydropower
Nuclear
Coal
Natural Gas
Petroleum

Conclusions

- Environmental impacts surpasses the benefits of avoided CO_2 emissions and electricity generation, in terms of EF.
- Ethanol use as fuel in both countries is not sustainable with current practices.
- Brazil produces 90% of the oil it consumes – argument of national security is no longer applies.
- To avoid CO_2 emissions in Brazil is better to control deforestation of amazon (187 Mg of CO_2 released per ha).

  rate of deforestation – 1.24 million hectares/year – 3.07million acres*
- In USA, the area required to grow corn makes it unfeasible
- Option should no be disregarded,

  - use of ethanol in cities or regions with critical pollution problems.
  - achieve a more sustainable way of production

- **NASA – Earth Observatory**

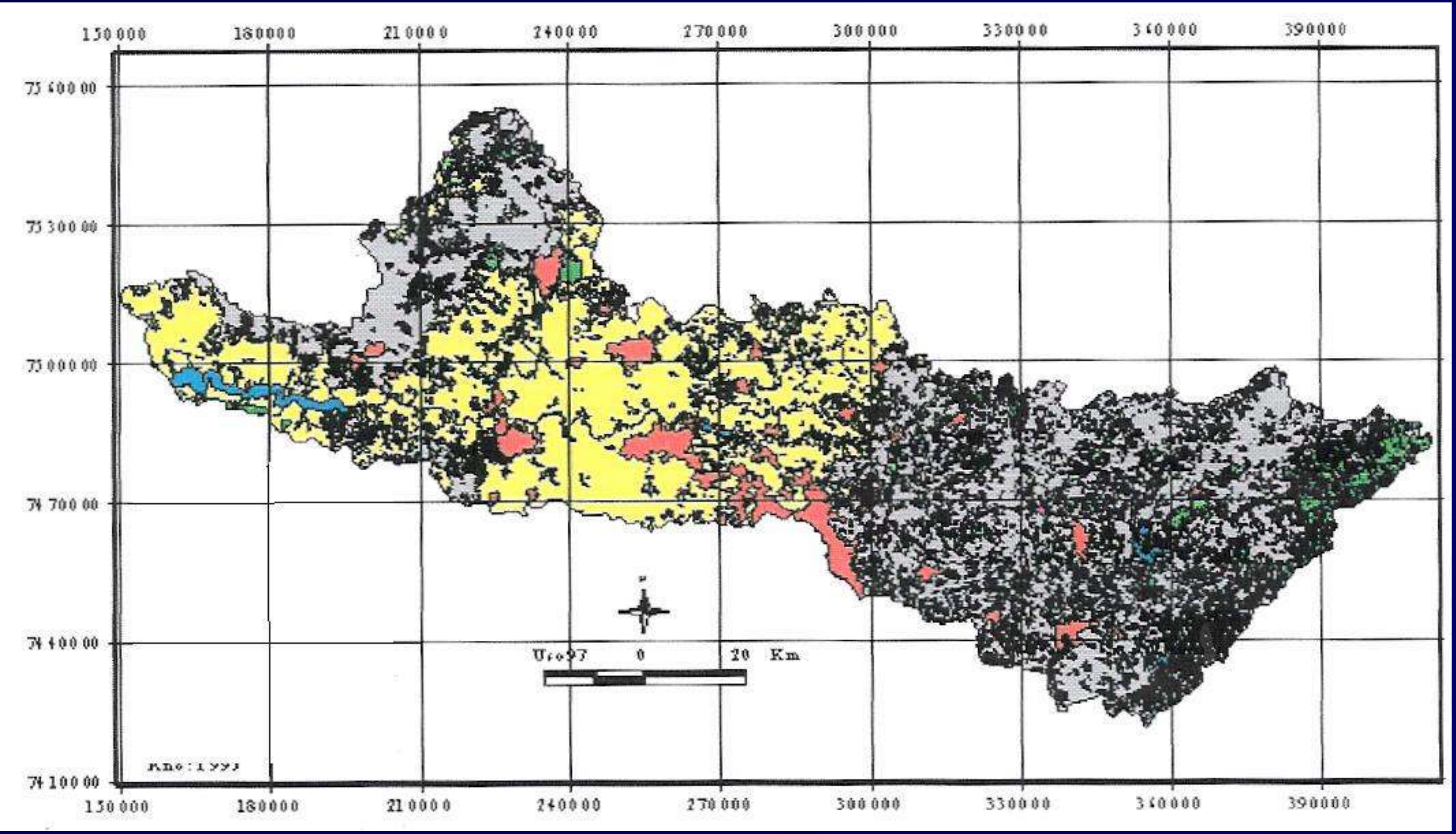
http://earthobservatory.nasa.gov/Library/Deforestation/deforestation_2.html

Conclusions – cont.

- **Substitution of fossil fuel will not be achieved with one option alone**
- **No option is free from environmental problems**


THE FRONT IS ELECTRIC, THE BACK IS HAMSTER.
HYBRID

Piracicaba River basin land use



Corn transportation and Ethanol distribution

Corn transportation to distilleries - 0.63 GJ m^{-3} of ethanol produced.

Ethanol distribution - 0.44 GJ m^{-3}

Possibility of ethanol production from sugarcane in USA.

- States of Florida, Louisiana,Texas and Hawaii.
- Total area - 414 thousand ha
- Average productivity - 85.5 Mg ha^{-1}
- Considering 80 l ethanol per Mg of sugarcane - 2.8 billion liters ethanol - 3.29 billion liters E85
- 1 million USA automobiles per year.

Sugarcane USA

- Deterioration of water quality at Everglades (Florida)
- Contamination by fertilizers, herbicides and insecticides of water bodies in Louisiana.