Energy 34 (2009) 655–661

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Can Brazil replace 5% of the 2025 gasoline world demand with ethanol?

Rogério Cezar de Cerqueira Leite [a,*], Manoel Regis Lima Verde Leal [b], Luís Augusto Barbosa Cortez [a,c], W. Michael Griffin [d], Mirna Ivonne Gaya Scandiffio [a]

[a] Interdisciplinary Center for Energy Planning—NIPE, State University of Campinas—UNICAMP, P.O. Box 6192, CEP 13083-970, Campinas, São Paulo, Brazil
[b] Alternative Energies and Environment Center—CENEA. Av. Dom Luis 500, Sala 1610, Bairro Meirelles, CEP 60160-230, Fortaleza, Ceará, Brazil
[c] School of Agricultural Engineering—FEAGRI, State University of Campinas—UNICAMP, P.O. Box 6011, CEP 13083-970 Campinas, São Paulo, Brazil
[d] Green Design Institute, Tepper School of Business/Engineering and Public Policy, Carnegie Mellon University, 5000 Forbes Ave., Pittsburgh, PA, USA

ARTICLE INFO

Article history:
Received 12 November 2007
Available online 21 December 2008

Keywords:
Fuel ethanol
Brazilian potential
Research and development
New technologies
Sugarcane

ABSTRACT

Increasing use of petroleum, coupled with concern for global warming, demands the development and institution of CO_2 reducing, non-fossil fuel-based alternative energy-generating strategies. Ethanol is a potential alternative, particularly when produced in a sustainable way as is envisioned for sugarcane in Brazil. We consider the expansion of sugarcane-derived ethanol to displace 5% of projected gasoline use worldwide in 2025. With existing technology, 21 million hectares of land will be required to produce the necessary ethanol. This is less than 7% of current Brazilian agricultural land and equivalent to current soybean land use. New production lands come from pasture made available through improving pasture management in the cattle industry. With the continued introduction of new cane varieties (annual yield increases of about 1.6%) and new ethanol production technologies, namely the hydrolysis of bagasse to sugars for ethanol production and sugarcane trash collection providing renewable process energy production, this could reduce these modest land requirements by 29–38%.

1. Introduction

It is generally recognized that driven by high oil prices and global warming something has to be done to reduce dependence and emissions derived from fossil fuel combustion. Ethanol from sugarcane can be produced in Brazil with minimal environmental impact and in sufficient quantities to be part of the solution [1]. Today, Brazil is responsible for about 33% of the ethanol produced worldwide and can play an important role in satisfying future ethanol demand.

Few countries have the natural resources to grow large amounts of energy crops without jeopardizing food production. Brazil occupies 851 million hectares, located mainly between the Equator and the Tropic of Capricorn. The climate allows sugarcane production at high yields with minimal or no irrigation. Brazil has developed, through 30 years of experience, a very efficient cane to fuel ethanol industry.

The Brazilian Government, through its Center for Management and Strategic Studies (CGEE), commissioned a study from NIPE/UNICAMP [2] that explored the issue of increasing sugarcane-derived ethanol production to support a robust export program in an environmentally and socially responsible way. The project's objective was to evaluate the country's potential for substituting ethanol for 5% (102 billion liters) of the world demand of gasoline by sugarcane ethanol in the year 2025. The study covered issues such as resources: land, people, infrastructure, as well as economic and social impacts for the country due to this projection of major increase in ethanol production. We report here on the land and infrastructure requirements and potential environmental impacts of the proposed expansion.

2. Historical background of ethanol production in Brazil

Since Brazilian colonial times, sugarcane has played an important role in the economy [3]. Climate conditions, a 365-day growing season, ample rainfall at the right times, and abundant and productive land allow Brazil to produce over 30 million tonnes of sugar and 20 billion liters of ethanol annually. Brazil has used ethanol as a motor fuel since the 1930s when the Federal Government introduced its use as a 5% blend with gasoline. However, it was not until the creation of the Proálcool Program, the National Alcohol Program, in 1975, that sugarcane-derived ethanol replaced a substantial portion of Brazil's gasoline demand [4].

Before Proálcool, Brazil fuelled its light-duty vehicle (LDV) fleet mainly with gasoline. In 1973, over 80% of the Brazilian petroleum use was from imported oil and the "First Oil Crisis" increased oil prices from US$2.70/barrel to US$11.50/barrel. This directly impacted Brazil's balance of trade with imported petroleum costs

* Corresponding author. Tel.: +55 19 3512 1120; fax: +55 19 3512 1006.
E-mail address: cerqueiraleite@uol.com.br (R.C. Cerqueira Leite).

0360-5442/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2008.11.001

increasing from US$ 469 million in 1972 to US$ 2.8 billion in 1974. The costs for 1974 represented 32.2% of the country's total imports expenses, compared to only 9.7% for the same volume of oil in just the prior year [5].

In response to high oil prices and the increasingly negative balance of trade, the government initiated three major projects: (i) national oil exploration and production; (ii) large-scale expansion of hydro-electricity generation and (iii) development of substitutes for the three major oil derivates: diesel, fuel oil and gasoline [6]. The Proálcool program addressed oil consumption and stabilization of the international sugar market, where prices had fallen from US$ 639/tonne in 1974 to US$176/tonne in 1979.

From 1975 to 1979, in the first phase of the Proálcool program, Brazil used annexed distilleries that produced only ethanol from molasses, to start ethanol production with minimal investment. The product, anhydrous ethanol, was blended with gasoline in various proportions up to E25 (ethanol: 25%; gasoline: 75%). Production of anhydrous ethanol increased from 220 million liters in 1975 to 2.8 billion liters in 1979 [5,6].

The "Second Oil Crisis" saw oil prices increasing from US$24–26/barrel in 1979 to US$40 in 1981. At this point ethanol became an important component of the Brazilian energy mix. From 1980 to 1985 sugar prices fell from US$638/tonne in 1980 to US$88/tonne in 1985 [6]. This permitted the construction of new autonomous distilleries, which produced only ethanol from both sugar and molasses, and could meet the increasing demand from the rapid production of ethanol-only vehicles. These vehicles used hydrated ethanol having a minimum ethanol content of 92.6% [7].

Dedicated ethanol vehicles reached 96% of automobile sales in 1985 [5,8]. But in 1989 an ethanol shortage jeopardized the market for these ethanol-dedicated cars [9,10], causing sales to drop to only 11% of total automobile sales [5]. Even though dedicated ethanol vehicle sales eventually ceased reducing hydrated ethanol production, anhydrous ethanol production rose during the 1990s, offsetting the reductions, due to growth in fleet gasoline use containing ethanol (Fig. 1) [10–14].

During the 1990s the growth of sugar-processing facilities that could make both sugar and ethanol—the "Brazilian model"—generated economies of scale that positively affected sugar production costs. In this period the sugarcane industry grew steadily, from 8 million in 1990 to 19 million tonnes of sugar production in 1999 [10].

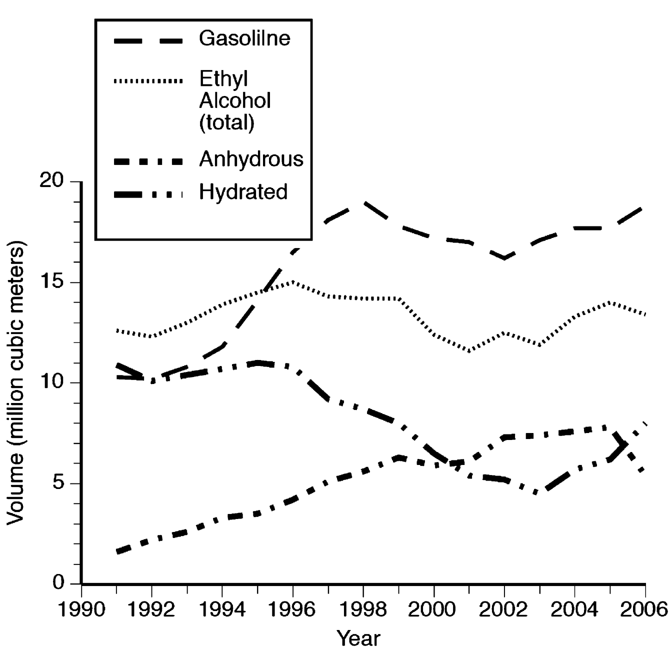

Fig. 1. Ethanol and gasoline use in Brazil.

Table 1
Brazilian ethanol exports by country in 2006.

Country	US$ FOB (10^6)	Liters (10^6)	US$/m^3
United States	882.25	1.416	469.69
Netherlands	151.58	0.345	439.35
Japan	95.34	0.228	418.15
Sweden	79.20	0.201	394.04
El Salvador	80.41	0.183	439.41
Jamaica	58.88	0.134	421.70
Venezuela	42.44	0.103	626.01
South Korea	58.22	0.093	360.74
Costa Rica	33.19	0.092	376.92
Trinidad and Tobago	27.14	0.072	461.13
Total	1604.46	3.416	469.69

Note: Adapted from [16].

In 2003 the "flex fuel vehicle" (FFV) was introduced in Brazil. The vehicle can run on the low-level ethanol gasoline blends typically sold in Brazil and on hydrated ethanol. The introduction of the FFV was motivated by, among others things, high oil prices. In the first year 48,000 vehicles were sold, about 4% of sales. In the most recent year, 2007, FFV accounted for 86% of all light-duty vehicles sold [8]. As can be seen in Fig. 1, the recovery of hydrated ethanol production began in 2003 through 2006 and was the direct result of the FFV fleet growth and beneficial ethanol pricing strategies. In 2006, anhydrous ethanol production dropped, reflecting the impact of the FFVs, which predominately used hydrated ethanol instead of gasoline. In that same year, ethanol provided 44% of the energy used for highway transportation [13,15].

Today the sugar–ethanol industry is growing. Brazil continues to produce sugar at low cost and ethanol production and use are increasing. Brazil produced 33 million tonnes of sugar, providing over 40% of world sugar demand [16] and 22.3 billion liters, 33% of world ethanol production in 2006 [17]. Brazil is the only major producing country that can significantly increase its production to meet its expected internal demand and have excess capacity to provide ethanol to the world market [18].

Eighty-four percent of Brazil's current ethanol production is for the domestic market and remaining 16% is for export. According to UNICA [19] most of the exports were sent to the US, Japan and India (Table 1). Foreign demand for fuel ethanol represents a relatively low-risk expansion for the current industry. The drivers for this market are very strong: global warming associated with gasoline use, rising oil prices and the desire for energy security.

3. The Brazilian expansion of sugarcane-derived ethanol

To take advantage of a developing export market opportunity and provide for Brazil's internal ethanol consumption, a formal analysis of the Brazilian ethanol production potential was conducted. In 2005, researchers at the Interdisciplinary Center for Energy Planning—NIPE at UNICAMP started a project to determine if sugarcane-derived ethanol could meet 5% of the projected of world gasoline demand in 2025.

World gasoline consumption was estimated to be 1.2 trillion liters in 2005 [20]. Based on the Annual Energy Outlook from the EIA [21], gasoline consumption would rise 46% by 2025 resulting in a projected gasoline use of 1.7 trillion liters. The study assumed that Brazil would provide 5% of the expected world demand. To achieve this level of production Brazil would produce 102 billion liters accounting for energy density differences and increased engine efficiencies [22,23].

4. Available land in Brazil for expansion of sugarcane-derived ethanol production

In partnership with the Sugarcane Technology Center (CTC), the study surveyed potential areas capable of economically producing sugarcane. First, all environmentally sensitive areas were eliminated—Amazon, Pantanal and the Atlantic Forest. Also excluded were forests, military and Indian reserves, and areas presenting technical difficulties, such as slopes greater than 12%, which makes mechanized cane harvesting impractical. Further, land was excluded if it had soil or climatic conditions not conducive to sugarcane production. Finally, all land occupied with other crops (permanent and temporary ones) such as soybean, corn, wheat, banana, cassava, etc. were not considered for sugarcane expansion. This made certain that ethanol production did not directly compete with food production.

The study assumed all sugarcane was mechanically harvested eliminating the need for burning [24]. This also implies the elimination of "cane cutters." The remaining lands available for possible sugarcane production are shown in Fig. 2. Also, delineated is the expected productivity for sugarcane using no irrigation and using current technology. With average yields of 71 tonne/ha of sugarcane and 85 l of ethanol per tonne of sugarcane it would take 17 million hectares of sugarcane to provide enough feedstock to meet the projected demand of 102 billion liters of ethanol. Brazilian law requires that the producer sets aside 20% of farm land for permanent environmental preservation [25]. Thus, to meet this requirement 21 million hectares are required, where 17 million hectares are in production (80%) and 4 million hectares are in preservation (20%). This is a three-fold increase in current land dedicated to sugarcane production. However, changes in technology for ethanol production and agricultural improvements could reduce the total land use need.

Brazil has 200 million hectares in pasture and 62 million hectares cropland. Of the cropland, 22 million hectares are used for soybean production, 13 for corn and 7 for sugarcane. The remaining 17 million hectares are used for other minor crops (Table 2) [26]. If sugarcane expansion is restricted to only pasture conversion and allowing for a slight intensification of cattle grazing, currently 1.0 head/ha to 1.3–1.5 head/ha, 50–70 million hectares land would be available [27]. This is more than enough land needed for the proposed ethanol expansion modeled here.

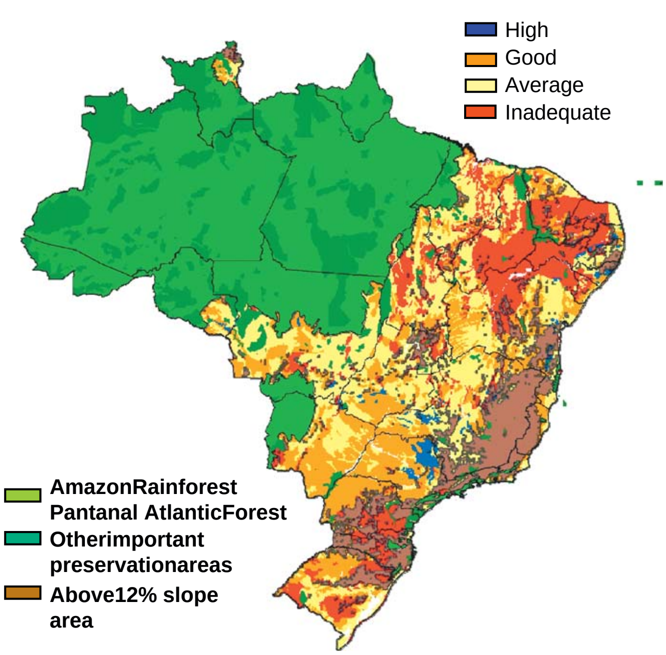

Fig. 2. Potential for sugarcane production without irrigation.

Table 2
Agricultural land in Brazil in 2006.

Category	Area (million hectares)	(%)
All crops	63	19
Soybeans	22	
Corn	13	
Sugarcane (all uses)	7	
Sugarcane for ethanol	4	
Oranges	1	
Others	16	
Pastures	200	58
Available agricultural land	77	23
Total agricultural land	340	100

Note: Adapted from [26].

This back of the envelope calculation does not take into account many factors, including land adjacency, climate and soil suitability, and, importantly, infrastructure. Based on potential productivity, location and logistics, 12 areas were selected as sites for potential expansion of fuel ethanol production. The areas are shown in Fig. 3. The areas are mostly located at the Brazilian Cerrado found between the states of Mato Grosso do Sul (MS) and the South of Maranhão (MA).

The Brazilian Cerrado is a complex ecosystem of grasslands and forest. The original extent of the area was just over 204 million hectares. Currently about 37% are in crops and other human uses and another 41% in pasture [28]. The remaining land, almost 43 million hectares, is native habitat. It is envisioned that current pasture could be converted to sugarcane production. As discussed in general for Brazil and now specifically for this sugarcane compatible region, with a slight intensification of cattle grazing more than enough land is available to meet the anticipated expansion. If the intensification reached 1.4 head/ha then slightly more that the 21 million hectare needed would be available. This is without displacement of agricultural activities into new or sensitive lands as anticipated by Fargione et al. [29] or Searchinger et al. [30]. However, it is important to note that during the implementation of such an expansion plan, caution and vigilance must always be maintained to assure the anticipated environmental benefits are realized.

Grazing in the Cerrrado has adapted over time. Originally, native pasture was used, but with time the quality of the land diminished. These lands were abandoned for new areas. However, in 2004 approximately 2/3 of the pasture was managed and planted in *Brachiaria*. This permitted increased animal carrying capacity and reduced land use and virtually all extractive land use and abandonment ceased [31]. For economic purposes novel cropping systems that use various crop rotations that include a pasture phase and zero tillage are being adopted. These developments provide a background for the expansion of sugarcane in the region.

5. Infrastructure needs

A survey of all existing railroads, pipelines, waterways and harbors available for internal transportation and exporting ethanol was conducted. Brazil has approximately 1.6 million kilometer of roads, 43,000 km of waterways capable of barging, 11,000 km of pipelines and 30,000 km of rail [32–34]. The standard distillery was defined as a mill crushing 2 million

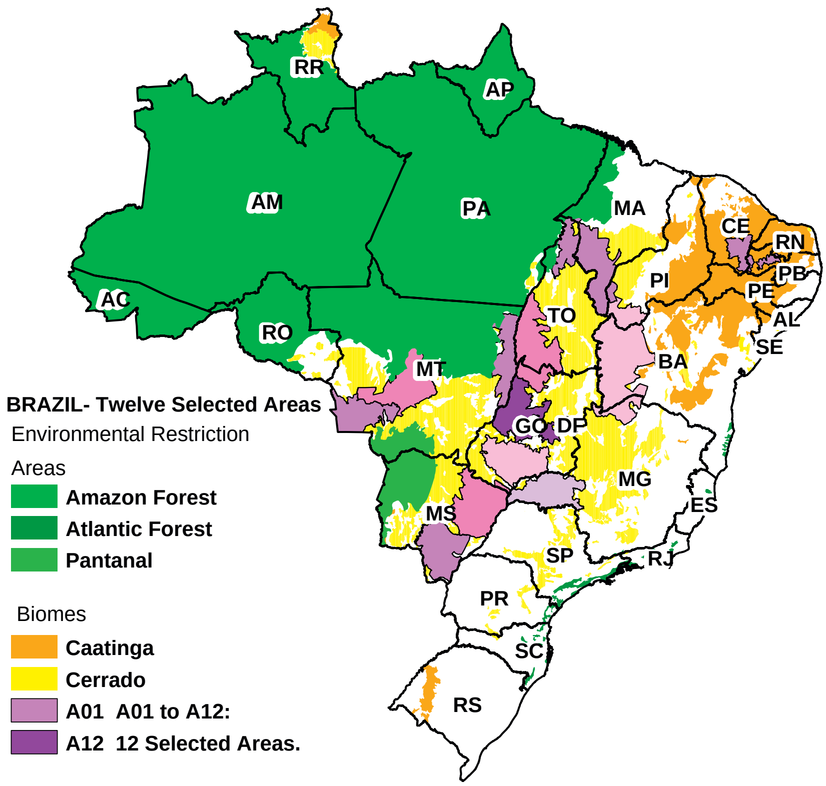

Fig. 3. Twelve selected areas for ethanol production (A = area).

tonnes of cane/year and producing 1 million liters per day of fuel ethanol during 170 days of operation. This standard is based on current economics with present technology. Clusters of these distilleries (a typical cluster has 15 distilleries) were placed in the areas that had agricultural capability to support sugarcane production and logistics for ethanol shipment. These production facilities produce only ethanol and utilize bagasse to meet energy needs, as is the present case. Excess electricity is sold to the grid.

Clusters, in this case capable of producing 2.5 billion liters per annum, justify the construction of ethanol pipelines based on economics [2]. The 12 selected areas contained 615 distilleries and produced a total of 104 billion liters of ethanol. Facility costs are estimated at US$ 100 million per facility and an additional US$ 40 million agriculture related investment. The total investment for a cluster would be around US$ 2.1 billion per cluster of 15 distilleries plus another US$ 500 million for the implementation of the new sugarcane production. Each cluster would produce 2.5 billion liters of ethanol a year and 1200 GWh/year of electric energy. The electricity produced by the ethanol mills is equivalent to 15% of the Brazilian energy generation in 2004 [15].

The US$5 billion per year, for 20 years, investment is required to provide 104 billion liters of ethanol for export in 2025. This amount includes the distilleries and pipeline transport and storage infrastructure. Other infrastructure is expanded through normal government activity (PAC) [33]. Assuming the world price of ethanol is US$0.31/l, the investment will result in an overall benefit of around US$31 billion in exports per year. The implementation of this macroproject will generate about 5.3 million jobs, computing direct, indirect and induced (or income) effects; about 2/3 of this number refers to induced effects. This impact on employment was evaluated using an input–output model of 46 aggregated Brazilian sectors, including sugarcane and ethanol production [35].

Also, the 12 regions will benefit from the infrastructure development provided and social development as new communities arise, with the construction of homes, schools, hospitals and public services in general.

6. Some environmental and social issues related to ethanol use

Increasing production of ethanol and other biofuels is controversial. Ongoing debates include net energy, diverting agricultural resources to fuel instead of food production, water use, and the potential impacts of land use and indirect land use change brought about by the cultivation of biofuel feedstocks.

For instance, in the net energy debate Pimentel and co-workers [36–39] have produced a series of articles arguing that it takes as much as 1.7 times the fossil energy to produce a gallon of ethanol from corn as contained in the ethanol. Most recently they extended their results to include cellulosic and sugarcane-derived ethanol [36]. In any agricultural-based production the overall production cycle will necessarily include fossil fuels to drive tractors, produce fertilizer and other chemicals, as well as providing process heat for biofuel production, etc. The underlying concept of the net energy debate is based on the idea that a sustainable fuel must not rely on non-renewable resources. Also, for those arguing for ethanol as a substitute for petroleum, using petroleum to produce the ethanol is self-defeating, especially if more fossil resources are used than would otherwise be used for the production of conventional fuels. In contrast to Pimentel's finding, others have found the net energy of ethanol production from various crops is positive [40–42]. The differences between the two sides of the debate are mainly related to assumptions [43] and co-product allocation methods [44,45]. A consensus is emerging that suggests the net energy is positive for corn ethanol, but only slightly, and much more positive for cellulosic and sugarcane-derived ethanol. The better performance of the latter two is mainly due to the biomass use (lignin and bagasse) for process fuel.

Brazilian sugarcane-derived ethanol has been shown to have a net energy ratio (NER = output of renewable energy/input of fossil energy) of about 8.0, meaning that on average there is 8 times more energy in the ethanol produced than fossil energy used for its production [46,47]. An important point here is that current Brazilian ethanol metrics are similar to those envisioned for future cellulosic ethanol production [48]. Additionally, as sugarcane ethanol technology improves, through increased sugarcane yields (increasing at about 1.6%/year) and new technology adoption, the NER would be expected to improve as well.

The food or fuel debate is ongoing. It is certainly important to have enough food to feed the world's population and two broad opposing opinions exist. There are those who are against the current biofuel strategies on a moral and ethical basis and think that biofuels should only be grown on lands where food cannot be effectively produced. This approach would limit biofuel feedstock to wastes, agricultural residues or energy crops produced on marginal lands. In contrast, biofuels proponents, who find a moral imperative in addressing environmental and security issues, say biofuels production, have little impact on food prices or availability. Any price increases or volume reductions will be temporary and ultimately offset by market forces, which will encourage others, particularly in less developed countries, to plant more grains. Increases in yields over time will also reduce land use needs, for both fuel and food production.

Currently, droughts around the world, especially in Australia, rising demand for food in the emerging economies of India and China and the rapid rise in fuel costs have all put upward pressure on food prices. A recent study by the US Department of Agriculture has shown that, in general, due to market forces like food substitution, only about 10% of the increase in corn costs makes it through to the retail price [49]. This debate will continue and requires additional studies to quantify the salient factors of the biofuel–food relationship and to think of ways to mitigate adverse impacts. As has been shown above, sugarcane production in Brazil can meet the food needs of the world sugar market and provide substantial ethanol production without necessarily displacing other agricultural-based activities.

With increasing ethanol production, water availability has recently become an issue of concern. For instance, in the US Midwest the Ogallala aquifer, which underlies most of the US corn belt, has decreased over 100 ft since the 1940s. This shows that human water use is exceeding the ability of aquifer recharge [50]. Thus, additional water use, especially that dedicated to biofuels production, must be viewed with caution. There are few publicly available data sources for water use by ethanol facilities, and water availability is not often considered as a potential limiting factor in locating facilities. Corn ethanol production with existing technology requires 3–4 l of water per liter of ethanol, in the processing phase, though water recycling is becoming more efficient over time [51]. Water use for Brazilian ethanol [52] due to sugarcane washing is 15 times higher and is viewed in Brazil as an important issue. Strategies for recycling are being incorporated to bring water use to 12 liter/l of ethanol. This will still be a large water use and can impact future plant placement. Continued efforts will be needed to mitigate any adverse impacts and continue to improve water use.

Numerous life cycle assessments (LCAs) have determined the greenhouse gas (GHG) emissions of biofuel production and use and compared them to gasoline [40,41,44,45,48,53–56]. The general consensus is that the use of biofuels for transportation results in a net reduction in GHG production. But two recent studies challenge this assertion. Most LCAs assume a neutral or a positive impact on soil carbon, i.e. soil carbon remains constant or accumulates. Through a detailed analysis of estimated land use changes, Fargione et al. [29] and Searchinger et al. [30] project a net increase in GHG emissions for biofuels from soil carbon loss. Fargione et al. [29] find that using Brazilian forested Cerrado for sugarcane ethanol it would take 17 years to repay what the authors call the carbon debt. The authors assume conversion of native land and not specifically pasture as envisioned here. Searchinger et al. [30] indicate that if Brazilian sugarcane converts only tropical grazing land, which is the strategy discussed here, then the payback is 4 years. However, if the grazing is displaced to the rainforest then a 45-year breakeven would be required. The Gallagher Review [57] indicates payback time for sugarcane ethanol between 3 and 10 years consistent with the Searchinger results. The report also asserts "there may be specific areas where conversion of pasture for biofuels will deliver feedstock providing good GHG savings, providing indirect land use change does not occur. This is notably the case for Brazilian sugarcane planted on some permanent pasture". We demonstrate here that sugarcane expansion does not necessarily require direct or indirect expansion into the Amazon region.

Brazilian sugarcane ethanol CO_2 life cycle emissions are much smaller than those of gasoline. Sugarcane ethanol releases only 0.6 kg of CO_2 per liter of equivalent gasoline in the production life cycle [46,58], about 80% less emissions than gasoline. The majority of emissions are from the production of the sugarcane. Sugarcane ethanol production takes advantage of the cane plant being a semi-perennial crop, not requiring many of agricultural operations of row crops, and the fact that biomass is used for all its process heat and electricity. These are key characteristics of advanced cellulosic technologies but are already in place for sugarcane production.

A number of GHGs are emitted during crop production; nitrous oxide (N_2O) generated directly by nitrification and denitrification and indirectly via runoff of various N-species, CO_2 from soil carbon transformations, methane (CH_4) from poorly drained soils and CO_2 emission-associated production and transportation of agricultural inputs (fertilizers, herbicides, etc.) and farm equipment use. In most LCA's N_2O is calculated using standard IPCC factors based on added nitrogen to determine the emissions. Recently, Crutzen et al. [59] have suggested that these factors might underestimate N_2O production by agriculture and that a 3–5% of nitrogen application may be more appropriate. Although these impacts might affect the conclusions of many biofuels, as suggested by the authors, for sugarcane the impact is minimal. Using the data from [46,58] and increasing the N_2O emissions to 5% of N additions to the soil results in increase in overall GHG emission to 0.9 kg/l of CO_2 per liter of equivalent gasoline. This level of emissions is 70% less than that of gasoline. These data were calculated with no credits for electricity sold to the grid from bagasse combustion, as would be the case in future expansion.

Other measures of sustainability have been evaluated for many biofuels. We refer the reader to an overall evaluation of many aspects of ethanol production from sugarcane in Brazil, including water use, biodiversity, wealth, etc. by Smeets et al. [58].

7. New technologies required for ethanol production expansion

Expansion of the ethanol production from 22.3 billion liters in 2007 to 104 billion liters in 2025 will necessitate the reduction of production costs to sustain transportation from more distant areas within Brazil to internal and external markets. In addition, as one adds more advanced technology to gain greater productivity per unit of land and provide better environmental performance the complexity of the production process necessarily increases. This almost always brings with it additional costs. Today a hectare of sugarcane can produce about 6,000 l of ethanol with production costs ranging from US$0.25 to 0.30/l. Around 70% of the ethanol production costs is raw material. In the last decades the programs developed by CTC, Ridesa group and the Cane Center (Centro de Cana) from the Agronomic Institute of Campinas (IAC) have resulted in a sustained increase in cane yield on the order of 1.6%/year [60]. These improvements are expected to continue. However, sugarcane varieties will need to be developed to adapt to new areas of the country, since nearly all commercial varieties in use in Brazil have been developed for the state of Sao Paulo, responsible for 62% of all sugarcane produced in the country [61].

Other concerns need to be addressed including the development of a new harvesting system, not only to make unburned cane harvesting more economical but to collect the trash on a widespread basis. Trash collection could increase the production of surplus electric energy and provide more bagasse for increased ethanol production via hydrolysis.

Hydrolysis technology can represent a true "break-through" in the ethanol production. This technology will create the basis for a second generation of ethanol. Several countries, particularly the USA, are working to develop this technology. Brazil has several research groups involved in hydrolysis development. The Brazilian Ministry of Science and Technology (MCT) has created the Bioethanol Research Group within the Center of Strategic Planning NIPE-Unicamp and, with the participation of several institutions in Brazil, will have the objective of conducting fundamental hydrolysis related R&D.

To illustrate the impact of hydrolysis, assuming that bagasse has a composition of 40% cellulose and 17% hemicellulose and the conversion efficiencies of these fractions from Wooley et al. [62], who modeled a dilute acid–enzyme processing of cellulosics similar to that being considered in Brazil, one could expect that bagasse could yield about 280–330 l per dry tonne of bagasse assuming cane yields increase at 1.6%, per annum as expected. Macedo [52] indicates that about 92% of the bagasse is used for process heat. If the 8% not used for process heat were converted to ethanol then one could expect an additional 2200 l of ethanol per hectare bringing the ethanol yield per hectare to 8200 l and reducing land use needs by 29% to 15 million hectares. If sugarcane trash were collected and used for energy, as discussed by Hassuani et al. [63] and 50% of the bagasse used for ethanol production this could generate an additional 3700–4000 l/ha ethanol (9700–10,000 l/ha total) and thus reducing the land use requirement by a total of 33–38% to 13–14 million hectares. Uncertainties exist; How much trash must remain in the field for soil preservation, how much bagasse can be diverted from process energy generation and replaced by trash, the actual process yields for conversion of the bagasse, and actual final costs for the bagasse-derived ethanol.

Given these uncertainties, some of which could increase and some decrease the GHG benefits of Brazilian sugarcane-derived ethanol, we estimated, using the data of Macedo et al. [46] and accounting for increase N_2O emission of Crutzen et al. [59], the impact of bagasse hydrolysis on GHG emissions. As discussed previously, current technology yields a value of 0.9 kg/l of CO_2 equivalent per of equivalent gasoline. Bagasse hydrolysis simply increases the yield of ethanol per unit of sugarcane production and thus, reduces this value to about 0.7 kg/l of CO_2 equivalent per liter of equivalent gasoline or 75% less than gasoline. Much research is needed to bring the hydrolysis technology to a commercially viable process that can be adopted widely in Brazil.

8. Conclusions

The discussion here illustrates two important points: (1) strategies can be found where large amounts of biofuels can be produced and can result in displacement of a significant amount of gasoline use in an environmentally responsible way, and (2) that any strategy must be deployed with care, and particularly those that rely heavily on agriculture, to make certain potential gains in efficiency and reduction in environmental impacts are realized.

Lastly, it is important to realize that no single fuel or technology will replace fossil fuel use alone, or, for that matter, petroleum use. Meeting future demands will require development of multiple fuels, new transportation technologies and even regionally specific scenarios. No technology currently envisioned will have a zero social or environmental impact. This is a standard worth pursuit, but only with the full knowledge that it is unachievable. The debate needs to move from avocation of a "favorite" to developing strategies to take advantage of positive attributes and ameliorate potentially negative impacts of promising technologies to move society to the most responsible future as possible.

The scenario presented here for increased production and use of Brazilian sugarcane-derived ethanol and the aggressive research agenda envisioned can assure that Brazilian sugarcane-derived ethanol can be part of the solution.

Acknowledgments

This research was financed by the Center for Management and Strategic Studies—CGEE and coordinated by Professor Rogério Cezar de Cerqueira Leite with the participation of the following researchers: Adriano Viana Ensinas, André Tosi Furtado, Arnaldo César da Silva Walter, Carlos Eduardo Vaz Rossell, Francisco Rosillo-Calle, Gilberto De Martino Jannuzzi, Gislaine Zainaghi, Jorge Humberto Nicola, José Antonio Scaramucci, Luís Augusto Barbosa Cortez, Manoel Regis Lima Verde Leal, Manoel Sobral Jr., Marcelo Pereira da Cunha, Mirna Ivonne Gaya Scandiffio, Oscar Antonio Braunbeck, Sérgio Bajay and other researchers and students from the State University of Campinas—UNICAMP.

References

[1] Leite RCC, Silva CETG. Energy for Brazil: a survival model (Energia para o Brasil: um modelo de sobrevivência). Rio de Janeiro, Brazil: Expressão e Cultura; 2002 [in Portuguese].
[2] Leite RC. Study of large scale production of ethanol, its possibilities and impacts, aiming the partial substitution of world gasoline (Estudo sobre as possibilidades e impactos da produção de grandes quantidades de etanol visando à substituição parcial de gasolina no Mundo), 2005 [in Portuguese]. See also: 〈http://www.cgee.org.br/prospeccao/doc_arq/prod/registro/pdf/regdoc2162.pdf〉.
[3] Guerra SMG, Cortez LAB. Biomass energy: a historical trend in Brazil. In: Proceedings of the World Renewable Energy Congress. Reading, UK, 13–18 September, 1992.
[4] Walter A, Cortez LAB. An historical overview of the Brazilian bioethanol program. Stockholm Environment Institute/Newsletter of the Energy Programme 1999;11:2–4.
[5] Scandiffio MIG. Prospective analysis of fuel ethanol in Brazil: scenarios 2004–2024. (Análise Prospectiva do Álcool Combustível no Brasil: Cenários 2004–2024). PhD thesis, University of Campinas; 2005. 182pp. [in Portuguese].
[6] Furtado AF. Biomass energy and methods of development (Energy de la Biomasse et Style de Development). PhD thesis, Universite de Paris I, Pantheon-Sorbonne, 1983 [in French].
[7] National Petroleum Agency (Agência Nacional do Petróleo-ANP). Decree No 2. Specification for commercialization of anhydrous and hydrated ethanol in national territory. 2002 [in Portuguese].
[8] Associação Nacional dos Fabricantes de Veículos Automotores—ANFAVEA—Brasil. Anuário da Indústria Automobilística Brasileira. Brazilian Automotive Industry Yearbook Edition, 2008.
[9] Cortez LAB, Griffin M, Scandiffio MIG, Scaramucci JA. Worldwide use of ethanol: a contribution for economic and environmental sustainability sustainable development of energy, water and environment systems proceedings, Dubrovnik, 2–7 July, 2002.
[10] Ramalho EL, Cortez LAB. Proalcool and crises in the sugar-ethanol sector (PROALCOOL e a Crise do Setor Sucroalcooleiro). In: Proceedings from

Congresso Brasileiro de Energia-CBE, Rio de Janeiro, Brazil, vol. 3, 1999. p. 1390–1396 [in Portuguese].
[11] Cortez LAB, Guerra SMG, Lamparelli RA. An overall evaluation of the alcohol programme in Brazil after 15 years of existence. In: Ninth international symposium on alcohol fuels. Florence, Italy, November 1991.
[12] Cortez LAB. The Brazilian ethanol program after twenty years (O Programa Brasileiro de Álcool Combustível 20 Anos Depois) III Congresso Nacional de Energia. 17–19 April, La Serena, Chile, 1996 [in Portuguese].
[13] Furtado AT, Scandiffio MIG. A Promessa do Etanol no Brasil (The ethanol promisse in Brazil). Scientific American, Edição Especial Brasil. Ano 5, No. 53Outubro 2006 [in Portuguese].
[14] Cortez LAB. A 30 years balance of the proalcool program (Um Balanço de 30 Anos do Proálcool). Event for the proalcool 30th anniversary. Ethanol: present and perspectives. UNICAMP 16-17/November, Campinas, Brazil. 2005. See also: 〈http://www.nipeunicamp.org.br/proalcool/Palestras/16/proalcool30%5B1%5D-Cortez.ppt〉 [in Portuguese].
[15] Brazilian Ministry of Mines and Energy [Ministério de Minas e Energia—MME] Brazilian Energy Balance (BEN). 2007. Brazilian Federal Government. Empresa de Pesquisa Energética. Rio de Janeiro, Brazil [in Portuguese].
[16] Datagro. Food and Agriculture Organization of the United Nations. Sugar Commodity Note, 2007. See also: 〈http://www.fao.org/es/esc/en/highlight10872en.html〉.
[17] Licht FO. 2007 In renewable fuels association—industry statistics, 2008. See also: 〈http://www.ethanolrfa.org/industry/statistics〉.
[18] Rosillo-Calle F, Cortez LAB. Towards proalcool II. A review of the Brazilian bioethanol programme. Biomass & Bioenegy 1998;14(2):115–24.
[19] União da Agroindústria Canavieira de São Paulo-UNICA. Statistics. 2008. See also: 〈www.portalunica.com.br〉 [in Portuguese].
[20] International Energy Agency—IEA Energy Statistic. Oil in World in 2005. See also: 〈http://www.iea.org./Textbase/stats/oildata.asp?〉.
[21] Energy Information Administration. Annual Energy Outlook, Table A2. Energy Consumption by Sector and Source, 2003.
[22] Joseph Jr, H. The vehicle adaptation to ethanol fuel. Presentation to the Royal Society Biofuels Meeting. The Royal Society, 23–24 April 2007, London, UK. See also: 〈www.royalsoc.ac.uk/downloaddoc.asp?id=4248〉.
[23] Bailey K. Performance of ethanol as a transportation fuel. In: Wyman CE, editor. Handbook of bioethanol: production and utilization. Washington: Taylor and Francis; 1996. p. 3–60.
[24] Braunbeck O, Macedo I, Cortez L. Increasing the available biomass from sugarcane for energy conversion. In: International workshop implementation strategies for biomass utilization in Europe and developing countries, 19–21 November 2001, Sweden.
[25] Brazilian Ministry of Environment [Ministério do Meio Ambiente-MMA]. Federal Law Nr. 4.771, dated September, 15, 1965, Article 16th. 〈http://www.lei.adv.br/4771-65.htm〉. See also: 〈http://www.cetesb.sp.gov.br/licenciamentoo/legislacao/estadual/decretos/2006_Dec_Est_50889.pdf〉.
[26] USDA Foreign Agricultural Service. GAIN report. Brazil Bio-Fuels Annual. Ethanol GAIN report number: BR7011, 2007. See also: 〈http://www.fas.usda.gov/gainfiles/200707/146291791.pdf〉.
[27] Jank MS. The Old Sugarcane. Fórum Internacional sobre o Futuro do Álcool. In Revista Opiniões Ed. Out-Dez: 12–16. São Paulo, 2007 [in Portuguese].
[28] Conservation International. Cerrado 2008. See also: 〈http://www.biodiversityhotspots.org/xp/Hotspots/cerrado/Pages/default.aspx〉 [Last accessed June 30, 2008].
[29] Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. Land clearing and the biofuel carbon debt. Science 2008;319:1235–8.
[30] Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, et al. Use of US croplands for biofuels increase greenhouse gases through emissions from land use change. Science 2008;319:1238–40.
[31] Landers JN. Tropical crop livestock system in conservation agriculture. The Brazilian experience. Integrated crop management, vol. 5-2007. Rome: Food and Agriculture Organization of the United Nations; 2007.
[32] Brazilian Ministry of Transportation [Ministério dos Transportes]. 2007, 2008. Homepage: 〈www.transportes.gov.br〉.
[33] Federal Government Development Program. [Programa de Aceleração do Crescimento-PAC 2007–2010, Casa Civil, Presidência da República]. Material para a Imprensa, Brasília, 2007.
[34] Transpetro Transportes Petrobrás, 2008. Homepage: 〈htt://www.transpetro.com.br/www.transpetro.com.br/TranspetroSite/appmanager/transpPortal〉.
[35] Cunha MP, Scaramucci JA. Bioethanol as basis for regional development in Brazil: an input–output model with mixed technologies. In: 46th Congress of the European Regional Science Association (ERSA). Volos, 2006.
[36] Patzek TW, Pimentel D. Thermodynamics of energy production from biomass. Critical Reviews in Plant Sciences 2005;24:327–64.
[37] Pimentel D. Ethanol fuels: energy balance, economics, and environmental impacts are negative. Natural Resources Research 2003;12:127–34.
[38] Pimentel D. Ethanol fuels: energy, economics and environmental impact. International Sugar Journal 2001;103:491.
[39] Giampietro M, Ulgiati S, Pimentel D. Feasibility of large-scale biofuel production. BioScience 1997;47:587–600.
[40] Graboski MS. Fossil energy use in the manufacture of corn ethanol. Prepared for the National Corn Growers Association, 2002. See also: 〈http://www.ncga.com/ethanol/pdfs/energy_balance_report_final_R1.PDF〉 [last accessed June 15, 2008].
[41] Shapouri H, McAloon A. The 2001 net energy balance of corn–ethanol. Washington, DC: US Department of Agriculture; 2004.
[42] Wang M. Development and use of GREET 1.6 fuel-cycle model for transportation fuels and vehicle technologies. Technical report no. ANL/ESD/TM-163. Argonne National Laboratory, Center for Transportation Research, Argonne, IL, 2001. See also: 〈http://www.transportation.anl.gov/modeling_simulation/GREET/publications.html〉.
[43] Farrell AE, Plevin RJ, Turner BT, Jones AD, O'Hare M, Kammen DM. Supporting online material to ethanol can contribute to energy and environmental goals. Science 2006;311:506–8 See also: 〈http://www.sciencemag.org/cgi/content/full/311/5760/506/DC1〉.
[44] Farrell AE, Plevin RJ, Turner BT, Jones AD, O'Hare M, Kammen DM. Ethanol can contribute to energy and environmental goals. Science 2006;311: 506–8.
[45] Kim S, Dale BE. Environmental aspects of ethanol derived from no-tilled corn grain: nonrenewable energy consumption and greenhouse gas emissions. Biomass & Bioenergy 2005;28:475–89.
[46] Macedo I, Leal M, Silva J. da. Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil. 2004. See also: 〈www.unica.com.br/i_pages/files/pdf_ingles.pdf〉.
[47] von Blottnitz H, Curran MA. A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. Journal of Cleaner Production 2007;15:607–19.
[48] Adler PR, Del Grosso SJ, Parton WJ. Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecological Applications 2007;17: 675–91.
[49] Leibtag E. Corn prices near record high, but what about food costs? AmberWaves 2008;6:10–5.
[50] National Academy of Science—NAS. Water implications of biofuels production in the United States. 2007. Report in brief. See also: 〈http://dels.nas.edu/dels/rpt_briefs/biofuels_brief_final.pdf〉 [Last accessed June 15, 2008].
[51] Keeney D, Muller M. Water use by ethanol plants: potential challenges. Minneapolis, MN: Institute for Agriculture and Trade Policy; 2006.
[52] Macedo I. A Energia da Cana-de-Açúcar (sugar cane's energy: twelve studies on Brazilian sugar cane agribusiness and its sustainability). UNICA (Sao Paulo Sugarcane Agro industry Union). Sao Paulo, Brazil. 2005. See also: 〈http://www.portalunica.com.br/portalunica/?Secao = referência&SubSecao = publicações&SubSubSecao = livros〉.
[53] Kim S, Dale BE. Life cycle assessment of various cropping systems utilized for producing biofuels: Bioethanol and biodiesel. Biomass & Bioenergy 2005; 29:426–39.
[54] Spatari S, Zhang YM, MacLean HL. Life cycle assessment of switchgrass and corn stover derived ethanol fueled automobiles. Environmental Science & Technology 2005;39:9750–8.
[55] Kim S, Dale BE. Cumulative energy and global warming impact from the production of biomass for biobased products. Journal of Industrial Ecology 2004;7:147–62.
[56] Sheehan JA, Aden K, Paustian K, Kilian J, Brenner, Walsh M, Nelson R. Energy and environmental aspects of using corn stover for fuel ethanol. Journal of Industrial Ecology 2004;7:117–46.
[57] The Gallagher Review. The Gallagher review of indirect effects of biofuels production. Report to UK Renewable Fuels Agency, 2008. See also: 〈http://www.renewablefuelsagency.org/_db/documents/Report_of_the_Gallagher_review.pdf〉.
[58] Smeets E, Junginger M, Faaij A, Walter A, Dolzan P. Sustainability of Brazilian bio-ethanol. Universiteit Utrech. Copernicus Institute, Department of Science, Technology and Society. Report NWS. 2006, E-2006-110. See also: 〈http://igitur-archive.library.uu.nl/chem/2007-0628-202408/UUindex.html〉.
[59] Crutzen PJ, Mosier AR, Smith KA, Winiwarter W. N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmospheric Chemistry and Physics Discussion 2007;7:11 191–205.
[60] Brazilian Institute of Geography and Statistics [Instituto Brasileiro de Geografia e Estatística–IBGE]. Evolução da Produtividade da Cana-de-Açúcar no Brasil. 2008. See also: 〈www.ibge.gov.br〉.
[61] Brazilian Ministry of Agriculture, Sugarcane and Agroenergy [Ministério da Agricultura, Pecuária e Abastecimento. Cana-de-Açúcar e Agroenergia-MAPA], 2008. See also: 〈www.agricultura.gov.br〉.
[62] Wooley R, Ruth M, Sheehan J, Ibsen K, Majdeski H, Galvez A. Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis current and futuristic scenarios, National Renewable Energy Laboratory NREL/TP-580–26157, 1999.
[63] Hassuani S, Leal M, Macedo I. Biomass power generation. Piracicaba: Programa das Nações Unidas para o Desenvolvimento and Centro de Tecnologia Canavieir; 2005.