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EXPANSION OF SUGARCANE ETHANOL PRODUCTION IN BRAZIL: ENVIRONMENTAL AND SOCIAL CHALLENGES

Luiz A. Martinelli[1,3] and Solange Filoso[2]

[1]*CENA-USP, Av. Centenário 303, 13416-000, Piracicaba-SP, Brazil*
[2]*Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, P.O. Box 38, Solomons, Maryland 20688 USA*

Abstract. Several geopolitical factors, aggravated by worries of global warming, have been fueling the search for and production of renewable energy worldwide for the past few years. Such demand for renewable energy is likely to benefit the sugarcane ethanol industry in Brazil, not only because sugarcane ethanol has a positive energetic balance and relatively low production costs, but also because Brazilian ethanol has been successfully produced and used as biofuel in the country since the 1970s. However, environmental and social impacts associated with ethanol production in Brazil can become important obstacles to sustainable biofuel production worldwide. Atmospheric pollution from burning of sugarcane for harvesting, degradation of soils and aquatic systems, and the exploitation of cane cutters are among the issues that deserve immediate attention from the Brazilian government and international societies. The expansion of sugarcane crops to the areas presently cultivated for soybeans also represent an environmental threat, because it may increase deforestation pressure from soybean crops in the Amazon region. In this paper, we discuss environmental and social issues linked to the expansion of sugarcane in Brazil for ethanol production, and we provide recommendations to help policy makers and the Brazilian government establish new initiatives to produce a code for ethanol production that is environmentally sustainable and economically fair. Recommendations include proper planning and environmental risk assessments for the expansion of sugarcane to new regions such as Central Brazil, improvement of land use practices to reduce soil erosion and nitrogen pollution, proper protection of streams and riparian ecosystems, banning of sugarcane burning practices, and fair working conditions for sugarcane cutters. We also support the creation of a more constructive approach for international stakeholders and trade organizations to promote sustainable development for biofuel production in developing countries such as Brazil. Finally, we support the inclusion of environmental values in the price of biofuels in order to discourage excessive replacement of natural ecosystems such as forests, wetlands, and pasture by bioenergy crops.

Key words: biofuel; deforestation; environmental degradation; ethanol; human social cost; riparian forest; Saccharum; *São Paulo, Brazil; sugarcane.*

Introduction

In recent years, energy consumption and global carbon intensity (the ratio between carbon emissions and energy supplied) have increased worldwide, reinvigorating worries about potential depletion of fossil fuel reserves. Such increase, accompanied by growing political instability in oil-producing regions, has instigated many countries to search for alternative forms of energy. However, concerns about rising atmospheric CO_2 concentration in the atmosphere due to fossil fuel burning and other anthropogenic activities, aggravated by compelling evidence of consequent dangerous changes in the climatic system of the Earth (IPCC 2007), have imposed some limits to the types of alternative energy that can be used, and conditions on how this energy is obtained. The most important limits and conditions are that the new forms of energy be renewable, environmentally friendly, and not contribute to the increase in atmospheric CO_2 concentration in the atmosphere.

Biofuel is a promising source of energy because it is generated by the process of photosynthesis, where energy from the sun is captured and transformed into biomass that can be combusted to produce energy. In most cases, this alternative source is renewable, since the CO_2 emitted into the atmosphere is recaptured by the growing crop in the next growth cycle. Ethanol from sugarcane is one of the most promising biofuels because its energetic balance is generally positive, meaning that the growing sugarcane absorbs more carbon than is emitted when the ethanol is burned as fuel (Oliveira et al. 2005). Moreover, the price of production is relatively low.

Brazil has several advantages in this new scenario of biofuel production due to its expansive territory, geographical position, abundant water resources, and

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[3] E-mail: martinelli@cena.usp.br

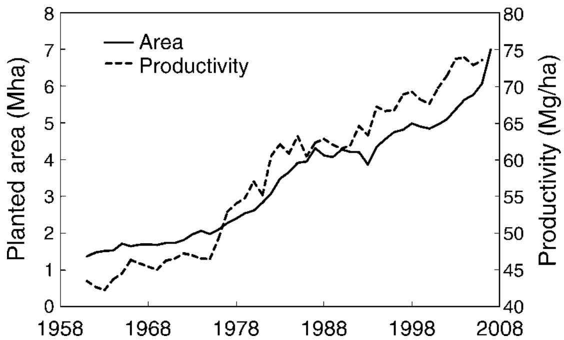

FIG. 1. Increase of planted area and productivity of sugar cane in Brazil from 1960 to 2007 (FAOSTAT 2007).

solar radiation. Moreover, for >30 years, the country has invested in improving the production of ethanol from sugarcane, reaching an estimated 19 billion liters of ethanol in 2007. This production is similar to that of corn ethanol in the USA.

Despite such advantages, the environmental sustainability and economic fairness of ethanol production in Brazil are issues that still need to be carefully debated in the scientific, political, and civic communities before sugarcane ethanol can be considered a "clean" fuel. For one thing, unrestrained use of natural resources and consequent excessive environmental degradation related to the expansion of sugarcane in Brazil may jeopardize important services provided by natural ecosystems, which are already experiencing a large degree of degradation worldwide (Millennium Ecosystem Assessment 2005); curbing such environmental degradation (e.g., deforestation) will also help to prevent further accumulation of CO_2 in the atmosphere. In addition, the exploitation of cane workers for the benefit of the ethanol industry, without any significant return to Brazilian society in terms of investments in education, health, and infrastructure, is also an issue.

The main objectives of this study are (1) to discuss environmental and social issues linked to the expansion of sugarcane in Brazil for ethanol production, and (2) to provide recommendations to help policy makers and the Brazilian government establish new initiatives to produce a code for ethanol production that is environmentally sustainable and economically fair.

PATTERNS OF SUGARCANE EXPANSION IN BRAZIL

From 1960 to 2007, the area planted with sugarcane in Brazil increased from ~1.4 million to 7 million ha. The increase rate averaged almost 120 000 ha/yr (FAOSTAT 2007) (Fig. 1), except for the period between 1985 and 1990, when the rate was slower. Accompanied by the expansion of sugarcane land cover, the productivity of sugarcane also increased dramatically from 45 to 75 Mg/ha. This increase in productivity, ~600 $kg \cdot ha^{-1} \cdot yr^{-1}$, was due to better agricultural techniques and an important genetic breeding program promoted by the Brazilian Government, particularly in the 1970s and 1980s.

According to the most recent land use data for Brazil, ~264 million ha of Brazil's land mass in 2005 was agricultural. Therefore, the area covered by sugarcane represented only ~2.5% of the total. Compared with the area planted with soybeans (23 million ha), sugarcane land cover is relatively small, and mostly confined to the southeast (64%), and along the coastline in the northeast (19%).

In the southeast region, the state of São Paulo has >50% of the country's sugarcane land cover. In the past 15 years this is where most of the expansion of sugarcane plantations occurred by replacing pasture by sugarcane, mostly in the western region of the state (São Paulo Sugarcane Agroindustry Union 2003, Rudorff et al. 2004), as shown in Fig. 2. Since 1990, the expansion of sugarcane in São Paulo averaged ~85 000 ha/yr. The Turvo River basin (area 11 000 km^2) is a typical case, where the land cover of sugarcane increased from 7% to 26% between 1997 and 2007, while the area of pasture decreased from 53% to 32% (Silva et al. 2007).

Presently, only ~8% and 9% of the sugarcane land cover in Brazil is located in the South and Center-West regions, respectively (Fig. 3). In the North, which is mostly Amazon rain forest, the area planted with sugarcane is still only ~0.4% (~21 000 ha) of the total. Expansion to the North will be restricted by physiological characteristics of the varieties of sugarcane planted in Brazil. Sugarcane typically needs a period of drought during its growing phase to concentrate sugars, and such a drought period does not occur in the Amazon region (Fig. 2). Another restriction has to do with a new Brazilian law being developed that prohibits sugarcane planting in ecologically sensitive areas, like the Amazon and Pantanal regions. In contrast, the Center-West region of the country (Fig. 2), where half of the soybean production in Brazil occurs, provides ideal climatic and topographic conditions for sugarcane. Depending on land and market prices, soybeans in the Center-West can be replaced by sugarcane. This pressures soybean farmers to move farther north toward the Amazon. Indirectly, sugarcane expansion could lead to additional deforestation in that region. Yet the area planted with soybeans in the Center-West region (10 million ha) is ~20 times larger than that of sugarcane; this scenario, therefore, is unlikely to occur in the near future.

Despite the fact that sugarcane expansion is not causing any significant decline in the land cover of natural vegetation, there are other important environmental problems associated with the cultivation of sugarcane in Brazil that need to be addressed to avoid the perpetuation of these problems as the ethanol industry expands.

ENVIRONMENTAL ISSUES

Soil degradation

Among the major problems linked to sugarcane cultivation is soil degradation caused by erosion and

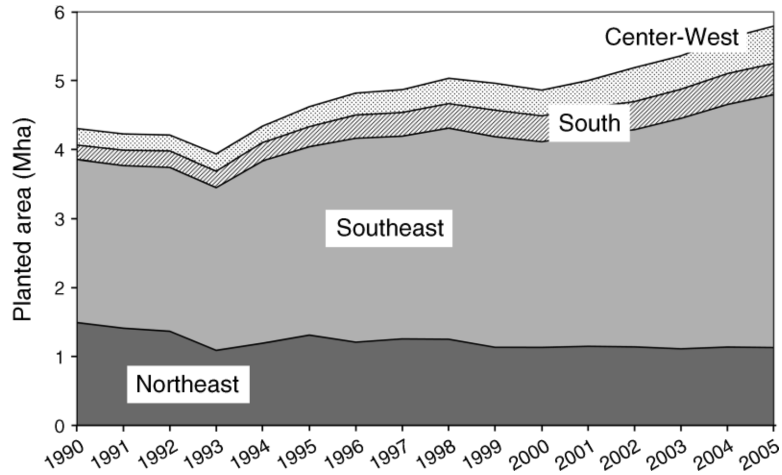

FIG. 2. Area cultivated with sugar cane in the main regions of Brazil from 1990 to 2005. Data are from Instituto Brasileiro de Geografia e Estatística (IBGE; ⟨www.ibge.org.br⟩).

compaction. Soil erosion tends to be high in sugarcane fields (Fiorio et al. 2000, Politano and Pissarra 2005) in comparison to pastures and forests because of extensive areas of bare soil that are associated with the management practices used. Bare soils are exposed to intense rain and winds, both during the initial process of land use conversion when grasses are killed to prepare for the planting of sugarcane, then again in the period between crop harvesting and regrowth. When sugarcane stalks are replaced with new ones every 5–6 years, soils remain bare for several months.

Soil compaction results from the constant traffic of heavy agricultural machinery associated with cultivation and harvesting operations in sugarcane fields. The compaction destroys soil physical properties such as porosity and density, which in turn decreases water infiltration and further enhances soil erosion (Cerri et al. 1991, Oliveira et al. 1995, Silva and Ribeiro 1997, Silva

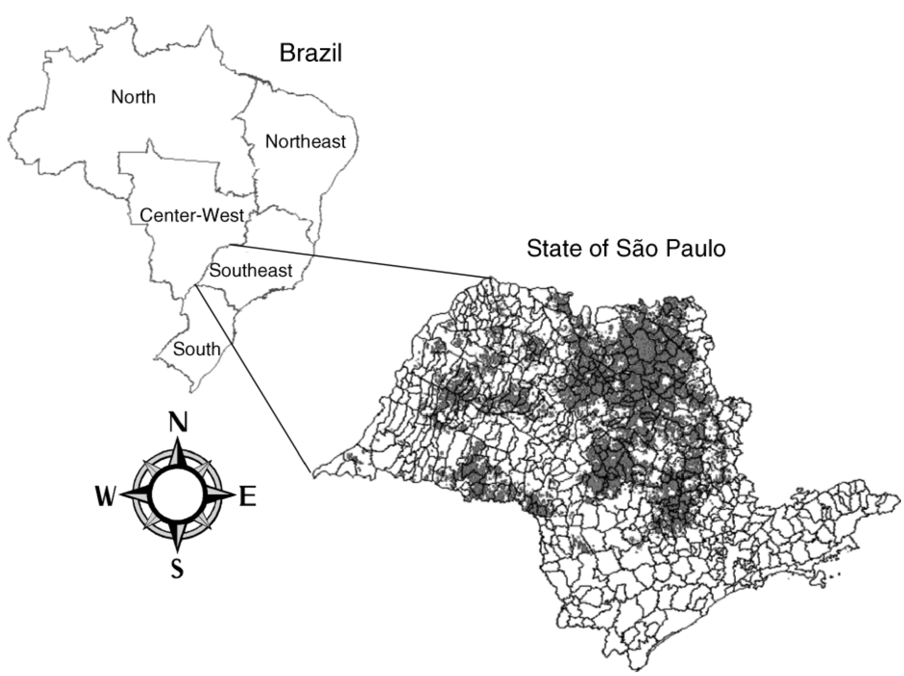

FIG. 3. Map of Brazil and political divisions in five main regions. The enlargement is a map of the state of São Paulo with county borders. Shaded areas were cultivated with sugar cane in 2003 (São Paulo Sugarcane Agroindustry Union 2003, Rudorff et al. 2004).

et al. 1998, Ceddia et al. 1999, Fiorio et al. 2000, Prado and Centurion 2001).

Sparovek and Schnug (2001) estimated erosion rates up to 30 Mg of soil$\cdot$ha$^{-1}\cdot$yr^{-1} for sugarcane fields in São Paulo state (Fig. 2), while rates in forests and pastures did not exceed 2 Mg$\cdot$ha$^{-1}\cdot$yr^{-1}. In one particular region of São Paulo, which has been intensively and extensively cultivated with sugarcane for many decades, Politano and Pissarra (2005) found that erosion varied from severe to extremely severe.

Deterioration of aquatic systems

The negative effects of accelerated soil erosion include not only soil degradation and subsequent poor crop development, but also deterioration of aquatic systems. As colluvium sediments are transported downhill across the landscape from sugarcane fields, they are deposited onto wetlands, small streams, rivers, and reservoirs. Deposition impacts water quality, ecosystem biodiversity (Politano and Pissarra 2005), and ecosystem functions.

An example that illustrates the problem of sedimentation in aquatic systems linked to sugarcane cultivation was described by Fiorio et al. (2000) for a small watershed in Piracicaba County, state of São Paulo (Fig. 2). This watershed had 25% sugarcane land cover in 1978 when a reservoir was built to supply water for a small town nearby. About 20 years later, almost 70% of the watershed was covered by sugarcane crops, and the reservoir could no longer be used as a water supply because of sedimentation and loss of 50% of its water-holding capacity. In a country like Brazil, where most of the water supply for cities and rural areas and most of the electrical power generated are from dammed rivers and reservoirs, sedimentation of aquatic systems can have serious consequences.

The severity of the problem of sedimentation is aggravated even further by the transport of contaminants such as pesticides and heavy metals used in sugarcane cultivation to aquatic systems. For instance, organochlorides were found in sediment and fish samples collected in the Piracicaba River basin in 1997 (Silva et al., *in press*), despite the fact that the use of this product was forbidden in Brazil in 1985. Similarly, organochlorides were found in samples collected in 2003 in streams that drain a sugarcane region in the central portion of São Paulo state (Corbi et al. 2006). This suggests that these compounds are still being used by farmers because the pesticides have a short half-life in the environment. (Silva et al., *in press*). Other contaminants such as atrazine, a herbicide used in sugarcane crops, and heavy metals such as copper (Cu), were also found in water samples and stream bed sediments collected in rivers draining regions that have extensive sugarcane cultivation (Carvalho et al. 1999, Azevedo et al. 2004, Corbi et al. 2006).

The industrial processing of sugarcane for production of ethanol and sugar is yet another source of pollution for aquatic systems, as large amounts of byproducts and waste are generated in the mills. The two most important are wastewater generated from the washing of sugarcane stems before they go through the mill, and the vinasse produced during the distillation process. Both of these waste products are rich in organic matter, and therefore increase the BOD (biochemical oxygen demand) of waters receiving these effluents. Elevated BOD promotes depletion of dissolved oxygen in the water and often causes anoxia (Ballester et al. 1999). High nutrient concentrations in these effluents also contribute to the problem by enhancing algal blooms and promoting eutrophication of surface waters (Matsumura-Tundisi and Tundisi 2005).

For each liter of ethanol that is produced from sugarcane, 12–13 liters of vinasse are generated. With the boom of ethanol production in Brazil in the early 1980s, new legislation was created to ban the direct discharge of vinasse onto surface waters. Since then, nutrient and carbon-rich vinasse is mixed with wastewater from washing sugarcane and is recycled back to sugarcane fields as organic fertilizer (Gunkel et al. 2007). This solution has helped to protect aquatic systems to a certain extent. However, it is not uncommon for small mills to discharge vinasse into streams and rivers because they lack the means of transport and application. Also, accidents or mishandling during storage and transport of vinasse are not uncommon, even in mills with adequate infrastructure.

In a monitoring study conducted on a small stream adjacent to a sugarcane mill in Piracicaba County, Ometto et al. (2000) reported significant changes in water quality along a 1.8-km reach downstream of a sugarcane mill (Fig. 4). Clear increases in water temperature, electrical conductivity, dissolved organic carbon (DOC), and dissolved inorganic nitrogen (DIN) were observed downstream from the mill. Moreover, concentrations of dissolved oxygen were significantly lower downstream, while dissolved inorganic carbon (DIC) was higher. Gunkel et al. (2007) reported similar changes along a reach of the Ipojuca River in the northeastern region of Brazil.

Martinelli et al. (1999*a*) used stable isotope techniques to determine the origin of organic matter in rivers draining watersheds that were predominantly covered by sugarcane and found that, in the samples collected, carbon originated from sugarcane. Sugarcane is a C_4 plant, which can be easily distinguished from C_3 plants (e.g., trees) because of a distinctive isotopic signature (expressed as $\delta^{13}C$). Therefore, these results suggested that either the discharge of vinasse into streams is substantial in the region, or that accelerated erosion in sugarcane fields transports organic materials to the water (Martinelli et al. 1999*a*, 2004). A combination of both scenarios is likely.

Nitrogen pollution

Like most annual crops, sugarcane requires the application of fertilizer to support an economically

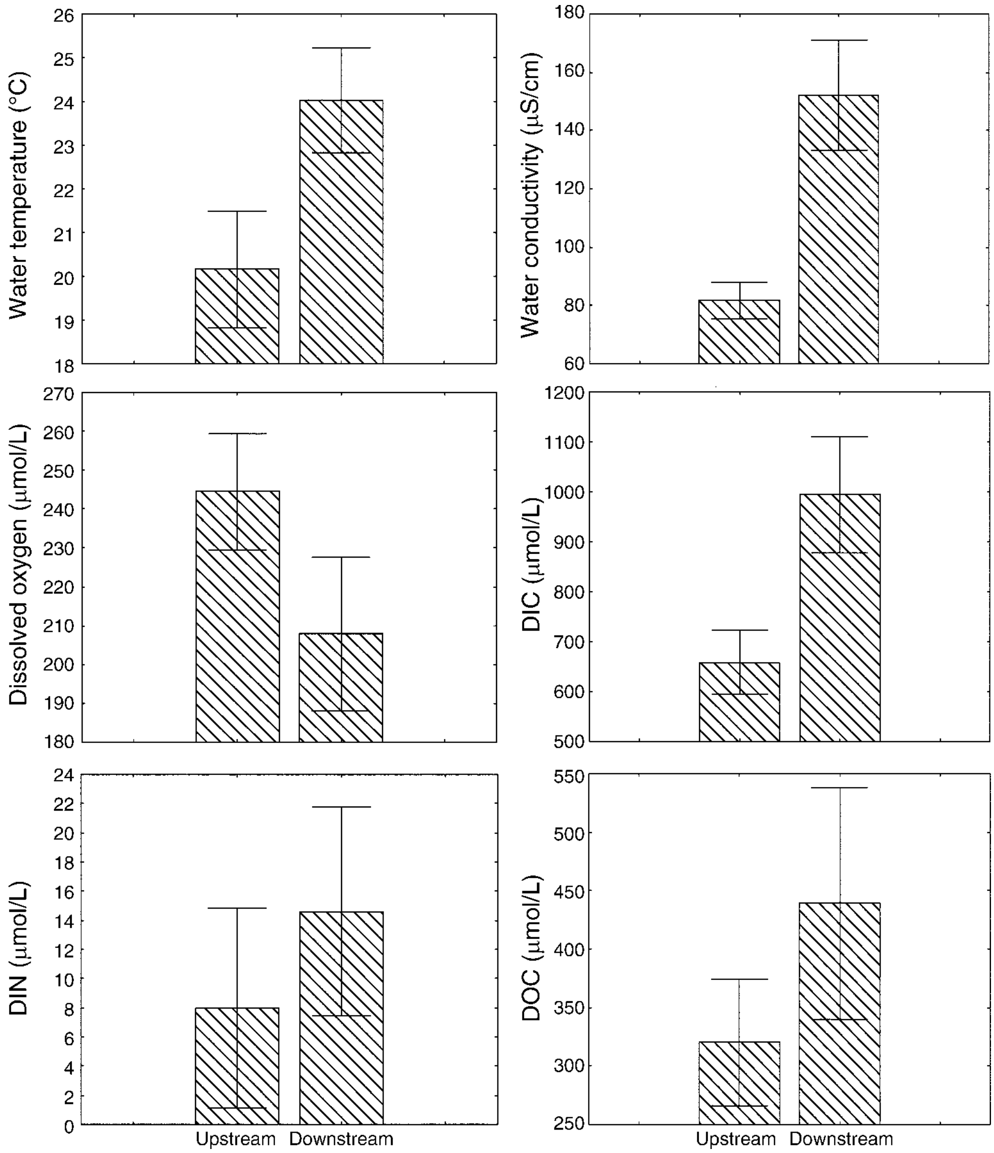

FIG. 4. Alteration of water parameters along a stream upstream and downstream from a sugar cane mill located in the state of São Paulo (Ometto et al. 2000). DIC = dissolved inorganic carbon; DIN = dissolved inorganic nitrogen; DOC = dissolved organic carbon. (See *Environmental issues: Deterioration of aquatic systems*.) Error bars represent ±SE.

viable production. In contrast to developed countries, over-fertilization and consequent losses of excess nutrients to aquatic systems have not been a major environmental problem in Brazil. However, the recent expansion of agriculture in the country coincides with a rapid increase in the consumption of fertilizer (ANDA 2006). The single largest annual crop in Brazil is soybeans, covering ~23 million ha of the 64 million ha of arable land in the country. Maize and sugarcane are grown on 13 and 7 million ha, respectively. While soybeans do not require application of N fertilizer, ~3.25 million tons of fertilizers (including nitrogen, phosphorus, and potassium) were applied to cornfields and ~3.13 million tons of fertilizers to sugarcane fields in Brazil in 2006. Therefore, much of this boost in the use of fertilizer in Brazil is attributed to the expansion and intensification of sugarcane production.

As more fertilizer is used in sugarcane crops, excess nutrients are likely to accumulate in the environment. Because of the high mobility of N, much of the excess is transported to aquatic systems. Excess nitrogen in agricultural fields has increased the export of N in streams and rivers worldwide and is one of the main causes of eutrophication of coastal waters and estuaries (Howarth 2005). In Brazil, eutrophication of dams and reservoirs are also related to increased inputs of reactive

N to landscapes (Matsumura-Tundisi and Tundisi 2005).

Nitrogen fertilizer is applied to sugarcane crops in Brazil at a rate of 80–100 $kg \cdot ha^{-1} \cdot yr^{-1}$. When compared to average amounts applied to annual crops in developed countries like the United States (140–160 kg $N \cdot ha^{-1} \cdot yr^{-1}$) and The Netherlands (300 kg $N \cdot ha^{-1} \cdot yr^{-1}$), and also in comparison to other important crops in Brazil like coffee and citrus, application in sugarcane fields is not considered excessive. Yet significant amounts of N from fertilizer can be lost to the environment in moist tropical and subtropical regions if application is poorly timed (Harmand et al. 2007). In addition, most of the N fertilizer in Brazil is applied in the form of urea ($CO(NH_2)_2$) (Cantarella 1998), and can easily be lost through volatilization of ammonia (NH_3) or during nitrification. Volatilization from soils occurs when urea is transformed into ammonium carbonate through the action of urease, an enzyme that catalyzes urea hydrolysis. Under specific conditions (high temperatures and high pH), ammonium carbonate is transformed into NH_3 and emitted to the atmosphere. Emission of N_2O occurs when NH_3 is oxidized into NH_4^+, which is then nitrified into NO_2^- and NO_3^-.

Several studies have shown that the use efficiency of fertilizer N by sugarcane crops in Brazil is rather low. On average, only ~20–40% of the N applied to sugarcane is assimilated in plant tissues, including roots, stalk, leaves, and tip (Oliveira et al. 2000, Trivelin et al. 2002, Basanta et al. 2003, Gava et al. 2005). Therefore, for every 100 kg N/ha applied to sugarcane fields, between 60 and 80 kg N/ha stays in the soil. Depending on soil and climate conditions, different fractions of this N in the soil are lost via volatilization, denitrification, erosion, and surficial water runoff, or assimilated later by sugarcane ratoons that will sprout in the next crop season (Trivelin et al. 1995, 1996, 2002, Cantarella 1998, Oliveira et al. 2000, Gava et al. 2001, 2005, Basanta et al. 2003). Leaching to groundwater also occurs, and ranges from 5 to 15 kg $N \cdot ha^{-1} \cdot yr^{-1}$, depending on soil characteristics (Oliveira et al. 2002).

Tracer experiments used to determine the fate of fertilizer ^{15}N within sugarcane revealed that 10% or 20% of the total fertilizer N applied to crops is assimilated in the stalks, which is the part actually used in the industry, while another 10–20% ends up in other aerial parts of the plant such as the tips and straw, which are either burned or decomposed in the field (Oliveira et al. 2000, Gava et al. 2001, 2005, Basanta et al. 2003). Based on these values, an estimated 10–20 kg N/ha of the fertilizer N applied to crops is transported to the mills in the sugarcane stalks for production of ethanol and sugar, while the remainder stays in the field or is emitted to the atmosphere. Eventually, even the relatively small amount of N transported to the mills is recycled back into the fields, because byproducts from sugarcane processing such as vinasse are used to fertilize and irrigate crops.

Large losses of N from sugarcane fields occur not only because of the relatively low use efficiency of N fertilizer by the plant, but also via ammonia volatilization during plant senescence due to the high evapotranspiration rates of sugarcane, which is characteristic of C_4 plants (Trivelin et al. 2002, Costa et al. 2003, Gava et al. 2005). Senescence is responsible for the emission of ~80 kg of N/ha (Trivelin et al. 2002), while volatilization from soils fertilized with N amount to 30–40% of the fertilizer applied, or 30–40 kg of N/ha, assuming a fertilizer application rate of 100 kg N/ha. Therefore, total gaseous losses from volatilization in sugarcane crops are an estimated 110 kg (80 + 30 kg) to 120 kg (80 + 40 kg) of N/ha annually. Although the soil organic matter reservoir is an additional source of reactive N, biological fixation may supply an important amount of reactive N. In Brazil, several varieties of sugarcane are able to fix N biologically in symbiosis with endophytic bacteria located in roots and foliage tissues (Boddey et al. 2001). Depending on environmental conditions, fixation by Brazilian sugarcane varieties is a maximum of 150 $kg \cdot ha^{-1} \cdot yr^{-1}$, with in situ rates averaging between 30 and 50 $kg \cdot ha^{-1} \cdot yr^{-1}$ (S. Urquiaga, *personal communication*).

Ammonia emitted during volatilization to the atmosphere is likely to be redeposited in the region in dry atmospheric deposition, and ammonium (NH_4) deposited regionally in wet deposition (Holland et al. 1999). In addition, most of the N from fertilizer absorbed by sugarcane and transported to ethanol production mills is likely to be recycled back into the fields. Therefore, while the addition of fertilizer N to sugarcane crops is relatively low in comparison to that of other crops, very little is likely to be exported from regions where sugarcane is cultivated. Hence, it is possible that sugarcane cultivation in Brazil may lead to an excess of N in soils, and subsequent higher delivery rates to aquatic systems. High rates of N export into rivers draining watersheds heavily cultivated with sugarcane in Brazil, such as the Piracicaba and Mogi river basins, have been reported (Filoso et al. 2003).

Besides higher delivery rates to aquatic systems, high inputs of reactive N to the landscape can accelerate the N cycle in sugarcane regions, and consequently, emissions of nitrous oxide (N_2O) associated with the processes of nitrification and denitrification. Nitrous oxide is a potent greenhouse gas which is ~300 times stronger than CO_2. Therefore, emissions of N_2O by sugarcane fields is an important trade-off in the global warming scenario, and must be taken into account in the whole balance of the sugarcane crop as renewable fuel (Crutzen et al. 2007).

Destruction of riparian ecosystems

The movement of solutes and eroded soils from the uplands to surface waters can be controlled by riparian forests that usually occupy a narrow belt of land along streams and rivers. When riparian forests are removed, the detrimental impacts of sugarcane cultivation and ethanol production on aquatic systems are exacerbated by degrading water quality, decreasing biodiversity, and increasing sedimentation (Corbi et al. 2006; see Plate 1). According to Brazilian legislation, the riparian vegetation on both margins of a stream or river must be preserved at a width that is relative to the channel width, with a minimum of 10 m for streams, and a maximum of 500 m for rivers. However, assuming a generalized buffer width of 30 m for both streams and rivers, Silva et al. (2007) reported that only 25% (500 km^2) of riparian forests remain in the seven major agricultural watersheds in the state of São Paulo. The other 75% (4500 km^2) of the riparian zone was converted to sugarcane and pasture.

In the two major watersheds that had the largest percentage cover of sugarcane in 1997 (Piracicaba and Mogi), only 13–18% of the riparian vegetation was preserved (Silva et al. 2007). The approximate cost for restoration of riparian forest in the region was estimated at US$3500/ha (R. R. Rodrigues, *personal communication*). Hence, restoring riparian vegetation in these basins would cost between US$200 and 250 million for both basins. Although costly, the price for restoration was equivalent to only 6% and 8% of the gross domestic product (GDP) from agricultural products and industries in the Piracicaba and Mogi basins, respectively.

Riparian forests are complex ecological systems localized at the land–water ecotone that perform a disparate number of ecological functions compared to most upland habitats (Naiman et al. 2005). These ecosystems typically maintain high levels of biodiversity (Naiman and Décamps 1997). Therefore, the ecological consequences of alterations to riparian forests include not only obvious changes in the plant community, but also in the animal community.

In sugarcane areas in Brazil, reported effects of degradation of riparian forests on animal communities range from increased numbers of fish species (Gerhard 2005) to decreased small-mammal species richness (Dotta 2005, Gerhard 2005, Gheler-Costa 2006, Barros Ferraz et al. 2007). The widespread increase of generalist species (which have the ability to live in many different places while tolerating a wide range of environmental conditions) that are typical of degraded areas (Gheler-Costa 2006), such as capybaras (*Hydrochoerus hydrochaeris*), and small rodents such as *Cerdocyon thous* and *Lepus europaeus* (Dotta 2005), is common. Moreover, 18 species of medium- to large-sized mammals typical of more preserved and larger forested fragments of the state of São Paulo could not be found in riparian forest fragments of sugarcane-dominated watersheds (Dotta 2005).

Besides the alteration in community structure, the widespread occurrence of generalist species of animals in sugarcane areas has been associated with public health problems. For instance, the increase of the capybara population in the Piracicaba River basin has lead to the spread of Brazilian spotted fever (Labruna et al. 2004), which has been reported as the cause of seven deaths in the region.

Environmental consequences of sugarcane burning

Sugarcane burning is a common crop management practice in Brazil, as it is used to facilitate manual harvesting by burning most of the straw and leaves. Generally, sugarcane is burned during the night, between April and December. An estimated 2.5 million hectares, or 70% of the sugarcane area, was burned in 2006 in the state of Sao Paulo (Folha de São Paulo, 11 August 2007, page A21 [*available online*]).[4] If we assume this same percentage area for other sugarcane regions in Brazil, we estimate a total of ~4.9 million hectares were burned in Brazil because of sugarcane.

Sugarcane burning increases soil temperature, decreases soil water content and bulk density and, consequently, leads to soil compaction, higher surface water runoff, and soil erosion (Dourado-Neto et al. 1999, Oliveira et al. 2000, Tominaga et al. 2002). Additionally, Pereira-Netto et al. (2004) detected high concentrations of polycyclic aromatic hydrocarbons (PAH) in soils located near sugarcane burning areas. Soils contaminated with these compounds, which are often carcinogenic, represent a risk for human health when leached to water bodies.

In one of the most important sugarcane regions of the state of Rio de Janeiro (Southeast region), PAHs were detected in recently deposited sediments in lakes (Gomes and Azevedo 2003). Because PAHs were also found in the atmosphere in this region (Azevedo et al. 2002, Santos et al. 2002), sugarcane burning was determined as the most likely source of PAHs in soils and sediments. Atmospheric PAHs were found in the region of Araraquara, one of the important sugarcane areas of the state of São Paulo (Zamperlini et al. 1997, Godoi et al. 2004), and one of the compounds, benzo[a]pyrene, which has high carcinogenic properties, was found in higher concentrations than in the atmosphere of large cities.

Biomass burning has been recognized as one of the main sources of pollution from aerosol particles, especially in tropical regions of the world (Crutzen and Andreae 1990). Aerosol particles are not only important in the radiative budget of the atmosphere (Oglesby et al. 1999, Ramanathan et al. 2001, Streets et al. 2001), but also affect the concentration of cloud condensation nuclei, which affect cloud albedo and rain droplet formation (Roberts et al. 2001).

The average concentration of total suspended aerosol particles (particulate matter $\leq$10 μm) collected in Piracicaba county during the sugarcane burning season was significantly higher (91 $\mu g/m^3$) than the average in the nonburning season (34 $\mu g/m^3$) (Lara et al. 2005). Principal component analysis (Lara et al. 2005) and

[4] ⟨http://www1.folha.uol.com.br/folha/ciencia/ult306u319319.shtml⟩

stable carbon isotopic composition of aerosol particles (Martinelli et al. 2002) revealed that sugarcane burning was the main source of particles during the burning season, while soil particles were the main source during the nonburning season. The annual average for suspended aerosol particles established by Brazilian law is 70 $\mu g/m^3$, but concentrations found in the Piracicaba region were higher during the burning season. Similar concentrations (70–90 $\mu g/m^3$) were reported for the city of São Paulo during the winter (Castanho and Artaxo 2001), and for the state of Rondônia, in the Amazon region, where extensive areas of forest are burned every year (Artaxo et al. 2002). The concentrations found in the Piracicaba region were also similar to those found during the burning season in Araraquara, another sugarcane region of São Paulo. In both regions, peak concentrations reached 240 $\mu g/m^3$ during the burning season (Allen et al. 2004). Black carbon concentrations were also significantly higher during the burning season, and days with burnings had higher black carbon concentration than days without burnings (Lara et al. 2005).

Gas emissions to the atmosphere are another aspect of atmospheric pollution associated with sugarcane burning. In sugarcane areas, concentrations of CO and O_3 are commonly high (Kirchoff et al. 1991), while nitrogen oxides (NOx) emissions reached 25 kg N/ha (Oppenheimer et al. 2004). Part of the N lost to the atmosphere during burning of sugarcane fields returns to the Earth's surface via wet and dry deposition. Rates of wet atmospheric deposition in the Piracicaba River basin were 5 and 6 kg $N \cdot ha^{-1} \cdot yr^{-1}$ (Lara et al. 2001), which are similar to those found in a region of intense forest fires in the Amazon, and also in areas of the northeastern United States where emissions of nitrogen from the combustion of fossil fuels by vehicles and from power plants are considered high. In comparison to pristine areas of São Paulo state and the Amazon region, N deposition rates in the Piracicaba basin are 3–4 times higher (Almeida 2006). As nitrogen oxides react with water to form nitric acid (HNO_3), acid rain becomes another problem associated with burning of sugarcane. In the Piracicaba basin where sulphur emissions are low, the average annual pH of rain varies between 4.5 and 4.8. Therefore, most of the acidity found in the rain comes from the formation of nitric acid (HNO_3) (Lara et al. 2001).

Acidification of surface waters has been one of the most prominent problems associated with emissions of acidifying compounds such as NOx to the atmosphere in the temperate zone. In contrast, high buffer capacity of streams and rivers of São Paulo, especially where untreated domestic sewage discharges are high (Ballester et al. 1999, Martinelli et al. 1999*b*, Krusche et al. 2003), have protected these systems from acidification. However, as the already basic cation-poor tropical soils in Brazil receive continuous acid rain, H^+ may replace the few remaining cations in the clay surface, causing further acidification and impoverishment of this type of soil (Matson et al. 1999, Krusche et al. 2003). The end of this process is the replacement of H^+ by Al^{+3}, which, in high concentrations, is toxic to plants (Schulze 1989).

Public Health and Social Issues

Sugarcane burning and respiratory diseases

In addition to the negative environmental effects, sugarcane burning also affects the health of people living in areas where burning is intense (Arbex et al. 2000, 2007). Epidemiological studies conducted in two counties in the state of São Paulo (Araraquara and Piracicaba), which are surrounded by sugarcane fields, show that respiratory morbidity increased significantly with the concentration of aerosol particles from sugarcane burning (Arbex et al. 2000, 2007, Cançado et al. 2006). During the sugarcane burning season of 1995 in Araraquara, a study found a significant correlation between the daily number of patients who visited hospitals in the region for inhalation treatment for respiratory diseases, and the mass of particle aerosols (Arbex et al. 2000, 2007). In a second study, conducted in the Piracicaba region, Cançado et al. (2006) found a significant correlation between $PM_{2.5}$ (particulate matter $\leq 2.5 \mu m$), PM_{10} (particulate matter ≤ 10 μm), and black carbon concentrations, and the number of children and elderly patients admitted to hospitals. According to their results, increases of 10 $\mu g/m^3$ of the $PM_{2.5}$ concentration lead to an increase of $\sim$20% in the number of hospital admissions.

Arbex (2003) concluded that sugarcane burning is responsible for aggravating the health of people prone to respiratory diseases, which, in turn, increases the demand and expenditure in the public health system. Thus the burning of sugarcane affects several sectors of society, and has negative impacts even for people living outside of sugarcane-ethanol industry areas. Yet sugarcane burning continues to be a widely used land management practice in Brazil, despite efforts by state and federal governments to eradicate it.

For instance, Law 11,241, established by the state of São Paulo in September 2002, requires that by 2006 only 30% of areas with slope lower than 12%, could be burned for sugarcane harvesting. The same law states that by 2011 half of the area in sugarcane farms must be protected from burning, and burning would be entirely outlawed by 2021. The São Paulo state government is trying to convince sugarcane growers to stop sugarcane burnings in 2014.

Exploitation of cane cutters

Sugarcane brought by the Portuguese from Africa was one of the first crops cultivated in Brazil. In the beginning, the Portuguese tried forcibly to make Native Brazilians work in the sugarcane fields and mills, but after failing, they started bringing African people to work as slaves. Although slavery was abolished in Brazil in 1888, most of the sugarcane in Brazil today is still

TABLE 1. Name, age, date, and cause of death for sugar cane cutters in counties within the state of São Paulo, Brazil, since 2004.

Name	Age	Date of death	Cause	County
Galvão, J. E.	38	April 2004	cardiac arrest	Macatuba
Santos, M. A.	33	April 2004	cardiac arrest	Valparaíso
Pina, M. N.	34	May 2004	cardiac arrest	Catanduva
Pinto, L. R.	27	March 2005	respiratory arrest	Terra Roxa
Santos, I. V.	33	June 2005	acute pancreatitis	Pradópolis
Lima, V. P.	38	July 2005	cerebrovascular accident	Ribeirão Preto
Sales, J. N. G.	50	August 2005	respiratory arrest	Batatais
Diniz, D.	55	Sept. 2005	unknown	Borborema
Souza, V. A.	43	Oct. 2005	unknown	Valparaíso
Gomes, J. M.	45	Oct. 2005	unknown	Rio das Pedras
Lopes, A. R.	55	Nov. 2005	pulmonary edema	Guariba
Santana, J.	37	June 2006	unknown	Jaborandi
Borges, M. N.	54	July 2006	unknown	Monte Alto
Gonçalves, C.	41	July 2006	unknown	Taiaçú
Almeida, O.	48	Sept. 2006	unknown	Itapira
Martins, J. P.	51	March 2007	cardiac arrest	Guariba
Souza, L. P.	20	April 2007	unknown	Colina
Souza, J. D.	33	June 2007	unknown	Ipaussu

Source: Inês Fascioli and Garcia Peres, 14 May 2007 (see footnote 5).

harvested manually, and the conditions for laborers have not improved much from over a century ago (Rodrigues 2006).

The workday consists of 8 to 12 hours of cutting and carrying sugarcane stalks, while inhaling dust and smoke from the burned residue (Rodrigues 2006). In addition, working conditions such as clean water, restrooms, and food storage facilities are usually absent in sugarcane fields. These poor working conditions often result in lawsuits against sugarcane employers by the Brazilian Ministry of Labor (Luze de Azevedo, "Força tarefa autua usinas na região de Prudente," 19 July 2007; Davi Venturino, "Juíza garante condições para bóia-fria," 4 August 2007; *available online*).[5] As many cane cutters are short-term migrants from other regions of Brazil, they have no alternative but to reside in inadequate lodging during cane harvest (Costa and das Neves 2005) (Luze Azevedo, "Alojamentos na mira do Ministério do Trabalho," 3 August 2007; see footnote 5).

Manual sugarcane harvesting in Brazil includes first the burning of dry leaves and other plant residues such as the tips to facilitate harvesting, and then the cutting of stalks as close to the ground as possible. Once cut, the stalks are transported manually to a depository, and the laborer is paid by the mass of sugarcane cut per day. According to Alves (2006), a cutter in 1950 cut an average of 3000 kg of sugarcane per day, while 30 years later the average was ~6000 kg/d. More recently, numbers have increased to almost 12 000 kg/d, but in the most intensively cultivated sugarcane regions in Sao Paulo, the average ranges between 7000 and 8000 kg/d (EPTV, "Pesquisa constata aumento no corte de cana," 18 May 2007 (see footnote 5). Alves (2006) estimated that for every 6000 kg of stalks cut, a cutter swings his machete ~70 000 times and walks a distance of 4.5 km to transport 15 kg of stalks at a time to a distance varying from 1.5 to 3 m.

Although the cane cutters are paid by the mass of sugarcane stalks cut per day, the mass is an estimate based on the linear distance that a cutter covered in one day. Employers convert the linear distance into an estimated area by multiplying the distance by a swath of 6 m. For instance, for every 1000 m covered by the cane cutter, the calculated area is 6000 m^2. This area is then converted into sugarcane mass by the industry according to numbers obtained from randomly selected areas where the sugarcane was actually cut and weighed in the field.

The problem with this method is that the mass of sugarcane can vary widely temporally and spatially depending on local conditions. The weighing is also done by the industry, and does not include any oversight by the field workers. The result is that cane cutters are usually underpaid (Alves et al. 2006). To compensate for low wages, cutters often try to maximize their daily earnings by working long hours, even under inappropriate conditions. Consequently, between 2004 and 2007, several deaths of cane cutters in sugarcane fields were reported in the state of São Paulo (Table 1). All of the deaths were of people younger than 55 years old, and most of them (67%) were younger than 45. Although the reported cause of death was unknown in half of the cases (Table 1), for the other half, cause of death could be linked to high working loads and poor working conditions (Scopinho et al. 1999).

The average price paid for 1000 kg of sugarcane stalks cut is equivalent to ~US$1.2. Therefore, for an average yield of 10 000 kg/d, the cane cutter earns US$12. On a monthly basis, and assuming 24 workdays per month, a cutter makes ~US$300 (José Maria Tomazela, "Canavieiro é o piro serviço do mundo," 31 March 2007; (see footnote 5). Considering that the total cost of produc-

[5] ⟨www.pastoraldomigrante.org.br⟩

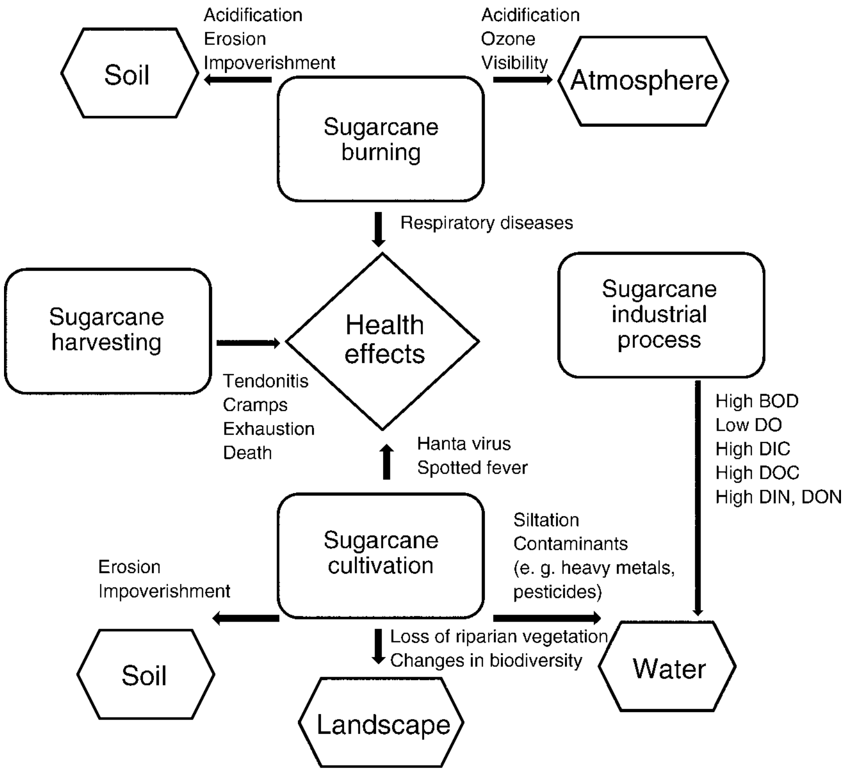

FIG. 5. Diagram showing the main environmental and social impact of the sugar cane agro-industry. For a list of water quality acronyms, see Fig. 4; BOD = biochemical oxygen demand; DO = dissolved oxygen.

tion of ethanol in Brazil was ~US$1.10 per gallon (1 gallon = 3.78 L) during the 2005 crop year, with variable costs of US$0.89 per gallon and fixed costs of US$0.21 per gallon, and that in early 2006, the wholesale price paid to the mills for anhydrous ethanol was US$2.05 per gallon (Martines-Filho et al. 2006), revenue values were in the order of 50% of the costs. However, it is clear that such high return rates are not being reflected in the salary and working conditions of cane cutters.

The typical sugarcane worker in Brazil is a migrant from a poor area of the northeastern region of the country who moves to the Southeast to work for 6–8 months as a sugarcane cutter. These migrants are usually hired and transported to sugarcane plantations by people known in Brazil as "gatos." The cane cutters are hired under false promises of a good salary and decent living conditions (Costa and das Neves 2005). In such situations, Brazilian labor legislation is entirely disregarded.

However, increasing pressure from authorities in Brazil and from the international community is making the ethanol industry recognize that it is not possible to claim that ethanol is a clean or sustainable fuel, when laborers are still working in extremely poor conditions, are severely underpaid, and worst yet, often die of exhaustion in the fields during sugarcane harvesting (Scopinho et al. 1999). Recently, one of the major industries in the sugarcane business, Cosan, signed an agreement under the Brazilian Law called "adjustment of conduct," promising sugarcane cutters better working and living conditions. In addition, this agreement assures the proper recruiting and hiring of sugarcane cutters to eliminate the work of "gatos" and the problems associated with them. As real employees, sugarcane cutters will also have the same rights and benefits as other categories of workers in the industry.

CONCLUDING REMARKS AND RECOMMENDATIONS

Poets—and city folks—love to romanticize agriculture, portraying it as some sort of idyllic state of harmony between humankind and nature. How far this is from the truth! Since Neolithic man—or most probably woman—domesticated the major crop and animal species some 10–12 millennia ago, agriculture has been a struggle between the forces of natural biodiversity and the need to produce food under increasingly intensive production systems.

—Norman Bolaug

These words, written by the father of the Green Revolution (Borlaug 2002), eloquently say that agriculture is in constant conflict with the environment. Yet why is this conflict usually downplayed when it comes to sugarcane and ethanol production in Brazil, while it is debated for other cultures that also cover extensive areas

PLATE 1. Aerial photo of a sugar cane plantation and a small water body with highly fragmented remains of riparian forest, Brazil. Photo credit: Geraldo Arruda, Jr.

in Brazil, such as maize (13 million ha) and soybeans (23 million ha)?

One of the reasons is that the sugarcane ethanol program in Brazil has been considered, by most Brazilians, a successful solution to the 1970s oil crisis, and for the problem of the country's past dependence on foreign oil. More recently, ethanol production in Brazil started being seen as a potential solution to global warming problems, which would also benefit the Brazilian economy by creating new international trade opportunities. Therefore, generally speaking, the loss of natural resources associated with the expansion of sugarcane and increase of ethanol production in Brazil is commonly seen as necessary and justifiable. Still, the OECD-FAO Agricultural Outlook 2007–2016 (2007) estimated that in 2016 Brazil will produce ~44 billion liters of ethanol, an increase of 145% relative to 2006. Assuming that one hectare of sugarcane is necessary to produce 6000 liters of ethanol, Brazil would have to double the present land cover of sugarcane in the country, from 7 to 14 million hectares. Approximately 60% of this total area would be utilized for ethanol and 40% for sugar. Furthermore, 44 billion liters of ethanol produces ~500 billion liters of vinasse, along with all the other environmental problems discussed above, and summarized in Fig. 5.

The sugarcane industry in Brazil has enjoyed support and protection from politicians and lobbyists for centuries. Consequently, the industry has created a legacy of disregard for environmental and social laws in the country. Bold examples include the several occasions that enforcement of laws regulating or banning sugarcane burning practices have been postponed, and civil suits regarding poor living conditions of sugarcane cutters have been ignored by the judicial system in Brazil. However, it is obvious that this template of environmental degradation and social injustice must go through major changes if the sugarcane-ethanol industry in Brazil is to be truly competitive in a market where biofuel production and use are expected to be sustainable and socially correct. Such changes should include: (1) proper planning and environmental risk assessments for the expansion of sugarcane to new regions such as Central Brazil, (2) improvement of land use practices to reduce soil erosion and nitrogen pollution, (3) protection of streams and riparian ecosystems, (4) banning of sugarcane burning, and (5) fair working conditions for sugarcane cutters. It is important to recognize, nevertheless, that a number of external factors, in addition to internal ones, contribute to the difficulties faced by Brazil and other developing countries in overcoming environmental and social issues associated with agrobusiness (Almeida et al. 2004). Hence, we support the idea that rather than creating more barriers to the trade of agricultural products from Brazil, a more constructive approach should be taken by international stakeholders and even the World Trade Organization (Almeida et al. 2004) to promote sustainable development in countries where agricultural expansion and biofuel production are likely to grow substantially in the next few years. In addition, we propose that environmental values be included in the price of biofuels from Brazil and elsewhere in order to discourage the excessive replacement of natural ecosystems such as forests, wetlands, and pasture by bio-energy crops.

If the same environmental and social problems linked with the sugarcane industry persist in Brazil into the future, most of the burden caused by these problems will be experienced by the whole society, especially those with lower incomes. On the other hand, the economic profits will be enjoyed by only a few, since Brazil has one of the largest economic inequalities in the world (CEPAL 2007).

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