Renewable and Sustainable Energy Reviews 52 (2015) 1847–1856

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Reassessing the environmental impacts of sugarcane ethanol production in Brazil to help meet sustainability goals

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ARTICLE INFO

Article history:
Received 13 January 2015
Received in revised form
5 June 2015
Accepted 4 August 2015

Keywords:
Sugarcane ethanol
Biofuel
Renewable energy
Environmental impact
Sustainability
Brazil

ABSTRACT

The potential for sugarcane ethanol from Brazil to mitigate GHG emissions is undeniable, but the way that ethanol is produced during the agricultural and industrial phases will ultimately determine its benefits to society. In this paper, we evaluate the environmental impacts of sugarcane agriculture and ethanol production in Brazil as management practices continue to change and production expands to new frontiers. We focused our evaluation on the impacts on water, atmosphere, and soils, including how the application of organic and inorganic fertilizers and the accumulation of crop residue in the field affect emissions of greenhouse gases (GHG). We also addressed the impacts of land use changes on threatened biomes and discussed some of the present obstacles regarding conservation and restoration efforts. We concluded that, since a similar assessment was put forth in 2008, our knowledge about the environmental impacts of sugarcane ethanol in Brazil has advanced with regard to soil degradation, nitrogen dynamics, and soil carbon stocks. However, more information is still needed about the impacts of the increasing use of pesticides, herbicides, and fertilizers in sugarcane agriculture, especially on water resources. Furthermore, without a better understanding about how landscape fragmentation affects the biodiversity of terrestrial and aquatic tropical ecosystems and the services they provide, policies created to protect and restore them may be ineffective. On the other hand, the use of presently available scientific information to end unsustainable farming and the implementation of conservation strategies proposed by the Brazilian Forest Code could be a first step to guarantee that ethanol is produced more sustainably in Brazil.

Contents

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http://dx.doi.org/10.1016/j.rser.2015.08.012
1364-0321/

1. Introduction

In 2009, Tilman et al. [1] affirmed that modern society could not miss the opportunity of using biofuels to help mitigate emissions of greenhouse gases (GHG), strongly emphasizing the importance of producing biofuel sustainably and without competing for land with food production. A couple of years later, the IPCC Special Report on Renewable Energy Sources [2] supported similar ideas, warning that indirect effects of land use changes associated with biomass production for bioenergy could decrease or even neutralize potential GHG savings. Therefore, it has become clear in recent years that biofuels can play a contradictory role. While the potential for biofuels to mitigate GHG emissions is indisputable, the way that feedstock for biofuels is produced ultimately determines the benefits to society [3], especially if land scarcity and environmental trade-offs are taken into consideration [4].

Sugarcane ethanol is an alcohol-based renewable biofuel produced by the fermentation of sugarcane extract and molasses, and Brazil is the world's largest producer of it. Brazil is also the world's largest producer of sugar. As such, sugarcane agriculture in the country is quite extensive, covering an area of about 10 million ha of arable land and ranking as the third largest crop after corn and soybean. Sugarcane agriculture in Brazil began about 500 years ago, but the expansion in crop area and yield over the past 20 years or so has been unprecedented [5]. Between 1990 and 2011, for instance, the area cultivated with the crop increased by 45% and yields increased from about 8 to 40 billion Mg yr^{-1}, averaging an increase of 1.5 billion tons per year.

Large scale production of ethanol biofuel in Brazil started in the late 1970s, amid concerns about energy security and the economy [6]. Essentially, petroleum shortages and elevated prices in the early 1970s propelled Brazil to invest in large scale ethanol fuel production to decrease its dependence on foreign oil and stimulate the economy by reducing imports and promoting agro business. Obviously, the idea of producing and using biofuel to mitigate GHG emissions and climate change was not a concern at the time.

Looking back, there is no doubt that Brazil's successful use of sugarcane significantly reduced the country's oil dependency, increased energy security, and contributed to a thriving economy. In more recent years, the increase in bioethanol consumption in the country and the production of bioelectricity from sugarcane solid waste have also guaranteed a considerable reduction in GHG emissions [7]. However, growing concerns about the social and environmental costs associated with ethanol production at the large scale (e.g. [8,9]) have led to the creation of indicators of environmental sustainability (e.g. [10–15]) to ensure that costs do not outweigh benefits to society.

Different indicators have been used to assess the environmental sustainability of biofuels. The criteria commonly employed include an assessment of the GHG balance and impacts of biofuel production on biodiversity, soil, water, and the atmosphere. The evaluation of the GHG balance is an obvious step, since the goal of using biofuels instead of other sources of energy is to reduce GHG emissions. Evaluating the impacts of biofuel production on biodiversity addresses the loss of sensitive habitats, fauna, and flora species associated with land-use change for production of biofuel feedstocks. The soil quality assessment addresses soil degradation from erosion and compaction, as well as soil acidification and the loss of key soil quality indicators such as carbon, nitrogen, and phosphorus. The water criterion evaluates impacts on water quantity and quality. Water quantity impacts are related to the use of water in the agricultural and industrial phases of biofuel production, while water quality impacts are usually related to the use of fertilizers and pesticides in the agricultural phase. Finally, the atmosphere criterion addresses the issue of air pollution from agricultural practices and industrial production. In the case of Brazilian sugarcane ethanol, air pollution associated with the practice of burning sugarcane fields prior to manual harvesting has been a serious problem[16–20].

The criteria adopted to assess biofuel sustainability are quite comprehensive and should help guarantee the benefits of biofuel use to society. Nevertheless, our knowledge about the impacts of sugarcane ethanol produced in Brazil is still limited, especially regarding water and soils [13], which presents a serious obstacle in assessing sugarcane biofuel sustainability. The limitation exists mostly because Brazil covers an extensive area with widely diverse regions, ranging from the rain forests of the Amazon and the Atlantic Coast to the dry lands of the Caatinga and savannas of the Cerrado.The impacts of sugarcane agriculture and ethanol production in these widely different biomes are likely to vary considerably [14]. Yet, little is known about this variation, especially when the diversity of agricultural practices is considered.

To address such concerns about sugarcane ethanol production in Brazil as it expands to different regions, we provide a revised assessment of the environmental impacts associated with the agricultural and industrial phases of production using the same evaluation framework proposed by Martinelli and Filoso [8]. In this revised assessment, we also take into consideration the different measures that have been adopted and implemented in the country in the past few years in order to improve the sustainability of ethanol production. Our ultimate goal is to highlight improvements as well as concerns related to environmental impacts in order to help guarantee that Brazilian ethanol is produced within the standards for sustainable biofuel.

2. Premise

2.1. The recent expansion of sugarcane cultivation in Brazil

For the past 50 years, most of the sugarcane cultivation in the country has been concentrated in the Southeast region, especially over former areas of Atlantic Forest in the states of São Paulo and Minas Gerais. Therefore, the expansion of sugarcane agriculture has occurred mostly over areas of degraded pastureland, citrus agriculture, and annual crops. Sugarcane has been largely planted in the Southeast region of Brazil because it is where most of the sugarcane mills are located. However, sugarcane is now fast expanding into the Cerrado region, mainly in the states of Mato Grosso do Sul and Goiás, and also not only over pastureland but in areas of natural vegetation. Sugarcane has been also cultivated for centuries along the northeastern coast of Brazil, but little expansion has happened in that region in recent years.

In 2012, the area covered with sugarcane in Brazil reached almost 10 Mha, with the largest expansion occurring between 2007 and 2008. In this period, the rate of sugarcane expansion reached approximately 1 Mha yr^{-1}. Approximately 1.5 million ha of the pasture land in Brazil was converted to sugarcane between 2000 and 2009. This area represented 64% of the area of sugarcane expansion in the country, while the area converted from annual crops and citrus, and natural vegetation represented a smaller fraction of the expansion area, with 44,000 ha and 17,000 ha, respectively [21].

The area of natural vegetation converted to sugarcane during this period of expansion was not significant in comparison to the other land cover types. However, because the area included some of the most threatened tropical biomes on Earth, such as the Cerrado [22], the expansion of sugarcane over natural vegetation cover has significant environmental relevance. The Cerrado region has already lost more than half of its natural land cover in the past 20 years [23] and it is considered one the most threatened ecosystems on the planet because of agricultural expansion [24].

Egeskog et al. [15] have estimated that in order to fulfill the land requirement for the 21 new sugarcane mills approved to be built in the state of São Paulo in the next few years, an additional 0.7 Mha of land will be needed to meet a growing demand for sugarcane. The prediction is that, in São Paulo, most of the land conversion will occur over other types of cropland and not over pasture [15]. At the country scale, modeling simulations predict that sugarcane will have to expand over an area of 5.7 Mha in order for Brazil to reach its biofuel target for 2020 [7]. About 90% of the expansion is supposed to occur over pastureland, which minimizes the loss of natural vegetation. Nevertheless, converting areas of low intensity agriculture, such as Brazilian pastureland, to intensive agriculture invariably results in impacts to water and soils due to the use of fertilizers and pesticides, among other agricultural practices.

Martinelli and Filoso [8] have shown the remarkable increase in the use of fertilizer and pesticides that accompanied sugarcane expansion in Brazil in recent years. Such increase certainly assured a rise in sugarcane production during this period, with yields reaching up to 80 Mg ha^{-1} in 2009. When the use of fertilizers and pesticides decreased after 2010 due to a reduction in financial incentives and limited government subsidies for sugarcane agriculture, productivity fell for the first time in many years, to about 74 Mg ha^{-1}. Climate variability and the containment of costly management practices used to help maintain high productivity, such as the replanting of cane ratoons after multiple harvests, also played a role. However, the fact remains that high productivity in sugarcane is maintained by the application of fertilizers and other potentially toxic chemicals. Therefore, the environmental risks of substituting natural vegetation or less intensive agriculture by sugarcane in Brazil deserves attention.

2.2. Potential environmental impacts of sugarcane ethanol production

2.2.1. Atmospheric pollution

Sugarcane fields in Brazil have been historically burned to facilitate manual harvesting. It is a dated management practice, but several attempts to end it in recent years have been unsuccessful in many parts of the country due to a lack of law enforcement. However, the state of São Paulo, the largest sugarcane producing state in the country, has made significant progress towards eliminating this old practice by signing an agreement with the sugarcane industry to end sugarcane burning in areas with slopes lower than 12° before 2021 [25]. After this agreement, sugarcane burning in São Paulo decreased from 65% of 2.1 Mha of sugarcane area to 16% (0.78 Mha) [25]. Yet, until the laws banning sugarcane burning are better enforced in all states, the impacts of ethanol production on the atmosphere continues to be a serious issue and should be considered in any assessment of environmental impacts of ethanol production in Brazil. Even with the progress of the sugarcane burning ban in the state of São Paulo, we estimate that approximately 5 Mha of the sugarcane fields burn every year in the country.

A series of studies designed to evaluate the impacts of sugarcane burning on the atmosphere in areas of intensive cultivation in the state of São Paulo (i.e. Araraquara, Piracicaba, and Ribeirão Preto) have shown a constant pattern. In all study areas, the chemical composition of rainfall is strongly influenced by particulate matter in the atmosphere originating from sugarcane biomass. Particulate matter concentrations were especially high during the burning season, when fires frequently reached the maximum levels permitted by the state of São Paulo legislation [16,17]. In addition, concentrations of dissolved organic carbon [19], nitrate, and ammonium in rainfall were high in comparison to those in more pristine regions, while acid rain was common [16,20].

Well-known adverse human health problems associated with the exposure to high concentrations of particulate matter in the atmosphere, such as asthma and other respiratory diseases, are common in sugarcane regions in Brazil [17]. More alarming, however, is the fact that a number of studies in these regions have found high polycyclic aromatic hydrocarbons (PAH) levels in particulate matter associated with sugarcane biomass during the burning season, especially at night, when fires usually occur [26–28]. The presence of organic compounds such as PAHs in the atmosphere can represent serious risks to human health, as PAHs have been linked to mutagenicity [29–31] and cancer [27,32].

In addition to concerns about human health (e.g. [27,28,32–36]), toxic compounds emitted during sugarcane burning can impact aquatic and terrestrial ecosystems [37,38]. According to Tsao et al. [39], sugarcane burning is the largest cause of air pollution in the whole life cycle of ethanol production in Brazil, and the consequences are pervasive.

2.2.2. Sustainable use of water Resources

2.2.2.1. Water quantity. The impacts of bioenergy crops on water quantity are multiple, starting with the effects of land-use changes on critical biogeophysical processes that control the water cycle, such as evapotranspiration (ET) and albedo (e.g. [40–43]). For instance, when land-use changes increase ET rates, regional temperatures decrease as more energy is required to evaporate water and less to warm up the air [44]. An increase in albedo has a similar cooling effect as more shortwave radiation is reflected back to the atmosphere [42]. Moreover, when ET rates increase, plants consume more water and potentially deplete the groundwater in drier regions, such as in the Brazilian Northeast or the Cerrado [40,42,45]. Higher ET rates combined with a growing demand for water for irrigation in dry regions of Brazil can aggravate the problem and result in severe water scarcity in these regions [46].

At the local level, the consequences of land use changes on the water cycle have been more difficult to detect [44]. However, a recent innovative study in the state of São Paulo using eddy-covariance techniques to assess ET to precipitation ratios in sugarcane fields for two consecutive years of the crop cycle reported that ET in the first year was equivalent to 70% of the precipitation volume, while in the second year it decreased to 50% [45]. Using this information, Georgescu et al. [47] parametrized a regional climate model to simulate the hydroclimatic impacts of converting present vegetation (annual crop and native vegetation mixture) with sugarcane in the south-central region of Brazil, and predicted that regional temperatures will potentially change seasonally according to the sugarcane annual cycle. During the growing season, an increase in albedo will result in a cooling effect equivalent to 1 °C (more radiation reflected to the atmosphere), while in the post-harvesting period, a decrease in albedo will have the opposite effect.

In a different study based on remote sensing observations, Loarie et al. [48] predicted that converting native Cerrado vegetation into a mixture of pasture land and non-sugarcane crops can have a warming effect in the region. However, if pasture land and non-sugarcane crops are subsequently converted to sugarcane, there would be a cooling effect, which might be a more desirable outcome in a global warming scenario.

Although it is difficult to compare the results from the studies conducted by Georgescu et al. [47] and Loarie et al. [48] because of the different techniques used and assumptions made, the fact remains that both have shown that expanding sugarcane agriculture to the south-central region of Brazil can have significant impacts on ET rates and air temperature at the regional scale. Therefore, it would be useful to expand such modeling efforts to different scenarios and regions of sugarcane expansion in Brazil in order to better evaluate potential impacts on water resources. Such analyses would be useful to determine guidelines and best management practices that prevent the unsustainable use of water resources and guarantee the sustainability of ethanol production.

While we are still learning about the impacts of the agricultural phase of ethanol production on water quantity, there is a significant amount of information available about water use during the industrial process (e.g. [49–52]). This information has helped the industry make important improvements to reduce water use in recent years, when consumption went from about 15 m^3 per ton of sugarcane to 5 $m^3\ ton^{-1}$ by the mid-1990s [53], and to less than 2 $m^3\ ton^{-1}$ presently [49–51].

The demand for water in the industrial phase of sugarcane ethanol production can be substantial throughout the entire production process. However, approximately 36% of the water consumed in mills is from washing sugarcane stalks to remove soil particles and small debris prior to the fermentation phase. The fermentation and distillation phases each account for 27% of the water use. Therefore, efforts focused on reducing or recycling water from the sugarcane washing can have a significant impact on the overall consumption in mills. In fact, Chavez-Rodriguez et al. [49] have estimated that increasing water reuse in sugarcane mills could decrease consumption by 0.8 $m^3\ ton^{-1}$ of sugarcane, and reduce total usage to approximately 0.6 $m^3\ ton^{-1}$.

The target for water use in sugarcane mills proposed by water resources authorities in the state of São Paulo is 1.0 $m^3\ ton^{-1}$ of sugarcane, and 0.7 $m^3\ ton^{-1}$ in areas of water scarcity. Therefore, if the improvements suggested by Chavez-Rodriguez et al. [49] are implemented in São Paulo mills, they would fulfill the requirements targeted by the state.

2.2.2.2. Water quality. The impacts of sugarcane ethanol production on water quality can be divided into two major categories. One is inherent to intensive agriculture in general and related to the use of fertilizer, pesticides, and other toxic chemicals such as heavy metals transferred to aquatic ecosystems via surface runoff or leaching [52,54]. The other is more specific to sugarcane agriculture in Brazil and is associated with liquid waste generated during the process of ethanol production in mills [49]. It is difficult to distinguish the importance of these different sources of pollution in terms of the magnitude of impacts since these will depend on loads as well as on the initial conditions of aquatic ecosystems [52]. Therefore, while our discussion about the impacts of sugarcane ethanol production on water quality is focused on specific sources of pollution because of data availability, we recognize that other sources can be equally as important.

Among the sources of pollution most extensively studied is the vinasse, which is the liquid waste generated in large quantities during sugarcane ethanol production. In Brazil, an average of 10–15 liters of vinasse are generated for each liter of ethanol produced [55]. In the harvesting season of 2007–2008 alone about 120 million m^3 of vinasse were generated [51]. Vinasse production is supposed to further increase to 20 liters per liter of ethanol in the near future, with the production of second generation ethanol from sugarcane crop trash. Vinasse has a high labile organic carbon content and, thus, high biological oxygen demand [53]. It also has high concentrations of essential nutrients such as potassium (K) and nitrogen (N) [53,56,57], which have the potential to enhance primary production in aquatic ecosystems and promote eutrophication [8].

We still do not fully understand the impacts of vinasse loadings on biogeochemical processes in freshwater ecosystems. Nevertheless, because of well-documented problems of anoxia in water bodies receiving high loads of vinasse in sugarcane regions [57–59], the ethanol industry in Brazil regulated the disposal of vinasse about 30 years ago to be recycled back into sugarcane fields. The vinasse is now applied with other organic matter-rich effluents in a process called fertirrigation.

Despite the rapid positive effects of fertirrigation on aquatic ecosystems [46,60], there have been increasing concerns about the application of vinasse to soils. Recent studies have shown that applying vinasse in soils treated with synthetic N fertilizer can increase emissions of N_2O [61–63] and lessen the advantages of using sugarcane ethanol to reduce GHG emissions from fossil fuels. More eminent, however, is the problem of K accumulation in soils and leaching to groundwater from repeated vinasse application [55,64]. Besides impacts to soil and groundwater, high concentrations of K can potentially affect aquatic ecosystems when soil water and groundwater move into surface waters [58,65].

The problem with K accumulation in soil and groundwater is so serious in São Paulo that restrictions in the use of vinasse in sugarcane fields have been imposed based on soil K content [55,64]. Such restrictions are forcing mills to apply vinasse in fields further away from the ethanol factory, which alleviates the groundwater pollution problem [55,60] but at a higher cost for the mills. Therefore, as ethanol production increases, it will be increasingly important to find solutions for the vinasse that are both, cost-effective and environmentally responsible [8,66].

Presently, one of the alternatives being explored to manage vinasse is the reduction of its water content to decrease volume and facilitate transport [56]. Concentrated forms of vinasse also have the advantage of lowering rates of N processing in relation to conventional vinasse, which potentially decreases N_2O emissions [56]. However, any alternative for dealing with the vinasse problem in Brazil needs to be carefully evaluated before implementated in larger scale, since success will depend on a series of economic and environmental factors that vary spatial and temporally [57,66].

Finding solutions for water quality problems associated with vinasse will probably take time and involve a great deal of research due to the complexities associated with the diversity of sugarcane regions in Brazil. In contrast, finding solutions for water quality problems common to most types of intensive agriculture should be just a matter of detecting them and adopting appropriate existing best management practices. For instance, the use of pesticides in sugarcane agriculture has increased substantially in Brazilian sugarcane in recent years [67,68], yet, legal requirements or voluntary management practices to promote safe, responsible, and effective use are either lacking or not enforced. According to Schiesari and Grillitsch [69], there are 225 presently registered formulas of pesticides allowed in sugarcane agriculture in Brazil, with approximately half of them classified as "highly dangerous" or "very dangerous", especially for aquatic ecosystems. About 40% of the pesticides used present risks to groundwater [69], and one of them (hexazinone) has already been detected in groundwater samples from a prominent sugarcane region in Brazil [70].

To date, most of the scientific information about the environmental impacts of pesticides from sugarcane agriculture on water is from studies in Australia (e.g. [71,72]). However, the few studies in Brazil already suggest that the use of pesticides in sugarcane fields is impacting soils and water bodies [30,73–75]. Organochlorine pesticides have been found in sediments, bivalves, and fish in the Piracicaba Basin, which drains one of the largest sugarcane producing regions in Brazil [30]. Also, high levels of ametryn have been found in water, sediment, and bivalve samples collected by Jacomini et al. [75] in the Mogi-Guaçu River basin, another important region of sugarcane cultivation in the country.

Atrazine, simazine, and ametryn are among the most used agrochemicals in sugarcane agriculture in Brazil, hence, there has been a growing number of studies trying to determine the presence of these pollutants in surface waters or groundwater in regions of sugarcane cultivation. So far, low concentrations of ametryn have been found in surface waters [73], while pesticides concentrations in the Guarany aquifer near Ribeirão Preto, one of the large recharge zones of the state of São Paulo, are under the detection limit [76]. However, Dantas et al. [77] have detected hexazinone and diuron in water wells used by the population of Ribeirão Preto city. While in low concentrations, the simple fact that these two compounds have been detected in well water poses a potentially serious risk to human health.

A couple of studies in the state of São Paulo have also reported elevated concentrations of heavy metals in sediments and aquatic organisms in water bodies surrounding sugarcane fields [78–81]. However, as for pesticides, there is limited information available about the environmental impacts of heavy metal contamination on aquatic ecosystems in sugarcane regions. What is known is that heavy metals in Brazilian sugarcane agriculture originate from the application of fertilizers made with raw materials containing toxic metals such as cadmium (Cd), lead (Pb), and chromium (Cr) [82]. Such fertilizers are used to supply important micronutrients to sugarcane crops but they often include, in addition to desirable elements, toxic metals in their composition.

Most studies available to assess the impacts of fertilizer use in sugarcane agriculture in Brazil focus on the transport of excess nutrients to freshwaters. Eutrophication of aquatic ecosystems is a common problem in agricultural watersheds worldwide [83], especially because of excess N, which is a limiting nutrient to aquatic organisms. However, excess N in watersheds dominated by sugarcane land cover in Brazil is more likely to originate from urban sources than from fertilizer application [84].

It is still unclear what is the fate of N in watersheds with sugarcane agriculture in Brazil. The limited information available indicates that loads to streams and rivers are not as high as in other intensive agricultural regions of the world. One of the explanations may be that the use of N fertilizers in sugarcane crops in Brazil is relatively low, at about 80–100 kg ha^{-1}, in comparison to N fertilizer use in other types of agriculture, especially in developed countries [8]. Also, sugarcane plants have high N demand, which could prevent leaching from sugarcane fields fertilized with N [85–88]. Even after heavy rains, N losses reported from sugarcane growing in Oxisol soils fertilized with 120 kg ha^{-1} of N (in the form of urea) were trivial [88]. Also, the presence of positive clay charges in deeper profiles of tropical soils can prevent deep leaching of nitrate to groundwater and, subsequently, the transport to surface waters [89]. Nevertheless, sugarcane plants have low N uptake efficiency rates (usually 20–40%) [86,90–92], hence, as more N fertilizer is applied to sugarcane crops, the potential for losses to aquatic systems via surface runoff and leaching increase [93,94].

In contrast to N, losses of major cations, such as K, calcium (Ca), and magnesium (Mg), can be significant in sugarcane fields in Brazil [88,95]. Oliveira et al. [85] have reported losses of Ca and Mg up to 320 kg ha^{-1} and 80 kg ha^{-1}, respectively, in sandy soils treated with 90 kg ha^{-1} of N fertilizer and 120 kg ha^{-1} of potassium chloride (KCl). Also, Ghiberto et al. [88] have reported that about 67% of the K, 22% of the Ca, and 5% of the P applied to Ultisols in with 120 kg ha^{-1} of potassium oxide (K_2O) and phosphorus pentoxide (P_2O_5) plus 2 Mg ha^{-1} of dolomite limestone can be lost via leaching. However, the fate of cations in sugarcane fields vary according to soil type. While Ca losses can be substantial in sandy soils and Ultisols, losses of K and Mg are more variable [88]. In either case, the consequences of cation losses from tropical soils characteristically base poor are soil acidification, and the increase in the solubility of aluminum (Al^{3+}) and decrease in P availability. The availability of P in sugarcane soils studied in Brazil is consistently low, despite the high rates of P fertilizer application [88].

In addition to leaching, major cations and other nutrients can also be lost and transferred to aquatic ecosystems via soil erosion, which is prevalent in sugarcane agriculture in Brazil [95]. Nutrients adsorbed onto soil particles are carried away to aquatic systems via surface runoff, especially when bare soils are exposed during intense rain events.

Rainfall simulation experiments in Oxisols (clayey texture) have shown that after 65 min of rain at 80 mm h^{-1}, nutrient losses via erosion were substantial for P, followed by K, Ca, and Mg [95]. Losses were relatively larger in Alfisols at a slightly lower rainfall intensity, starting with Ca and P and followed by Mg and K [96]. Losses were even higher when soils were treated with 80 m^3 of vinasse and 550 kg ha^{-1} granular NPK (5-25-25), which simulates the fertilization scheme commonly used for sugarcane in Oxisols. In this instance, after about one hour of rainfall at 65 mm h^{-1}, substantial amounts of Mg were lost followed by Ca, K, and P [96].

In the tropics, P is usually a limiting nutrient in freshwater ecosystems [97,98]. Hence, excess loads entering waterways can result in eutrophication and cause impacts similar to those observed for excess N in temperate regions [99]. The difference, however, is that P losses result mostly from soil erosion and not from leaching. Therefore, efforts to prevent eutrophication in sugarcane watersheds should focus on best management practices to reduce soil erosion rather than on P fertilizer application. Moreover, because most of the electric energy produced in Brazil is hydroelectric, preventing soil erosion and eutrophication of water bodies and dams can be beneficial not only for aquatic ecosystems but for the country's economy as well.

2.2.3. Soils

Soil degradation in Brazilian sugarcane agriculture results from physical degradation as well as from erosion and the gradual loss of soil quality indicators, such as nutrient content and C stock. Because these issues can be prevented or minimized with the implementation of best agricultural management practices, we describe, below, key factors known to lead to soil degradation in an attempt to help guide the development of practices that would improve the sustainability of sugarcane ethanol production in Brazil.

2.2.3.1. Physical degradation of soils. Several studies have demonstrated that soils cultivated with sugarcane in Brazil undergo significant changes in terms of physical characteristics (e.g. [100–102]). Usually, changes begin with soil compaction and disaggregation linked to the use of heavy machinery during soil preparation and harvest, and progress into soil erosion and reduced sorption. Soil compaction from the use of heavy machinery has been an issue in sugarcane agriculture in Brazil for many years, and it is predicted to worsen with the implementation of green cane operation practices [103], where sugarcane harvesting will switch from manual to mechanical. Also, the indiscriminate construction of small access roads for heavy trucks and tractors used to transport harvested sugarcane to mills aggravates the problem [102].

Soil compaction decreases soil permeability and, consequently, increases the production of surface runoff during rain events [102]. Soil compaction eventually leads to the loss of topsoil with important nutrients and carbon. Such losses are common in most types of intensive agriculture in Brazil, but are particularly problematic in sugarcane. This is due to the extended periods of time that bare soils are exposed during preparation for cane planting at the beginning of the rainy season [83,104–106].

In a comprehensive literature review, Hartemink [83] has determined that erosion losses in sugarcane agriculture vary from 16 Mg ha^{-1} yr^{-1} to approximately 150 Mg ha^{-1} yr^{-1}, depending on factors such as topography, rainfall, and soil type. Also, model simulations from a small watershed in the Southeast region of Brazil have predicted erosion rates as high as 30 Mg ha^{-1} yr^{-1} [107]. However, G. Sparovek (personal communication) has cautioned that rates at or above 30 Mg ha^{-1} yr^{-1} are at the high end for sugarcane agriculture in Brazil.

In fact, another modeling effort to estimate erosion rates in sugarcane agriculture in Brazil [108] reported values equivalent to about a third of those found in Sparovek and Schnug [107]. Rainfall simulation experiments used by Martins-Filho et al. [96] to determine erosion rates in sugarcane agriculture recorded values between 4 and 9 Mg ha^{-1} yr^{-1} for bare soils, and less than 2 Mg ha^{-1} yr^{-1} for soils covered by sugarcane crop residue. Similar results have been reported by Cantalice et al. [109], Vasconcellos et al. [110], and Sousa et al. [111] using soils with cover crop and bare soils. These studies reported higher erosion rates for bare soils, highlighting the importance of soil management practices for erosion control.

2.2.3.2. Soil carbon stocks. Carbon stocks in soils cultivated with sugarcane in Brazil change with land use conversion [112] as well as with different agricultural practices [113]. Therefore, understanding how sugarcane agriculture affects soil C stocks is important not only to help develop best management practices that prevent soil degradation, but also to improve assessments of the GHG balance in bioenergy production in order to guarantee that the biofuel from Brazil is advantageous in terms of GHG mitigation [113].

Studies about the impacts of agricultural practices on soil C stocks carried out in sugarcane areas in São Paulo have shown that burning sugarcane leaves and tops on standing mature crops prior to harvesting reduces soil C stocks [114], while the accumulation of crop residue in the field has the opposite effect [35]. Vinasse application can also increase the accumulation of organic C in the soil [61]. However, the effects of vinasse on soils covered with crop residue are likely to be different from the effects on bare soil, but our knowledge about the issue is still limited [61].

Regarding the effects of sugarcane land use conversion, there is a rich body of literature showing that soil cultivation generally leads to a decrease in soil C stocks, at least in surface layers [115–122]. There are also cases in specific sites where soil carbon stocks increase with crop cultivation [117,118,122–124]. This is especially true when soil conservation practices (no-till and crop rotation, for example) are adopted.

The most comprehensive survey on changes in soil C stocks associated with land use conversion from native vegetation (Cerrado) to a mixture of pasture and croplands and then to sugarcane was conducted by Mello et al. [112]. Their overall conclusion was that soil C stocks in sugarcane fields were lower than in native vegetation and in pasture soils. However, the trend was not as clear for crop land soils since changes were not significant. The authors also estimated the payback time for soil C during the different stages of land-use changes assuming an ethanol C offset of 9.8 Mg ha^{-1} yr^{-1} of CO_2. From the conversion of native vegetation to sugarcane, they estimated that the payback time would be 8 years, and from the conversion from pasture to sugarcane, the time would vary between three and 4 years. However, Macedo and Davidson [125] recently estimated that if the C lost from the aboveground woody vegetation is included in the equation, the payback time increases to 17 years.

2.2.4. Evaluating the GHG balance, with an emphasis on N_2O

Available life cycle analyses (LCA) for ethanol have shown that substituting fossil fuel for ethanol can lead to substantial savings of GHG and energy [15,126,127]. However, as stated by Hoefnagels et al. [128], the final GHC balance and energy savings from biofuels will depend on where in the world the biofuel is produced. Factors such as reference land cover conditions, location of crop cultivation, productivity, and soil N_2O emission rates are important considerations in the evaluation scheme.

Emissions of N_2O vary substantially depending on soil type and the fertilizer used during feedstock cultivation [61]. For sugarcane in Brazil, emission factor (EF) values can range from 0.20 to 14.9% (Table 1). However, field data on emissions are scarce, therefore, estimates used in LCAs are mostly based on the IPCC Tier 1 EF, which assumes N soil emissions to be equivalent to 1% of the applied N-fertilizer [61].

Estimates of N_2O emissions for sugarcane ethanol produced in Brazil have been vastly improved in recent years by *in situ* measurements in sugarcane soils treated with N-mineral fertilizers and vinasse [61–63]. Two studies using urea as N-fertilizer reported N_2O emissions generally lower than the 1% default value EF of the Tier 1 IPCC guidelines [61,62]. Despite being relatively low, such values can represent 40–60% of the total emissions in the production cycle of ethanol. Furthermore, emissions are likely to increase when vinasse is applied with nitrogen fertilizer [61], a common practice in sugarcane agriculture in Brazil.

Carmo et al. [61]reported an EF of approximately 3.0% when vinasse was applied with mineral fertilizer to sugarcane fields. Paredes et al. [62] estimated an EF of 2.5% in soils treated only with vinasse, while Oliveira et al. [63] reported an EF lower than 1%.

It is difficult to know exactly why the results from the three studies varied. However, it is now clear that factors such as soil characteristics, precipitation regime, and the type of N fertilizer used play an important role in determining N_2O emissions. It is also clear that the use of vinasse combined with N fertilizer enhances emissions, resulting in an EF higher than the 1% EF value associated with the use of N-fertilizer alone. Based on these results, Paredes et al. [62] proposed that the LCA for ethanol from Brazil adopt an EF of 1.9% for areas where vinasse is used as fertilizer. Although somewhat conservative, this value is almost double that of the IPCC Tier 1 default value.

If we consider the combined effects of N-fertilizer application and vinasse plus the accumulation of residue from sugarcane crop associated with the mechanization of harvesting in Brazil, emission values can be even larger [61]. According to Carmo et al. [61], the accumulation of crop residue in the field beyond 10 t per hectare enhances N_2O emissions during the first months after fertilization and vinasse application, affecting the final GHG balance of ethanol biofuel. On the other hand, crop residue should help improve soil quality by increasing soil moisture and protecting against erosion and improving aggregate stability [129]. Moreover, crop residue may increase N immobilization because of its high C:N ratio [130].

2.2.5. Impacts on the landscape and biodiversity

Brazil has an environmental law locally named *Código Florestal* (Forest Code, FC), which regulates the area of natural land cover in rural private properties. The FC was extensively revised in 2012 and resulted in a New Forest Code (NFC), which designates areas along river banks and on hilltops as "permanently protected areas".

The area of protection along banks is based on the width of the stream or river. The area of forest protection or the so called "legal reserves" is based on the size of the property and the type of biome that it belongs to. For instance, in the Amazon region, 80% of the native forest in private property is supposed to be protected, while in the Cerrado region, the protected area is 35% of the property. In the remaining Brazilian biomes, the protected area is supposed to be 25% of the property.

Table 1
Nitrogen fertilizer emission factor values available in the scientific literature for sugarcane growing in Brazil.

Growth stage	N source	Added N (kg ha^{-1})	Emission factor (%)	Reference
Plant cane	Urea	60	1.11±0.75	[61]
Plant cane	Urea + filter cake	122	1.10±0.54	[61]
Plant cane	Urea + *vinasse*	87	2.65±1.13	[61]
Plant cane	Urea + filtercake + *vinasse*	149	1.56±1.01	[61]
Ratton cane	Trash + vinasse	120 – 142	0.59±0.29 to 3.03±1.22	[61]
Ratton cane	Urea + Filter cake	–	0.21±0.05	[144]
Ratton cane	Urea + vinasse	–	0.59±0.19	[144]
Ratton cane	Urea	120	0.83±0.22	[144]
Ratton cane	Urea	60	0.52±0.15	[144]
Ratton cane	Urea	120	0.69	[146]
Ratton cane	Urea	120	0.75	[146]
Ratton cane	Ammonium nitrate	100	0.21	[145]
Ratton cane	Ammonium nitrate + trash	100[a]	1.06	[145]
Ratton cane	Ammonium nitrate + vinasse	161	1.34	[145]
Ratton cane	Vinasse + trash	61[a]	2,75	[145]
Ratton cane	Vinasse	61	1.86	[145]
Ratton cane	Concentrated vinasse + trash	37[a]	1.86	[145]
Ratton cane	Concentrated vinasse	37	1.32	[145]
Ratton cane	Vinasse	–	0.44 to 0.68	[63]
Ratton cane	Urea	225	0.8	[62]
Ratton cane	Old vinasse	9	11.5	[62]
Ratton cane	Fresh vinasse	13	14.9	[62]
Ratton cane	Filter cake	79	0.2	[62]

— Value not provided by the authors.
[a] Trash N content not considered.

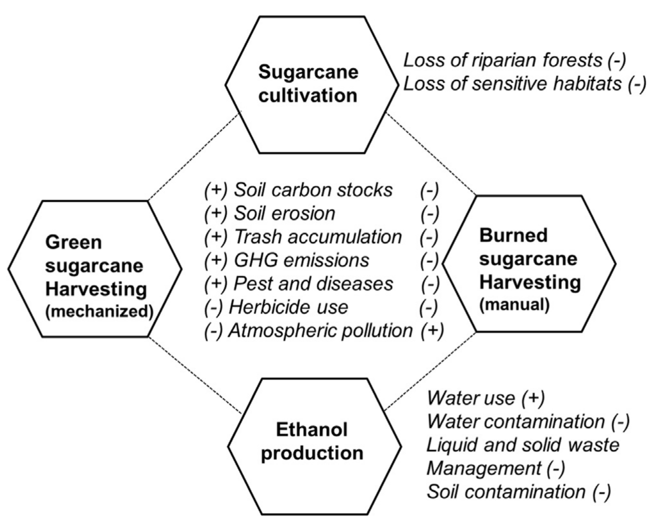

Fig. 1. Schematic showing aspects of sustainable production of sugarcane ethanol in Brazil that have improved in recent years and areas that have not. Areas of improvement are indicated with a plus sign (+) and areas that have not improved or worsened are indicated with a negative sign (−).

The FC is vital to the conservation of Brazilian natural landscapes as approximately 50% of the country's natural vegetation is in private land [131]. Yet, compliance of environmental regulations in Brazil has been historically low while pressures on natural landscapes are constantly high. Unfortunately, the NFC may worsen the situation because it effectively reduced the total area of natural vegetation protection in the country. Under the old FC, a total of about 50 Mha of natural vegetation was under protection or supposed to be restored. Under the NFC, this area decreased to less than half, or approximately 21 Mha [131].

Sugarcane agriculture is embedded in the Brazilian landscape and compliance with the FC has never been a priority, as illustrated by the decimation of riparian forests along streams and rivers in sugarcane farms [132]. However, a recent study by Rodrigues et al. [133] shows a changing trend in sugarcane regions as farmers try to comply with the guidelines mandated by the NFC. Also, as forest protection and restoration help recover key ecosystem services and biodiversity in human-modified landscapes [134–136] compliancy should increase even further [137]. Hopefully, as more studies show that the NFC does not have a negative effect on agriculture [138], more farmers will be willing to comply with the law and help restore the natural vegetation.

The problem facing the restoration of forests in conservation areas in most sugarcane farms in Brazil is that they are usually have only small fragments of forest scattered among cropland, pasture, and second growth vegetation. Therefore, whether restored forests can fully thrive in areas protected by the FC is still unknown [139,140], especially if they lack the capacity to regenerate and sustain the biodiversity characteristic of old-growth forests, especially in the early stages of succession [141,142]. Also, small forest fragments contain only a small fraction of the genetic pool of the original vegetation. Therefore, restored forests may tend towards biotic simplification and homogenization. Yet, Brancalion et al. [143]

advocate that ecological restoration in such fragmented landscapes is vital to reestablishing the biodiversity and ecosystem services needed to guarantee restoration success.

3. Conclusions

Sugarcane agriculture in Brazil is an old practice, while the production of ethanol has been developed to meet economic and security needs of the country in the 1970s and 1980s. Therefore, producing sustainable ethanol to mitigate GHG emissions is a relatively novel concept that has had to adapt from traditional production methods and practices used in the country. Accordingly, periodic assessments of the environmental impacts of ethanol production, like this one, are needed to ensure that sustainable guidelines are implemented as production expands and evolves.

Based on our present evaluation, sustainable sugarcane ethanol production in Brazil has made significant progress in certain areas but not in other key areas discussed by Martinelli and Filoso [8], as summarized in Fig. 1. Areas of progress include the official agreement to end sugarcane burning in the state of São Paulo, efforts to reduce water use in mills, regulation of vinasse application in areas with groundwater K contamination, and the enforcement of FC guidelines to protect and restore riparian buffers and forest fragments in sugarcane farms. Major improvements are still needed with regard to the prevention of soil erosion and degradation, protection of water resources against pollution from pesticides and other toxic chemicals, and the expansion of sugarcane agriculture to areas of natural vegetation, especially within threatened biomes. It is also essential that we improve our understanding of how to implement effective ecosystem restoration projects to help reverse biodiversity and ecosystems service losses associated with sugarcane expansion in Brazil. However, solving any of these issues will depend upon the availability of science-based information about the causes and effects of environmental impacts in ethanol production and, most importantly, on the use of this information by sugarcane growers to end unsustainable farming practices. Without this, the costs of sugarcane ethanol production to society might outweigh gains.

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