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REVIEW ARTICLE

Sustainability of sugarcane production in Brazil. A review

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Abstract

Brazil is a major sugarcane producer and its production more than doubled over the last decades to meet global bioenergy demands for reducing crude oil dependency and mitigating climate change. Nevertheless, the adverse effects of this growth on jeopardizing the sustainability of sugarcane production are not known, especially when environmental impacts of agricultural inputs and production processes are not judiciously managed. This article is a comprehensive review of the state-of-the-knowledge and the main advances made thus far in the sugarcane sector. Here, we review the major environmental impacts of rapidly expanding sugarcane plantation on the land use change and its competition with food production, as well as those associated with sugarcane cultivation in Brazil. Our main finding are that sugarcane plantation did not contribute to direct deforestation, and its expansion on degraded pastures with the attendant increased yields of food crops and livestock intensification decreased land competition between food and sugarcane. Non-burning sugarcane harvesting is a win-win strategy because of its benefits involving agronomic and environmental aspects, but soil compaction is among the main issues in sugarcane cropping systems. Sugarcane is highly efficient in terms of nitrogen use efficiency, which is an important factor for its high energy balance. But, special attention should be given regarding emissions of nitrous oxide when straw mulching is combined with application of nitrogen fertilizer and vinasse. Recent advances in the sugarcane sector also show significant reductions in water consumption, making sugarcane ethanol one of the most favorable options in terms of water footprint. Growing realization of a vast potential indicates the need to further enhance the environmental benefits of sugarcane ethanol by optimizing the agricultural production chain. Based on this improved knowledge, the adoption of best management practices is among researchable priorities that can be developed to consolidate the large potential of sugarcane production towards greater sustainability.

Keywords Ethanol production · Food security · Water resources · Sugarcane harvest · Land use change · Greenhouse gas mitigation

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Contents

1 Introduction

The ever increasing concentration of anthropogenic greenhouse gases (GHGs) has a causal link with some external drivers of climate change and with the observed changes in climatic impacts (e.g., precipitation intensity, cyclones, floods, and droughts; IPCC 2013). The observed increase in global temperature is largely driven by the burning of fossil fuels (Popp et al. 2014), while agriculture contributes about 14% of global anthropogenic GHG emissions and an additional 17% is contributed through deforestation and conversion of land to agricultural use (Lybbert and Sumner 2012). Over and above its impact on climate change, agriculture itself is affected by those impacts, with projections of additional risks to regional and global food security (Schmidhuber and Tubiello 2007).

Over the past decade, sources of the largest net GHG emissions in Brazil are the land use change and forestry (LULUCF) sectors, especially those associated with conversions of forests and cerrado vegetation to agricultural production. However, the recent report from the Brazilian government indicated a decrease of 85% in GHG emissions from the LULUCF sector between 2005 and 2012 (MCTI 2014), which could be attributed to the reduction in deforestation in the Amazon region (Nepstad et al. 2014). In 2005, the LULUCF sector contributed 58% of Brazil's total anthropogenic GHG emissions. Therefore, the observed reduction in deforestation decreased the total national emissions by 41% (from 2043 to 1203 Tg CO_2eq) in 2012 (MCTI 2014).

Brazil has contributed to the global development and use of bioethanol, which is a feasible option and that can result in negative GHG emissions through replacement of fossil fuels, and a reduction of up to 85% has been reported (Börjesson 2009). Bioethanol is one of the most widespread biofuels with a global production of 96 billion liters in 2015 (RFA 2016). Trailing USA with a production of 58% of global ethanol, Brazil is the world's second largest producer (28%) of ethanol. Thus, Brazil plays an important role in globally supplying the present and future ethanol needs (Manochio et al. 2017). Several food crops that can be used for biofuel production include grains (maize, sorghum, and wheat), sugar crops (sugarcane, sugar beet), starch crops (cassava), and oilseed crops (canola/rape, soybean, and oil palm). Brazil is the world's largest sugarcane producer (Fig. 1), with a cultivated area of 9.1 million hectares in 2016/17 mostly in the south-central (90%) region of the country (CONAB 2017).

Fig. 1 A recent view of the sugarcane cultivation under green cane management conducted without the preharvest burning in Brazil. The trade-offs between the need to preserve soil health and produce more bioenergy have been the subject of intense discussion, since the adoption of sustainable management practices such as crop residue retention could increase the productivity of agricultural ecosystems and mitigate the effects of climate change through enhanced carbon sequestration. Photographed by J.L.N. Carvalho

The Brazilian Alcohol Program (*Proálcool*) was launched in 1975 and was aimed at reducing the reliance on oil imports through production of sugarcane-based ethanol. Nonetheless, the environmental benefits were soon recognized by presenting an avoided emission of 27.5 Tg CO_2equivalent in 2003 due to partial substitution of gasoline use in Brazil (Macedo 2005). In addition to these advances, the Brazilian government has announced ambitious targets in the last Paris climate agreement within the United Nations Framework Convention on Climate Change: reducing GHG emissions by 43% below 2005 levels by 2030 (iNDC Brazil 2015). To meet this target, among other strategies, the Brazilian government has recently launched the "RenovaBio" program to boost the share of renewable fuels in its energy mix, with the attendant increase in ethanol production from 28 billion liters per year in 2015 to around 50 billion liters by 2030 (MME 2017).

Despite numerous advantages as a sustainable feedstock for biofuel production, there are growing concerns regarding the potential environmental impacts of expansion of sugarcane cultivation and the attendant land use change, disruption of food supply, GHG emissions from agricultural inputs and farming operations, excessive water use and eutrophication, loss of soil biodiversity, accelerated soil erosion, etc. Further, the avoidance of GHG emissions by biofuels depends on the competing uses of feedstocks and the associated agricultural management practices (Davis et al. 2013). Recent analysis of the energy balance and GHG emissions from alternative options of biofuels created a major controversy and raised concerns about its sustainability (Seabra et al. 2011; Tsao et al. 2011; Macedo et al. 2008; Renouf et al. 2008; Dunn et al. 2013). Therefore, continuous scientific and technological developments are essential to ensuring the sustainability of sugarcane ethanol, especially with regard to sugarcane agricultural sector, which accounts for 81–90% of total GHG emissions from ethanol production in Brazil (Pereira and Ortega 2010; Seabra et al. 2011).

Among concern regarding the increase in world's biofuel production is the need for additional land required to meet the future demands of ethanol (Leal et al. 2013b). Indeed, world ethanol production from corn and sugarcane is expected to increase from 80 billion liters to approximately 200 billion liters in 2021 (Goldemberg et al. 2014). Several aspects regarding the ethanol production chain that must be assessed to achieve this target in an environmentally compatible manner include the land use change (Fargione et al. 2008; Lapola et al. 2010), food security versus ethanol production (Tilman et al. 2009), agricultural management practices (Lal 2004), water quality and availability (Hernandes et al. 2014; Filoso et al. 2015), the energy balance (Macedo et al. 2008), and the carbon (C) footprint (Bordonal et al. 2012; Lal 2014). In this context, the sugarcane cultivation has a vast potential to enhance the environmental benefits by optimizing the agricultural production chain (e.g., integrating sugarcane with food production, intensifying pastoral land use, narrowing the yield gaps, increasing N use efficiency, prohibiting residue burning, and using no-till or reduced tillage) and thereby moderating their local environmental impacts.

Based on the literature review and with focus on the sugarcane agricultural sector, the objective of this article is to address the major sustainability issues associated with the environmental consequences of rapidly expanding sugarcane cultivation in Brazil. Specific objective is to identify knowledge gaps and prioritize future research. Therefore, the goal of this article is to synthesize the existing knowledge on the implications of sugarcane expansion on land use change and its competition with food production, along with the potential opportunities for agricultural intensification. The article also addresses recent advances in the environmental impacts of sugarcane cultivation and identifies opportunities to improve Brazil's sugarcane production chain and enhance its sustainability.

2 Impact of sugarcane expansion on land use change

Growing population has aggravated the stress on land and other natural resources to meet the growing demands for food, fiber, fodder, and fuel. The land use changes (LUC) in Brazil for producing soybean and timber and raising cattle have been the main drivers of the deforestation of the Amazon (Nepstad et al. 2014), which had the highest global rate of deforestation in 2005 (MCTI 2010). Even with the largest potential of agricultural expansion in the near future, there has been a 40% decrease in national GHG emissions since 2005, and a potential cooling of the climate at the local scale through reduction in area of deforestation (Lapola et al. 2013). Public policy interventions in beef and soybean supply chains have contributed to the recent 70% decline in deforestation in the Brazilian Amazon, and the target of reducing emission by 90% in 2018 compared with the baseline rate of 2005 may also be met (Nepstad et al. 2014).

Being the world's top producer of soybeans, coffee, sugar, beef, chicken, dry beans, oranges, and tobacco, Brazil is one of the world's most important agricultural countries. Yet, its agricultural land area in 2016 was merely 78 million hectares out of the total national land area of 851 million hectares (IBGE 2017). Concerns about the sustainability arise from the extent of displacement of food and feed crops by sugarcane and/or deforestation for biofuel feedstock (Walter et al. 2011; Nguyen et al. 2010). Loss of biodiversity, increase in food prices, and GHG emissions from LUC may be significant depending on the specific practices used for production of biofuels (Popp et al. 2014). Indeed, any savings in C from biofuels may be negated by any pressure of sugarcane expansion over native forests or grasslands (Fargione et al. 2008; Searchinger et al. 2008). Nevertheless, assessing the direct LUC to sugarcane plantation during 2000–2009 in south-central Brazil, Adami et al. (2012) reported that ~96% of recent expansion has occurred over pastures (69.7%), annual crops (e.g., soybean, corn, sorghum, and cotton; 25%), and citrus (1.3%). Corroborating these findings, Sparovek et al. (2009) reported that sugarcane expansion resulted in a significant reduction of pastures during 1996–2006 but did not contribute to direct deforestation in the agricultural region where most of the expansion occurred.

Presently, estimates of the effects of LUC on soil C balance also take into account the CO_2 savings from cultivation of the sugarcane. For the 20-year period, Mello et al. (2014) estimated the soil C debt at 21 and 5.7 Mg C ha^{-1} upon conversion of native vegetation and pastures into sugarcane, respectively. With consideration of the ethanol C offset (2.7 Mg C ha^{-1} $year^{-1}$) by displacing the fossil fuels (Fargione et al. 2008), the magnitude of soil C debts would take 8 and 2–3 years to be offset following the LUC from native vegetation and pastures, respectively. However, most of sugarcane areas in this study were either harvested with burning or this practice had just been stopped for 3 years or less prior to obtaining the soil samples. Therefore, the effects of converting pastures into sugarcane on soil C debts remain unclear for areas where sugarcane residues are retained on the soil surface upon harvest without burning (green harvest). Recent studies on long-term simulations show that the conversion of pastures into sugarcane with green harvest is associated with soil C accretion at a rate of 0.16 Mg C ha^{-1} $year^{-1}$ (Oliveira et al. 2017a). Furthermore, 15.9 Mg C ha^{-1} is also stored annually into sugarcane biomass (Beeharry 2001), and therefore the replacement of the ecosystems containing the lowest biomass C stocks (e.g., degraded grasslands) by high yielding energy crops (e.g., sugarcane, oil palm) may reduce or even eliminate the payback time of the C debts incurred from LUC (Gibbs et al. 2008).

Assuming that more than 50% of the pastureland in Brazil is degraded (Costa and Rehman 1999) and the LUC-induced debt of soil C depends on the current condition of the pastures (Mello et al. 2014), the effects of direct land use change to sugarcane plantation could lead to indirect climate benefits by cooling the local climate (Loarie et al. 2011) and mitigating GHG emissions (Bordonal et al. 2015). Similar to the expansion of sugarcane over the 2006–2011 period (Fig. 2), converting citrus and natural forests into sugarcane is also inevitable (Bordonal et al. 2015). Indeed, converting degraded pastures into sugarcane plantations is an important strategy to ensure the environmental benefits of sugarcane ethanol for enhancing the C budget in both soil and the biomass (Fig. 3) (Oliveira et al. 2016; Bordonal et al. 2017). Further, sugarcane expansion reintegrates degraded pasturelands into a more productive system, so that even the slight improvements in soil quality (i.e., increased soil chemical quality) have already been reported when extensive pasture is converted into sugarcane (Cherubin et al. 2016). The soil under sugarcane functioned at 74% of their potential capacity compared with those under extensive pasture at 70%. While the expansion of sugarcane on extensive pastures leads to slight but significant improvements in soil quality, there can be a significant loss in soil biodiversity by sugarcane expansion from pasturelands, in which the diversity and abundance of soil macrofauna groups have been reduced by 39 and 89%, respectively (Franco et al. 2016). These data validate the importance of the advances in management in agricultural systems for reducing the risks of future decline in soil quality and for improving biodiversity in sugarcane fields.

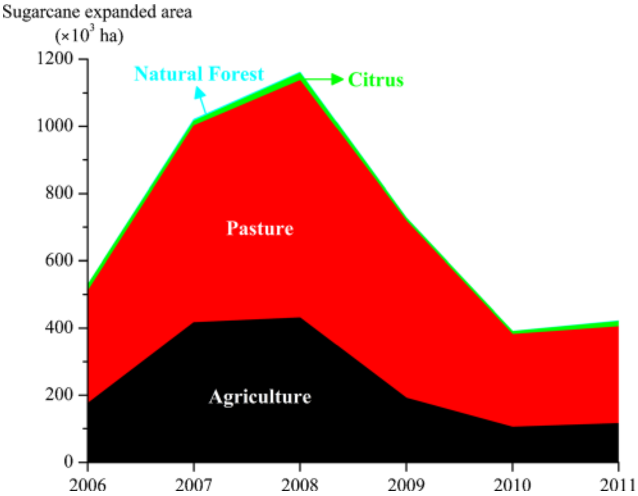


Fig. 2 Dynamic of direct land use change of recently sugarcane expansion over diverse agricultural uses (e.g., annual crops, pastures, citrus, and natural forest) in south-central Brazil during 2006–2011. Adapted from Bordonal et al. (2015)

Fig. 3 Extensive pasture and sugarcane agrosystems represent the most intense land use change associated with sugarcane expansion in south-central Brazil. The typical pasture management in Brazilian tropical soils is characterized by the pasture degradation due to low grass productivity and inadequate grazing management. Note the sparse vegetation cover. Photographed by M.R. Cherubin

The reality of rapidly expanded sugarcane crop across south-central Brazil also raises concerns regarding the indirect land use change (iLUC), in which the agricultural land use type converted into sugarcane plantation is displaced elsewhere. However, the magnitude of iLUC to replace either pastoral or arable lands displaced by biofuel expansion in Brazil is highly uncertain (Searchinger et al. 2008; Verstegen et al. 2016) and poorly understood (Zilberman 2017), mostly by pushing rangelands frontier into the Amazon and Cerrado biomes (Lapola et al. 2010). Zilberman (2017) suggested that these estimates may be seriously distorted not only because iLUC is uncertain and estimates vary substantially but also because it fails to capture the basic features of agricultural industries and land resources. Further, existing methodologies for quantifying iLUC caused by sugarcane expansion and its impact on total GHG emission and other environmental issues are still controversial due to the lack of empirical data and of the solid model representations of Brazilian land use (Sparovek et al. 2009).

Principal reasons of the small iLUC include livestock intensification, ample availability of land, improvements in agronomic yield, and expansion of sugarcane over low intensity pastures (Walter et al. 2014). Another important point arises from the expansion of sugarcane into regions with higher potential for agricultural productivity, where iLUC effects associated with sugarcane expansion may have been attenuated by higher productivity in sugarcane production in Brazil (Ferreira Filho and Horridge 2014). Corroborating these assumptions, Lapola et al. (2013) have also shown that decoupling of deforestation and agricultural expansion in the Amazon has occurred because of the convergence of several factors such as internal market regulations, creation of more protected areas, command-and-control crackdown on illegal deforestation, and credit barriers imposed by the federal government on municipal counties in deforestation frontiers.

Regardless of the magnitude of iLUC, it is important to identify the strategies that reduce the risk of iLUC emissions. Integration of sugarcane and livestock sectors can improve land use efficiency in Brazil, since more intensive cropping systems can maintain, or even increase food production while reducing the impacts of direct and indirect LUC from agriculture expansion (Egeskog et al. 2011). Establishing sugarcane plantation on marginal and degraded lands with simultaneous pasture intensification is also an important strategy to avoid iLUC effects of ethanol production (Lal 2014; Egeskog et al. 2014). The intensification and restoration of degraded pastures for livestock sector lead to higher meat yield and reduce the land occupation factor, thereby avoiding further deforestation and providing additional land for other agricultural uses such as sugarcane bioenergy systems (De Figueiredo et al. 2017). Incentives through public policies and technology development are needed to ensure the expansion of sugarcane towards a sustainable path, and aimed at meeting the global demand for both food and biofuel feedstocks while avoiding the undesirable LUC (Tilman et al. 2009).

3 Land competition versus food production

Land availability and competition between supply of energy and other commodities (e.g., food, sugar, milk, and grain) have global implications, especially if biofuels can be produced in harmony with other needs, without jeopardizing food production, C reservoirs, and biodiversity (Valentine et al. 2012). Under certain conditions, modern bioenergy can even be an important strategy of advancing food security in some countries. For example, biofuels could be produced from inedible plants that grow on land that is not well suited for growing food (Lynd and Woods 2011). In contrast, indirect effects of land use conversion and cultivation of food-based biofuel crops may impact the food prices and determine the availability/access of food for the poorest (Searchinger et al. 2015). While some argue that biofuel production may have a large impact on global food prices (Chakravorty et al. 2009), there are others who argue against it and state that ~ 88% of the growth in food prices is triggered by factors other than biofuels (Timilsina and Shrestha 2011).

Livestock production is the largest anthropic use of land resources worldwide, which includes grazing land and cropland dedicated to feed production. Thus, it is pertinent to analyze the area devoted to produce ethanol from sugarcane with the availability of land. In 2007, Brazil had a total cultivable land area of 354.8 million hectares, as estimated by considering the areas allocated to forestry, native forests, natural and planted pastures, and perennial and annual crops. Of the total cultivable land, 48.6% (172.3 million hectares) is under pastures and 21.6% (76.7 million hectares) is cultivated for soybean (5.8%), corn (3.9%), and other crops (8.5%). Energy crop (i.e., sugarcane for ethanol) represents 1.0% of the Brazilian cultivable lands and 4.4% of the cultivated area, which is relatively small compared to the allocated area for other commodities (e.g., corn and soybean). Yet, potential of agricultural expansion in Brazil is large since an additional area of 105.8 million hectares (29.8%) remains available (Fig. 4; Goldemberg and Guardabassi 2010).

While the production and use of ethanol in Brazil increased substantially between 2005 and 2015, a large growth has also occurred in food production and in the expansion of land area (Gauder et al. 2011). Soybeans, corn, sugarcane, beans, and rice are the most important annual crops, occupying ~ 90% of the cultivated area in Brazil. Whereas the area under soybean increased significantly (~ 10 million hectares) during 2005–2016, those under sugarcane and corn increased at a lower rate (Fig. 5; IBGE 2017). The fact that little changes occurred in other types of land uses indicates little if any competition for land between food and sugarcane, and it adversely affects neither food production nor the commodity prices. Even biofuels perceived as the main driver of increase in food prices and widespread hunger among the poor around the world, Brazilian ethanol production from sugarcane neither has been a serious problem with regard to the spike in international food prices in 2008 nor has a negative effect on poverty (Ferrera Filho 2013).

The strong expansion of sugarcane agricultural frontier on degraded pastures (Fig. 2), the increased yields of food crops and livestock intensification between 1995 and 2015 have attenuated land competition between food and sugarcane plantation (Nogueira and Capaz 2013). For instance, the Brazilian cattle herd increased by 251% between 1960 and 2010, but the stocking rate increased from 0.47 to 1.2 head ha^{-1} (McManus et al. 2016). Additionally, an important strategy to avoid further deforestation has been the land use program (e.g., Agro-ecological Zoning) launched by the national government in 2009 for guiding ethanol production on a sustainable pathway and for respecting environmental boundaries by avoiding the expansion and cultivation of sugarcane in areas under native vegetation and devoted to food-based crops. By classifying and identifying regions with the highest potential of sugarcane yield, 64 million hectares is found to be suitable for sugarcane plantation. Of this, 53% (34 million hectares) is marginal land and degraded pastures (Manzatto et al. 2009), which would be enough to meet the projected biofuel and food demands necessary for well-being of the future generations.

3.1 Opportunities for agricultural intensification

The projected climate change may affect agricultural production in several ways. Thus, the conventional agriculture is in dire need of sustainable intensification to protect ecosystem C pools and biodiversity. Rather than expanding cultivation into

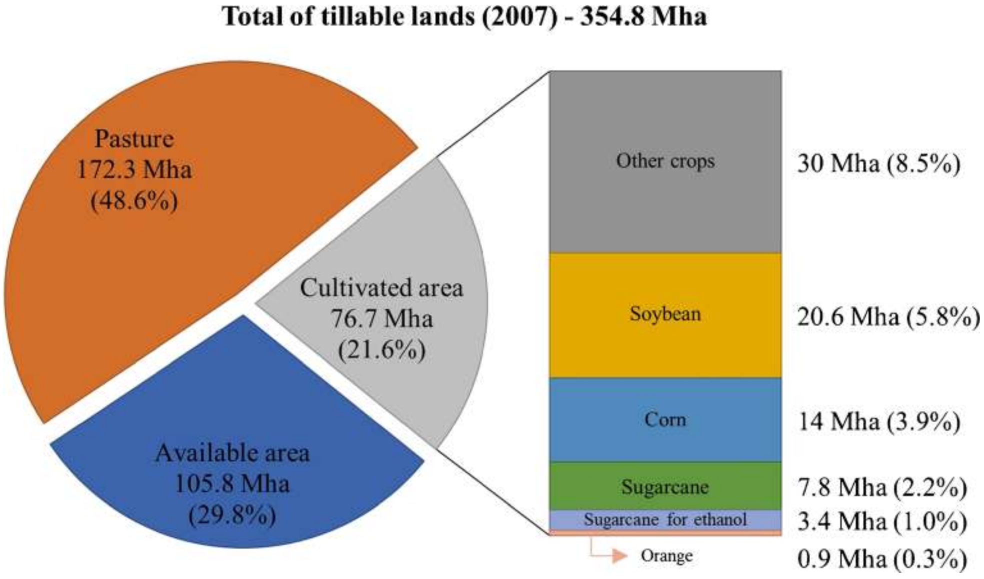


Fig. 4 Total of tillable lands (million hectares–Mha) and types of land use in 2007. Adapted from Goldemberg and Guardabassi (2010)

new lands, the key strategy of sustainable intensification is to produce more from the same area and with fewer resources, while minimizing the negative externalities. In this context, there is a potential to produce 60–100% additional food by minimizing losses and waste (Lal 2013). Closing yield gaps, adopting systems of sustainable management (i.e., improved pasturelands, agroforestry systems, conservation agriculture), restoring soil organic carbon, adopting precision application of inputs, using legumes in the rotation cycle, and intercropping systems are among the several opportunities that must be prioritized and explored (Tilman et al. 2002; Lal 2006; Johnston et al. 2011).

Through high-yielding technologies (e.g., genetic engineering, advanced hybrids, new biorefinery technologies, and new cultivation practices), Brazilian capacity for ethanol production could also quadruple without major implications to land use (Mathews 2007). The yield gap in sugarcane in Brazil is 76 Mg ha^{-1}, because of the low national average yield of 72 Mg ha^{-1} (CONAB 2017) compared with the attainable yield of 148 Mg ha^{-1} (Carvalho-Netto et al. 2014). Marin et al. (2016) also reported that the current national average yield (82 Mg ha^{-1}) is 62% of the potential yield (134 Mg ha^{-1}) under dryland conditions. Narrowing the exploitable yield gap to 80% of the potential yield is the key strategy of meeting the projected sugarcane demand by 2024, with an 18% reduction in sugarcane area for the low-demand scenario or a 13% expansion for the high-demand scenario (Marin et al. 2016).

In Brazil, a large proportion of agricultural land is under pastures (~ 172.3 million hectares). However, increasing demand for food, fiber, and energy production has necessitated conversion of additional land to crop production (Barretto et al. 2013). Because of extensive practices (e.g., traditional management and low adoption of improved technology), the

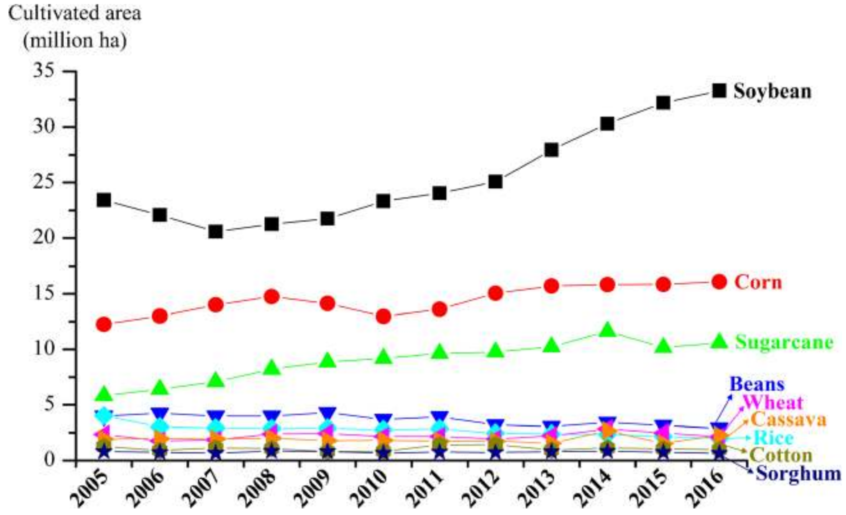


Fig. 5 Temporal dynamics associated to land use with the main temporary crops and evolution of sugarcane planted area across Brazil during 2005–2016. Adapted from IBGE (2017)

productivity of Brazilian pasturelands is 32–34% of its potential. Thus, an improvement to 49–52% of the potential would free up some land to meet demands for crops, meat, wood products, and biofuels without the need for any new deforestation until at least 2040. This strategy would also avoid emission of up to 14.3 Gt CO_2eq per annum (Strassburg et al. 2014). Important strategies of improving productivity include assessing the potential for agricultural intensification under pasture, avoiding further deforestation, and reducing the associated GHG emissions.

Livestock intensification in Brazil is a distant reality. Thus, it is justified to assume that ~60–75 million hectares of degraded pastures could be reclaimed to provide more areas for agriculture and bioenergy in the near future (Nogueira and Capaz 2013). Initiatives such as crop-livestock integration and pasture improvement could release up to 41 million hectares of land from pasture to other agricultural uses. Through increasing the pasture carrying capacity in Brazil from 1.09 to 1.53 animals ha^{-1}, expansion of sugarcane for biofuel on pastureland would have no adverse impact on any of its natural ecosystems (Goldemberg et al. 2014). Walter et al. (2014) observed that an improvement of 10% in the current pasture carrying capacity of just one more head per hectare would release 20 million hectares for agricultural expansion without any deforestation. The land area thus saved is enough to meet the national land demand of 22 million hectares needed for global production of 300 billion liters of ethanol demand by 2030, based on a combination of first- and second-generation technologies in Brazil (Leal et al. 2013b).

There exists a large scope for productivity improvements in livestock sector through the use of surplus bagasse as animal feed, which could reduce GHG emissions associated with meat/dairy production and attenuate the possible effects of LUC induced by sugarcane expansion on pastures (Egeskog et al. 2014). Integrated ethanol/livestock systems reduce the risk of displacement and increase the land use efficiency in meat/dairy production (Egeskog et al. 2011). Several sugarcane-processing byproducts (e.g., hydrolyzed bagasse/treated bagasse, raw bagasse, sugarcane straw, liquid yeast, dry yeast, molasses, and cane tops) can be combined or treated to feed cattle, in which different pretreatment alternatives can be used to increase digestibility and nutritional value of animal feed (Dale et al. 2010). However, the use of sugarcane byproducts to feed cattle is currently a non-conventional business option, and additional research is needed on this topic.

Better economic and environmental developments have also been observed in Brazil with incorporation of sunn hemp (*Crotalaria juncea*) in rotation with sugarcane (Bordonal et al. 2012; Chagas et al. 2016). However, leguminous cover crops (e.g., peanut, soybean and sunn hemp) are typically grown during the fallow period of renovation of sugarcane fields every 5 or 6 years. Another opportunity for addressing the need for both food and biofuel productions is through adoption of the intercropping systems, in which food and energy crops are grown simultaneously (Malezieux et al. 2009). A large proportion of the rainfall, soil nutrients, and solar energy between the rows remain unexploited during the initial stages of sugarcane growth immediately after the harvest (e.g., 90–120 days). Because sugarcane takes 2 to 3 months to get established, any short-duration inter row crops can be grown during this period (Teshome et al. 2015).

In India, Singh et al. (2008) observed that sugarcane-based intercropping system improved profitability and resulted in higher sugarcane yield than that under sole stand. In China, Yang et al. (2013) concluded that sugarcane-soybean intercropping is an optimum agricultural system for land use efficiency, nitrogen use efficiency, crop yield, production cost, and environment protection. Therefore, intercropping with sugarcane could be agronomically advantageous and provide additional revenue (Teshome et al. 2015). Intercropping legumes or grain crops between sugarcane ratoon rows is an uncommon practice in Brazil and is poorly understood from an agronomic and environmental point of view (Bolonhezi et al. 2010). Practical issues and agricultural management are the key barriers to be overcome, and a concentrated and well-funded research and extension efforts are required to elucidate intercropping systems in sugarcane areas as a feasible opportunity for agricultural intensification and additional food production.

4 Sugarcane production-related impacts

Bioenergy crops have been proposed as an alternative to increase global sustainability while also meeting the energy demand (Koçar and Civaş 2013). Several studies have highlighted the environmental benefits of sugarcane ethanol as an effective option to mitigate GHG emissions when compared to other biofuel feedstocks (Seabra et al. 2011; Goldemberg and Guardabassi 2010; Muñoz et al. 2014). Based on studies of life cycle assessment, Table 1 summarizes the commonly evaluated parameters (e.g., energy balance, GHG savings, biofuel yield, and water footprint) and compares the main energy crops (e.g., corn, sugarcane, wheat, sugar beet, and sorghum) used to produce the world's bioethanol.

The sugarcane-based ethanol is reportedly the most effective option for all mentioned parameters, with the highest energy balance (9.1) in comparison with corn (1.4), wheat (5.2), sugar beet (2.0), and sorghum (2.8). Thus, ethanol from sugarcane reduces emissions of GHGs by 85% through substitution of fossil fuels as compared with emission avoidance of 30% for corn, 45% for sugar beet, 53% for sorghum, and 64% for wheat. The use of biomass as biofuel for power generation during the industrial phase is the major factor of achieving desired emission reductions (García et al. 2011). Sugarcane-based ethanol (L ha^{-1}) has higher average yield

Table 1 Average parameters associated with the main feedstock sources used for the global ethanol production

Feedstock	Energy balance*	GHG savings** (%)	Fuel yield (L ha^{-1})	Water footprint*** (L of water per L of ethanol)
Corn (*Zea mays* L.)	1.4[a,b]	30[a]	4010[a,j,k]	2486[n,o]
Sugarcane (*Saccharum spp.*)	9.1[c,d]	85[a,d,f,g,h]	6900[c,d,g,j]	2245[n,o]
Wheat (*Triticum*)	5.2[b]	64[i]	2450[l]	4339[n,o]
Sugar beet (*Beta vulgaris*)	2.0[b]	45[a,h]	5250[a,l]	1176[n,o]
Sorghum (*Sorghum bicolor* L. Moench)	2.8[e]	53[e]	2990[m]	8317[n,o]

Mean values were computed according to the arithmetic average of the data found in the literature (superscript letters) for each assessed parameter. Otherwise, absolute values were considered when there is only one available data

*Ratio of energy output in a liter of ethanol over the fossil fuel energy input required to produce it

**Avoided greenhouse gas (GHG) emission through substitution of fossil fuels

***Water footprints of bioenergy crops were estimated considering the green and blue components

[a] Goldemberg and Guardabassi (2010), [b] von Blottnitz and Curran (2007), [c] Boddey et al. (2008), [d] Macedo et al. (2008), [e] Wortmann et al. (2010), [f] Börjesson (2009), [g] Seabra et al. (2011), [h] Smeets et al. (2006), [i] Larson (2006), [j] Balat and Balat (2009), [k] Dunn et al. (2013), [l] Rocha et al. (2014), [m] Vinutha et al. (2014), [n] Gerbens-Leenes et al. (2009), [o] Mekonnen and Hoekstra (2011)

of 6900 compared with 5250 from sugar beet, 4010 from corn, 2990 from sorghum, and 2450 from wheat. The water footprint (liter of water per liter of ethanol) of ethanol from sugarcane, the second most efficient crop, is 2245 compared with that of 1176 for sugar beet, the most efficient crop. In comparison, the water footprint of ethanol is 8317 from sorghum, 4339 from wheat, and 2486 from corn.

While those benefits of ethanol from sugarcane have been widely reported (Goldemberg 2007; Farrell et al. 2006), there are also reports negating the desired mitigation through biofuel production (Searchinger et al. 2008; Lapola et al. 2010). Important explanations of these apparent contradictions include the use of diverse methodologies and assumptions, and differences in system boundaries, emission factors, agricultural inputs, geography, land use change, and in allocating emissions to coproducts, etc. (Davis et al. 2009; García et al. 2011). Major trends on sustainability of sugarcane production systems, as well as management strategies to overcome their related impacts, are discussed in the following subsections, in order to provide easily available information regarding the current status of agricultural production and the advances made thus far.

4.1 Green mechanized harvesting and tillage practices

In addition to the release of soot, GHGs and particulate matter into the atmosphere, burning of residues prior to harvest has also significant detrimental effects on human health (Tsao et al. 2011). Several studies have reported a correlation between emissions of particulate matter from sugarcane burning and diseases such as asthma, respiratory problems, lung cancer, and hypertension hospital admissions (Silveira et al. 2013; Cançado et al. 2006; Arbex et al. 2007). Furthermore, sugarcane burning is responsible for an emission of 941 kg CO_2eq ha^{-1} $year^{-1}$, which corresponds to 30.3% of total GHG emission related to sugarcane agricultural production (De Figueiredo and La Scala Jr. 2011). In the last decade, there has been a gradual decrease from 61 to 6% (2.3 million hectares) in areas under sugarcane burning in south-central Brazil (Fig. 6), especially in the São Paulo state with the implementation of legislation to banish the burning practice (Aguiar et al. 2011). Capaz et al. (2013) observed a 39.3% reduction in GHG emissions (i.e., from 1.015 to 0.639 Mg CO_2eq ha^{-1}) through conversion from burned to green harvest during 1990–2009 in São Paulo. Likewise, a shift on harvest management had an improvement in more than 90% on human health impacts, and the global warming potential and black C emissions are expected to be 70% and 216 times lower with complete mechanization in the future, respectively (Galdos et al. 2013).

Non-burning harvesting is well known in the scientific literature as a win-win strategy because of its benefits involving agronomic and environmental aspects. However, in the green harvest system, the higher levels of soil compaction have been recognized as the main issue in traditional sugarcane cropping systems in Brazil because of heavy and intense traffic during mechanical harvest and transport (Otto et al. 2011; Souza et al. 2014). A substantial drop in sugarcane yield has been observed since 2008, when the mechanization (e.g., harvest and planting operations) was intensified (Fig. 7). Best management practices are and will continue to be crucial to overcome this issue, including the retention of straw in sugarcane fields, inclusion of crop rotation within the

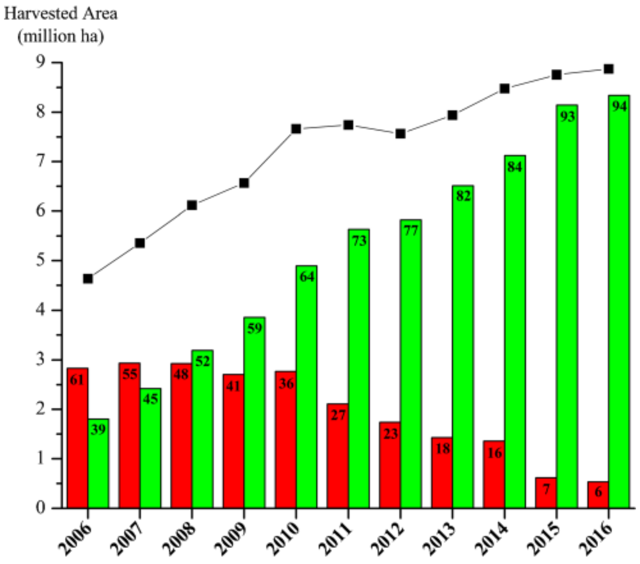
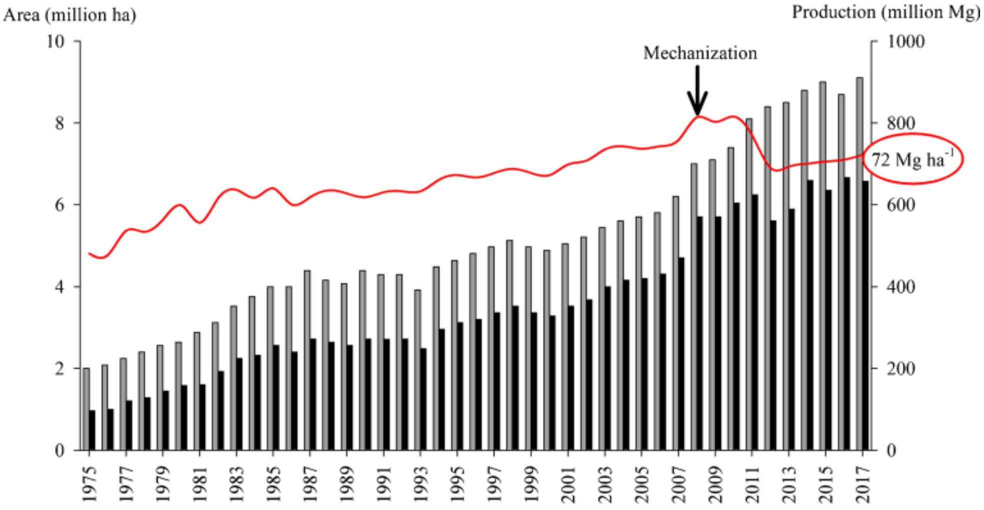


Fig. 6 Total harvested area (black line) in south-central Brazil and evolution (in percentage) of the type of harvest during 2006–2016: manual burned (red bars) versus green mechanized (green bars). Data adapted from Bordonal et al. (2015), CONAB (2017), and UNICA (2017)

sugarcane cropping cycle, and adoption of no-till or reduced tillage. These management strategies are essential to increasing sugarcane yields to 100 Mg ha^{-1}. Yet, the high degree of harvest mechanization increases diesel consumption and its contribution on the overall GHG emissions. Brazilian sugarcane sector was an important contributor to GHG emissions (~ 40% in 2009) from the high consumption of diesel in the mechanized harvest (Capaz et al. 2013). The replacement of diesel by a renewable fuel (e.g., biodiesel from vegetable oils and fuel ethanol) and higher efficiency of machinery and transportation vehicles are some options that can reduce the associated GHG emissions (García et al. 2011; Ometto et al. 2009).

Sugarcane has an average yield of ~ 80 Mg ha^{-1}, of which 14 Mg ha^{-1} of dry matter is currently left on the soil surface after each harvest (De Figueiredo and La Scala Jr. 2011). However, the amount of biomass retained varies with crop cycle, variety, site, soil fertility, etc. (Menandro et al. 2017). From an agronomic point of view, the practice of maintaining the sugarcane straw on the soil surface brings numerous ecosystem services in the long term, including lower variation in soil temperatures, better water infiltration and availability due to smaller evapotranspiration, effective weed control, and protection against soil erosion (Carvalho et al. 2017a). The latter is a very important issue in sugarcane fields. Soil covered with sugarcane straw reduces soil erosion by dissipating the kinetic energy of raindrops, decreasing the flow velocity, and increasing the depth of the water layer on the soil surface (Martins Filho et al. 2009). Soil erosion losses can range from 16 to 150 Mg ha^{-1} year^{-1} and strongly depend on the terrain slope, rainfall, soil type, and soil coverage (Hartemink 2008). Martins Filho et al. (2009) reported that the maintenance of 50 and 100% of the sugarcane straw on the soil surface in comparison with a bare soil reduced soil ersion by 68 and 89%, respectively. These authors concluded that erosion losses in sugarcane areas may decrease exponentially with increase in soil cover, especially with straw coverage equal to or more than 7 Mg ha^{-1}. In this context, the removal of high rates of sugarcane straw for other purposes may aggravate erosion losses and compromise soil quality in sugarcane fields of Brazil and elsewhere (Carvalho et al. 2017a).

Fig. 7 Reported annual sugarcane production (black bars) and evolution of cultivated area (gray bars), including average yields of sugarcane (red line) in Brazil between 1975 and 2017. After 2008 crop season, the intensive mechanization of sugarcane clearly shows the impacts of soil compaction and degradation due to the traffic of large and heavy agricultural machines associated with management and harvest operations. Data acquired from FAOSTAT (2017), IBGE (2017), and CONAB (2017)



However, some adverse effects have also been observed with the maintenance of large amount of straw in some specific edaphoclimatic conditions, including difficulties in the mechanical cultivation (Magalhães et al. 2012), increased risk of fire (Rossetto et al. 2008), and reduction in the initial tillering of sugarcane (Aquino et al. 2017). Furthermore, straw mulching can create an ideal microclimate (mainly temperature and humidity) for the development of pest and disease infestations (Dinardo-Miranda and Fracasso 2013; Hassuani et al. 2005), which could adversely affect crop yield and increase production costs. In some cases, especially in the cooler temperate regions, maintaining straw on the soil can hinder the ratoon sprouting, resulting in gaps in the stand and reducing the sugarcane yields (Campos et al. 2010; Ramburan and Nxumalo 2017). On the other hand, straw retention in warmer climates has resulted in higher yields by conserving soil moisture and decreasing soil temperature (Aquino et al. 2017).

Elimination of straw burning in sugarcane fields along with efficient use of crop/industrial residues (e.g., sugarcane straw, filtercake, and vinasse) and, mainly, high level of electricity generation exported to the grid could reduce the net ethanol-related emissions to zero by 2020 (Seabra et al. 2011), attaining the energy balance ratio of 11.6 compared with the present value of 9.1 (Table 1; Macedo et al. 2008). With the switch from burned to green harvesting, renewable energy ratio improved from 7.0 in 2002 to 9.4 in 2009 (Chum et al. 2014). Despite the large energy potential associated with the sugarcane straw, additional efforts should be made to establish an appropriate technique to harness such potential (Lisboa et al. 2017).

In the short term, the combustion of sugarcane straw in boilers for bioelectricity generation is likely to be the main application. If 40–50% of the straw available in the field is used in co-combustion with bagasse, the total electricity surplus from the sugarcane mills can be as much as 468–670 MJ Mg^{-1} (130–186 kWh Mg^{-1}) of cane (Seabra et al. 2011), indicating an additional potential to be explored as a renewable bioenergy generation. However, a lot of controversy still remains regarding the removal/retention of sugarcane straw on soil after harvest, since it can be used to produce either electricity or second-generation ethanol, and/or could be left in the field to improve soil productivity (Silva et al. 2014; Carvalho et al. 2017a). These aspects should be addressed through further research in order to minimize adverse impact on agricultural sustainability (e.g., soil erosion, nutrients recycling, soil carbon storage, and soil water availability) while still providing biomass-based energy (Leal et al. 2013a).

Systematic removal of straw for ethanol and/or electricity purposes may increase soil CO_2-C emission (De Figueiredo et al. 2015; Moitinho et al. 2013) and reduce soil organic matter content (Bessou et al. 2011). A positive correlation between the maintenance of sugarcane straw and the soil C accretion has been reported by several studies (Galdos et al. 2009; Cerri et al. 2011; Pinheiro et al. 2010; Carvalho et al. 2017b). La Scala Jr. et al. (2012) reported a mean rate of soil C accretion from 1.02 to 1.87 Mg C ha^{-1} $year^{-1}$ in sugarcane fields under green cane management. These variations in sequestration rate may be attributed to differences in soil texture (e.g., sandy or clay soils), the time since adoption of the green harvest system (Cerri et al. 2011), and the soil management during the sugarcane-replanting period (De Figueiredo et al. 2015). Above all, soil C sequestration may increase crop yields by enhancing soil functions and properties related to the accretion of soil organic matter (Delgado et al. 2011). For instance, soil structure and aggregate formation would increase soil fertility (e.g., cation exchange capacity) and water holding capacity under green cane management through soil coverage upon harvest without burning (Souza et al. 2012; De Luca et al. 2008).

Although the conversion from burned to green harvest has a vast potential to increase soil C stocks, most of the accumulated C during the sugarcane cycle can be lost as CO_2-C emission after soil disturbance during the replanting operations, which are performed once every 5 or 6 years (De Figueiredo et al. 2015). Silva-Olaya et al. (2013) reported that up to 3.5 Mg CO_2 ha^{-1} could be released after tillage of soil in Brazilian sugarcane fields. Cerri et al. (2011) concluded that the lowest C accumulation rates are observed in fields where soil disturbance and sugarcane replanting were the most recent (<2 years), indicating that part of the C accumulated over the crop cycle was lost during this process. Tillage disrupts soil aggregate and exposes the protected organic matter to microbial activity and consequently a decay of soil organic matter, which increases CO_2-C emissions to the atmosphere (Six et al. 1999; La Scala Jr. et al. 2008). Moreover, tillage operations improve conditions for decomposition of soil organic matter because it temporarily reduces soil compaction, increases soil porosity, improves aeration and oxygenation, and increases soil temperature (La Scala Jr. et al. 2006).

New management practices (e.g., reduced tillage during the sugarcane-replanting period) could reduce decomposition of soil organic matter and increase soil C accumulation. La Scala Jr. et al. (2006) observed that adoption of no-till reduced the CO_2 emissions by 8.4 Mg ha^{-1} compared to conventional tillage practices. In a 7-year study, Segnini et al. (2013) isolated the impacts of the maintenance of straw on soil surface versus tillage operations during sugarcane renovation. Adoption of green cane and conventional tillage resulted in C retention rates of 0.67 Mg ha^{-1} $year^{-1}$, while the adoption of green cane and no-till accumulated 1.63 Mg C ha^{-1} $year^{-1}$. Maintaining the sugarcane straw on the soil under no-till is, therefore, a sustainable management option to be considered during the sugarcane-replanting period. Furthermore, the adoption of no-till reduces the numbers of tillage operations, decreases CO_2 emission by fuel consumption, and indirectly mitigates GHG emissions in agricultural production (West and Marland 2002; Antle and Ogle 2012), beyond other aspects such as air and water quality impacts (Smith et al. 2007). Importantly, no-till or reduced tillage is one of the strategies contributing to global food security and the protection of soils, and thus to climate change adaptation through building agricultural systems that are more resilient to climate and weather variability (Powlson et al. 2014).

Despite many benefits, no-till system is not yet widely used in sugarcane fields in Brazil. Derpsch et al. (2014) opined that no-till is a conservation farming system, in which seeds are placed into untilled soil by opening a narrow furrow with only a sufficient width and depth to obtain proper seed placement and coverage and no other soil tillage is done. However, in traditional sugarcane fields in Brazil, the planting furrow disturbs about 30% of the soil surface (0–30 cm) and makes it difficult to adopt no-till in its totality. Therefore, until now, no-till in sugarcane fields is a type of reduced tillage where around 30% of surface layer is disturbed by the planting furrow made once every 5- or 6-year period. In the future, the adoption of new technologies of planting, such as transplanting sugarcane seedlings already used in some areas, can change this scenario. This improved technology will reduce soil disturbance, improve the potential for soil C accumulation, and contribute to mitigating GHG emissions in sugarcane crop production.

Severe soil compaction is another constraint to adopting no-till in sugarcane. In traditional green cane areas in Brazil, soils are compacted during the replanting period, and in most cases, tillage operations are performed. The intense machinery traffic and the attendant trampling aggravate soil compaction (Braunack and McGarry 1998; De Souza et al. 2012). It is assumed that adoption of reduced tillage in sugarcane fields should involve strategies of controlled and reduced traffic to minimize the stump trampling and soil compaction in the seedling zone (Braunack and McGarry 2006). These strategies are needed to increase the rate of water infiltration and soil biological activity (Tullberg et al. 2007), and enhance soil C sequestration. However, studies evaluating the adoption of reduced tillage in sugarcane fields under controlled traffic conditions in Brazil are scanty and a researchable priority.

4.2 Inorganic synthetic N fertilizer

The consumption of synthetic nitrogen (N) fertilizers in Brazil has increased ~ 30 times during 1960 to 2002 (Filoso et al. 2006), and there is a great concern regarding the rational management of N fertilizer. Sugarcane cultivation in Brazil is highly efficient because of favorable growing conditions and produces high yields even with low N fertilizer inputs compared with that from other biofuel feedstocks such as corn (Heffer and Prud'homme 2008). Recommended rates of N application in Brazil (60–100 kg N ha^{-1} $year^{-1}$) are significantly lower than those in Australia (160–200 kg N ha^{-1} $year^{-1}$), India (150–400 kg N ha^{-1} $year^{-1}$), and China (100–755 kg N ha^{-1} $year^{-1}$) (Robinson et al. 2011), which is an important factor leading to a high energy balance in sugarcane ethanol production (Manochio et al. 2017).

Further, biological N fixation can also supply a part of N demand for sugarcane cultivation in Brazil (Boddey et al. 1995; Medeiros et al. 2006; James and Baldani 2012; Urquiaga et al. 2012). An annual N input through biological fixation in sugarcane has been estimated at 58 kg ha^{-1} $year^{-1}$ by Resende et al. (2006) compared with that of 40 kg N ha^{-1} $year^{-1}$ by Urquiaga et al. (2012). However, studies conducted in Brazil (Cantarella et al. 2014), Australia (Biggs et al. 2002), and South Africa (Hoefsloot et al. 2005) did not show any positive impact of inoculation and concluded that N inputs via biological fixation may be insignificant in sugarcane fields. The contribution of biological N fixation on sugarcane-N budget is, therefore, a debatable issue and a researchable priority.

Thus, chemical N fertilization is needed to maximize sugarcane yields. Input of synthetic N into agricultural systems contributes to increased N losses via atmospheric, surface, and/or leaching pathways (Lal et al. 2011). While synthesizing the data regarding in situ measurements of losses of N by leaching, denitrification, uptake, immobilization, and volatilization under Brazilian field conditions, Otto et al. (2016) concluded that 26% of N fertilizer applied in sugarcane fields is absorbed by crop, 32% is immobilized in the soil, and the remaining 42% is lost by NH_3 volatilization (19%), leaching (5.6%), N_2O emissions (1.8%), and other pathways (16%). Otto and colleagues reported that only 28% of the aboveground sugarcane N content comes from N fertilizers and 72% is derived from other sources, such as mineralization of soil organic matter, biological N fixation, and dry and wet deposition. Several studies in Brazil with ^{15}N-labeled nitrogen have shown that mineralization of soil organic matter is the main source of N for sugarcane rather than N fertilizers (Dourado-Neto et al. 2010; Franco et al. 2011; Otto et al. 2013; Vieira-Megda et al. 2015), indicating that N supply from mineralization is an important aspect to be considered in N management systems, especially where increasing the N use efficiency is a primary goal.

NH_3 volatilization is one of the main sources of N losses in sugarcane fields, and such losses are mostly associated with application of urea on the soil surface without incorporation into the soil (Otto et al. 2016). The application of urea on top of the sugarcane straw layer may lead to losses by NH_3 volatilization ranging from 24 to 37% of applied N fertilizer (Mariano et al. 2012; Soares et al. 2012). However, using other types of N fertilizers in sugarcane fields (i.e., ammonium nitrate and ammonium sulfate) could be an important strategy to attenuate these losses (Costa et al. 2003). Further, the incorporation of N urea into the soil and the use of urease inhibitors (Cantarella et al. 2008) can significantly reduce NH_3 volatilization and increase biomass production (Castro et al. 2014; Gava et al. 2001; Soares et al. 2012).

The recent adoption of green cane harvest has enhanced N losses by volatilization in sugarcane fields (Costa et al. 2003; Mariano et al. 2012). Sugarcane straw has a high C/N ratio and its deposition on the soil surface leads to N immobilization by microorganisms (Vitti et al. 2007), and thereby higher N rates have been recommended to enhance availability to the sugarcane crop. In a long-term perspective, however, the adoption of green harvest system may also attenuate losses by volatilization from synthetic N fertilization. Basanta et al. (2003) indicated that unburned straw remaining on soil surface would result in an average N recycling of 105 kg ha^{-1} $year^{-1}$, which may lead to a more efficient recycling of fertilizer N applied to the system. The available information indicates that the fertilizer N application should not be reduced during the first 6 years after adoption of residue mulching in sugarcane management, and small reductions may only be possible over a longer term (> 15 years; Robertson and Thorburn 2007).

Several studies in sugarcane fields in Brazil have also shown that losses through NO_3^- leaching may range from 0 to 22.5% (Oliveira et al. 2002; Ghiberto et al. 2009; Ghiberto et al. 2011; Ghiberto et al. 2015), indicating that a large proportion of the N applied in sugarcane production is lost to the atmosphere. Leaching of NO_3^- can aggravate several environmental problems, especially concerning water quality and the groundwater pollution. The reported rates of NO_3^- leached in sugarcane fields in Brazil are smaller than those observed in Australia, which reflect the lower N application rate and best soil conditions (Otto et al. 2016). In Brazil, sugarcane is cultivated mainly in deep, well-drained, and highly weathered soils, which cause relatively small amounts of NO_3^- entering into the groundwater. However, NO_3^- losses can be higher when sugarcane is cultivated in sandy and/or shallow soils, and additional research is needed to validate this hypothesis.

Nitrous oxide (N_2O) is another potent GHG emitted mainly from agricultural activities such as application of N fertilizer. Field experiments show that N_2O emissions in sugarcane fields may range from 0.21 to 3.03% depending on soil type and the amount of N fertilizer and sugarcane residues maintained in sugarcane fields (Carmo et al. 2013; Pitombo et al. 2016; Siqueira Neto et al. 2016). Because of the scarcity of field data, Life Cycle Assessment inventories are based on emission factor of 1% of the N fertilizer applied (IPCC 2006), and therefore N_2O emissions from N fertilization may represent 30–40% of the total GHG emissions associated with sugarcane production (Bordonal et al. 2013; Lisboa et al. 2011).

Adoption of best management practices (e.g., switching the sources of N, split application to coincide with crop demand, precision farming to reduce rates of N application in over-fertilized regions, slow-release fertilizers, and nitrification inhibitors) has a potential to mitigate N_2O emissions and enhance N use efficiency by up to 50% (Reay et al. 2012). For instance, application of urease inhibitors can reduce the N volatilization by 15 to 78% during the sugarcane-growing season (Cantarella et al. 2008; Soares et al. 2015). Also, N_2O-induced emissions by N fertilizers depend on the N sources (e.g., ammonium nitrate and urea) and the application rate (Signor et al. 2013; Allen et al. 2010). The application of ammonium sulfate and the incorporation of urea into the soil can decrease N losses through volatilization and water runoff from sugarcane fields (Prasertsak et al. 2002).

Enhanced efficiency of fertilization, optimization of byproduct usage (e.g., vinasse and filtercake), and increased use of green manure through crop rotation are important strategies to reduce N fertilizer inputs and associated N_2O emissions (Otto et al. 2016). Further, including legumes in crop rotations makes considerable net input of N to soil (Peoples et al. 1995). However, little is known about how much sugarcane could assimilate N from biological fixation by using legumes as N-fixing crop. Hemwong et al. (2009) observed that legume residues can substitute only the basal fertilization of N, but sugarcane requires additional N supplement at later stages. Park et al. (2010) estimated potential reduction in fertilizer application rate through biological N fixation at 100% in the first ratoon, and 60, 25, and 10% in the subsequent ratoons.

Further research is needed to elucidate and validate the benefits of N-fixing crops as a source of N in sugarcane-legume rotation cropping systems. Furthermore, N input in the soil by biological fixation is part of a natural process, whereas the use of chemical N fertilizer requires energy (Crews and Peoples 2004). Research is also needed to establish the link between biological N fixation and N_2O emissions from N-fixing crops (Jensen et al. 2012). Some researchers argue that biological N fixation may not be a direct source of N_2O (Barton et al. 2011; Rochette and Janzen 2005). Similarly, inoculation with plant growth promoting microorganisms is a promising management option to increase the efficiency of fertilizers use, promote plant nutrient use efficiency (Adesemoye and Kloepper 2009), and protect plants against pathogens. Based on these beneficial aspects, plant growth-promoting microorganisms are potential alternatives or have synergistic effects with traditional fertilizers for enhancing plant productivity and improving soil quality without environmental pollution (Bhardwaj et al. 2014).

4.3 Vinasse fertirrigation

Vinasse is the main residue of the sugarcane biofuel industry and is produced on average of 13 L for each liter of ethanol (Kumar et al. 1998). Vinasse is a dark-brown high-strength wastewater with dissolved organic C content of 50–150 g L^{-1}, which may be 100 times more than that in the domestic sewage (Fuess and Garcia 2014). The ethanol industry in Brazil regulated the disposal of vinasse during the mid-1980s to be recycled back into the fields (Filoso et al. 2015), because of well-documented problems of anoxia in water bodies due to the high loads of vinasse (Christofoletti et al. 2013). Thus, the primary use of vinasse at present is an application in sugarcane fields as fertirrigation.

The application of vinasse in sugarcane fields is the least expensive and the simplest solution with several agronomic benefits (Oliveira et al. 2015), including increase in sugarcane yields (Resende et al. 2006), improvement in soil quality (Christofoletti et al. 2013), increase in soil inputs of C and N (Parnaudeau et al. 2008), reduction of fresh water used in full and salvage irrigation, and decrease in synthetic fertilizers use (Smeets et al. 2008; Macedo et al. 2008). Vinasse fertirrigation improves sugarcane yields in both short and long term primarily because of its high potassium content (Resende et al. 2006). However, the repeated application of vinasse may lead to potassium accumulation and leaching into the groundwater (Da Silva et al. 2014b), which can potentially affect aquatic ecosystems (De Moraes et al. 2010). The adverse effects of vinasse fertirrigation also include soil salinization, soil over fertilization, soil and groundwater acidification, contamination by specific ions, among others (Fuess and Garcia 2014).

Vinasse is also an important source of GHG emission: during storage and transportation (Oliveira et al. 2015; Oliveira et al. 2017b) and after the application in sugarcane fields (Carmo et al. 2013; Oliveira et al. 2013; Paredes et al. 2014; Siqueira Neto et al. 2016; Pitombo et al. 2016; Silva et al. 2017). Assessing the emissions from vinasse during storage and transportation by open channels, Oliveira et al. (2015) concluded that this phase is an important source of CH_4 (ranging from 394 to 1092 mg m^{-2} h^{-1}) and should be included in future GHG inventories for sugarcane ethanol production. Further, comparing the two most widespread systems of vinasse storage and transportation—open channels and tanks—Oliveira et al. (2017b) observed higher emissions from vinasse stored and transported by channels (1.36 kg CO_2eq m^{-3} of transported vinasse), whereas 85 to 90% of these rates were measured from the uncoated section of channel. Oliveira and colleagues concluded that improvements in the vinasse distribution systems through adoption of new technologies, such as the adoption of closed pipes instead of open channels, could reduce GHG emissions and make a significant contribution towards a cleaner production of sugarcane ethanol.

Application of vinasse in the field does not influence CH_4 emissions but reduces soil aeration and increases the availability of dissolved organic C to microorganisms, in which the higher microbial activity in anaerobic sites leads to high N_2O losses (Siqueira Neto et al. 2016). Estimating N_2O emissions from soils treated with vinasse and mineral N fertilizer at different stages of sugarcane growth, Carmo et al. (2013) observed higher N_2O emissions in treatments receiving vinasse than those receiving only the mineral fertilizer. Similar trends have been reported in other studies (Paredes et al. 2014; Siqueira Neto et al. 2016; Pitombo et al. 2016; Silva et al. 2017). Application of vinasse associated with sugarcane straw on the soil surface can also increase N_2O emissions (Carmo et al. 2013; Pitombo et al. 2016; Oliveira et al. 2013).

N_2O emissions from vinasse fertirrigation also depend on the method of its application. An application of concentrated vinasse reduces N_2O emissions compared with that of fresh vinasse and can be considered a key strategy to mitigate GHG emission in the Brazilian sugarcane bioethanol sector (Pitombo et al. 2016). Similarly, evaluating the trade-offs between N_2O emissions, crop productivity, and irrigation in sugarcane plantation, Silva et al. (2017) concluded that applications of synthetic N fertilizer and vinasse separated in time by at least a month can avoid the synergistic effects of joint application on N_2O emissions and might be considered a mitigation strategy.

Another possible GHG mitigation strategy is the anaerobic digestion and concentration of vinasse. Assessing GHG emissions from fresh and biodigested vinasse from sugar beet ethanol production in different time of storage and after application in the soil, Moraes et al. (2017) observed that anaerobic digestion was effective in mitigating GHG emissions during storage, in which no CH_4 emissions were observed in digested vinasse against 333 g CH_4 L^{-1} of fresh vinasse and after field application. The digestate also showed lower N_2O emissions by 48–78% than those from fresh vinasse, depending on the retention time prior to soil application.

The concentration of vinasse is an economic alternative to reduce transportation and logistical costs, which reduces the large amount of water that makes up its composition (Otto et al. 2017) and contributes to mitigating GHG emissions. While this practice introduces high efficiency and quality in the field application, it is not well known whether the concentrated vinasse can reduce the GHG emissions in comparison with the application of the fresh vinasse. However, it is likely to reduce the N losses once this practice may increase the nutrient efficiency by the crop. The impacts of vinasse loadings on soil biogeochemical processes are not fully understood (Filoso et al. 2015).

4.4 Water use and quality

Numerous crops are used globally to produce bioenergy, but not all of them meet the requirements of a high yield and environmentally sustainable feedstock. Approximately 70% of the global water withdrawals are attributed to agricultural activities (Aquastat 2012), and the increased demands for food in combination with a shift from fossil energy towards bioenergy are putting additional pressure on freshwater resources (Gerbens-Leenes et al. 2009). Concerns regarding the environmental impacts of biofuel production have increased considerably since the 2000s, including those related to water quantity and quality (Filoso et al. 2015).

Sugarcane is one of the most favorable options to produce ethanol in terms of water footprint (WF; Table 1), which represents the amount of water consumed per unit ethanol produced (Gerbens-Leenes et al. 2009). Over the three decades (1985–2015), sugarcane mills have been relatively inefficient water users because of the adoption of water open-circuit technology, which accounts for a water withdrawal of 15–20 m^3 Mg^{-1} of cane. Currently, there has been a substantial reduction in consumption to ~ 1.85 m^3 Mg^{-1} of cane, especially by implementing better technologies to improve water use efficiency (Yeh et al. 2011; Filoso et al. 2015). Reducing or recycling water from the sugarcane washing has also an important impact on the overall improvement during the industrial stage, since the burnt sugarcane is dirtier than the green and requires larger volume of water for washing (Silva et al. 2014). For instance, in the São Paulo state, which has the largest concentration of ethanol and sugar mills in Brazil, authorities established a target to limit water use in sugarcane industry by 1.0 m^3 Mg^{-1} of cane and 0.7 m^3 Mg^{-1} of cane in areas under water scarcity (Agro-Environmental Zoning for Sugar Alcohol Sector for the São Paulo State). One means of achieving such commitment is through optimization of water reuse in sugarcane industry, which could decrease consumption by 0.8 m^3 Mg^{-1} of cane and lead to a total usage of around 0.6 m^3 Mg^{-1} of cane (Chavez-Rodriguez et al. 2013).

Despite the developments so far achieved in the industrial phase of ethanol production, assessment of water consumption is also pertinent during the sugarcane agricultural production. In Brazil, bioethanol is produced from sugarcane under dryland conditions, but the use of irrigation can boost sugarcane yields particularly in regions with limited water availability (Scarpare et al. 2016a). Nevertheless, the necessity for irrigation to meet large-scale ethanol demand may further strain limited water resources (Popp et al. 2014). The average WF of the sugarcane production in south-central Brazil is 137 m^3 Mg^{-1} of cane, ranging from 124 m^3 Mg^{-1} in São Paulo state to 170 m^3 Mg^{-1} in Paraná (Hernandes et al. 2014). Variations in WF may be due to the crop evapotranspiration in relation to climate and the yield potential, which vary with soil and management.

Agronomically, there are several options to reduce the sugarcane WF. Full and supplemental irrigation reduce water deficit in critical period of the crop development and are important strategies to increase biomass yield with a little additional water use (Rockström et al. 2010; Cardozo et al. 2016). The adoption of salvage and full irrigation regimes in south-central Brazil reduced sugarcane WF by about 1 and 7% compared to that under rainfed condition, respectively (Hernandes et al. 2014). Irrigation may also reduce the C footprint of sugarcane production by 59% against dryland areas and promote the intensification of land use (Cardozo et al. 2016).

However, the production of sugarcane in Brazil is currently managed by applying merely vinasse or wastewater as a salvage irrigation. The salvage irrigation is applied under low volumes (e.g., ranging from 100 to 200 m^3 ha^{-1} $year^{-1}$) and largely uses nutrient-rich wastewater generated from industrial production (e.g., sugar and bioethanol) instead of freshwater (Yeh et al. 2011). The use of vinasse as salvage irrigation supplies nutrients and increases soil moisture during periods of water stress, resulting in better sugarcane sprouting and higher yields (Scarpare et al. 2016b). The adoption of irrigation in bioenergy production systems can change the field-level water availability, evapotranspiration rates, and downstream water flows (Berndes et al. 2015). However, the direction and magnitude of such changes depend on the location and the specific management (Sterling et al. 2013).

There exists a vast potential in agricultural sector to improve water availability and quality by increasing soil water storage and reducing losses. Semi-perennial bioenergy crops (i.e., sugarcane) have an extensive root system, reduced need for tillage operations during the crop cycle, and long-term soil cover and better soil protection, which tend to have lower water quality impacts than conventional crops (Dimitriou et al. 2011). Using a Life Cycle Assessment approach, recent studies estimated that the adoption of no-till in sugarcane fields improves the quality of freshwater and reduces the contamination of water bodies (Da Silva et al. 2014a; Chagas et al. 2016). Adoption of conservationist management practices (e.g., reduced tillage, soil cover by crop residues after green harvest and cover crops) also attenuates the erosion-induced losses (e.g., water, sediment, and nutrients) in sugarcane fields (Martins Filho et al. 2009; Da Silva et al. 2012), and consequently reduces WF of ethanol production. Scarpare et al. (2016b) estimated sugarcane WF and observed average green, blue, and gray WFs of 145, 38, and 18 m^3 Mg^{-1}, respectively. The larger fraction of green against blue WF confirms the importance of rainfall, which endorses why Brazilian sugarcane growers limit their production to reasonable rainfall regions.

Even with the smaller gray component of WF, Scarpare et al. (2016b) highlighted the lack of good indicators of the impacts of fertilizers, herbicides, insecticides, and fungicides on water bodies, suggesting that comprehensive assessments by gray WF should be performed to identify the most hazardous substances in the sugarcane production chain. Corroborating these findings, Guarengui and Walter (2016) concluded that it was not possible to rigorously determine the contribution of large-scale production of sugarcane for changing water flows and reducing water quality, despite the use of the best publicly available database in the São Paulo state, Brazil.

Similar to the cultivation of other commercial crops in Brazil (e.g., soybean and corn), cultivation of sugarcane also requires the application of pesticides. An effective disease, pest, and weed control is crucial because a reduction of more than 80% can occur in sugarcane production (Smeets et al. 2008). Pesticides are typically used, but in limited quantities per hectare compared to those in conventional crops (e.g., 40% less compared with corn and more than 90% less than in other crops such as coffee, citric, or soybean) (Macedo 2005). Agrochemicals usually applied in sugarcane areas include herbicides, insecticides, maturators, adhesive spreading agents, biological and microbial products, vegetable extracts, and pheromones that are used to control pests and undesirable weeds, with biological products having no toxicological characteristics and risks.

Despite the fact that sugarcane plantation consumes less pesticides in comparison with other crops, some researchers argue that the use of pesticides in sugarcane areas has increased substantially in Brazil in recent years (Velasco et al. 2012; Warren et al. 2003). The advent of green mechanized harvest with the absence of fire has caused significant changes in sugarcane agrosystems due to modification in soil cover conditions related to annual deposition of large amount of straw on the soil surface (Carvalho et al. 2007a). The residue retention can aggravate infestation by weeds and the populations of pests and their natural enemies (Dinardo-Miranda and Fracasso 2013). Assessing the contamination by herbicides in Ipojuca River in northeast Brazil, Ferreira et al. (2016) observed residual detection of diuron and ametryn at all collection points. The presence of these molecules in water bodies, even at low concentrations, may originate perceptible alterations on long-term basis. Jacomini et al. (2011) also observed high levels of ametryn in three rivers from areas under sugarcane cultivation in southern Brazil. These findings provide new insights into the impact of sugarcane bioethanol on the pollution of freshwater at a watershed level.

Regardless of the impacts of increased use of pesticides, some adaptations in agricultural management are needed to minimize future risks to quality of natural waters. Among several opportunities to decrease the use of pesticides include the application of biological control, in which Brazil's major programs in this field are already incorporated within the sugarcane cropping systems. Integrated pest management with introduction of biological control and crop rotation could also reduce the use of agrochemicals in the future, besides the development of resistant cane varieties especially in relation to disease control (Smeets et al. 2008). Without adequate environmental and regulatory policies, therefore, future expansion of sugarcane in Brazil could pose a threat to water quality and put drinking water supplies at risk (Hess et al. 2016).

5 Conclusions

Barriers to large-scale deployment of biofuels include concerns regarding the sustainability of agricultural practices, high consumption of agricultural inputs, greenhouse gas emissions, land use change, food production, water use and quality, among others. Appropriate agricultural practices are those that reduce the impact of greenhouse gas emissions while enhancing the adaptive capacity of agricultural systems to climate change, increasing crop yields, and advancing food security. Sugarcane ethanol can play an important role in greenhouse gas mitigation providing that sustainability of agricultural practices and the efficiency of ethanol production are enhanced and sustained.

Adoption of innovative technologies indicates that improvements in both agricultural and industrial sectors have led to a better sustainability and acceptance of sugarcane-derived products (e.g., ethanol, sugar, and bioelectricity) in the global market. Great advances made in the sugarcane crop production from 1975 to 2015 in Brazil (e.g., the improvement of energy balance, greenhouse gas savings, water recycling, lower water footprint, and higher yields with low fertilizer inputs than other biofuel feedstocks) make the sugarcane-based ethanol as one of the most successful global bioethanol programs. Continuous developments in sustainability of agricultural practices during the decade ending in 2015 have also contributed to these outcomes. Notable among these are as follows: reducing area under residue burning in the sugarcane preharvest, decreasing the input of synthetic fertilizers by recycling the industrial byproducts (e.g., vinasse), achieving a rational and sustainable pathway for sugarcane expansion through Agro-ecological Zoning program, and avoiding the sugarcane transition over biomes such as Amazon and Pantanal.

However, there is a large potential of improving the efficiency of agricultural management in sugarcane cropping systems, such as closing the yield gaps and decreasing inputs of synthetic fertilizers. Along with these improvements, the intensification and restoration of degraded pastures for livestock sector are key opportunities that must be encouraged to provide additional food and ensure the benefits of sugarcane as a sustainable feedstock for bioenergy production. There also exists a strong need for a more integrated perspective on the management of agricultural systems, so that synergies among sugarcane with food and feed crops are important developments that deserve special attention. To meet the increasing world demand for bioethanol in a sustainable manner beyond the avoided emissions provided by substitution of fossil fuels, further advances may be achieved through the potential to recovering sugarcane straw for bioenergy production (e.g., bioelectricity and second-generation ethanol), as well as implementing best management practices in the sugarcane production chain (e.g., total eradication of preharvest burning, accurate straw recovery rate, enhancing N use efficiency, anaerobic digestion and concentration of vinasse, increased use of green manure as crop rotation, application of slow-release fertilizers and nitrification inhibitors, and adoption of reduced tillage involving strategies of controlled traffic in sugarcane fields) across all regions in Brazil. These are among researchable priorities for consolidating the large potential of sugarcane for increasing soil C stocks, offsetting the anthropogenic CO_2, and effectively mitigating the global climate change.

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