Advanced Review

Brazilian sugarcane ethanol: developments so far and challenges for the future

Arnaldo Walter,[1]* Marcelo Valadares Galdos,[2] Fabio Vale Scarpare,[2] Manoel Regis Lima Verde Leal,[2] Joaquim Eugênio Abel Seabra,[1] Marcelo Pereira da Cunha,[2] Michelle Cristina Araujo Picoli[2] and Camila Ortolan Fernandes de Oliveira[1]

Sugarcane ethanol has been produced in Brazil since the early 20th century, but production increased in the mid-1970s aiming at substituting 20% of the gasoline. Despite an increase in the 2000s production has been stable since 2008. This paper presents a review of the main developments achieved and future challenges. The sector has had positive economic and environmental results through technological development, as a result of research and development by private companies and strong public support. Sugarcane yield has steadily increased and positively impacted production costs, primarily due to better agronomic practices and breeding programs. Owing to environmental and economic reasons, there are on-going programs to phase out burning, with the gradual replacement of manual harvest with burning by unburnt mechanised harvest. Important agronomic impacts are expected, caused by the large amount of straw left on the soil surface, which also represents a significant bioenergy potential. The sugarcane industry in Brazil has taken advantage of the combined production of sugar and ethanol, and, recently, many mills have enlarged their revenues with surplus electricity. The current efforts for diversification aim at ethanol production through hydrolysis of sugarcane residues and the development of chemical routes. From an environmental point of view, impacts related to land use change are expected on greenhouse emissions, water resources, and biodiversity. Ethanol production is likely to expand in Brazil due to the potential size of the domestic market and to the opportunities for exporting, but this will occur in a context of different and new challenges.

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INTRODUCTION

The production of liquid biofuels is rapidly increasing, as governments are setting targets to enlarge the share of biofuels in the energy matrix for the purposes of climate change mitigation, improving energy security, and fostering rural development. It was estimated that the production of fuel ethanol was nearly 86 billion liters (BL) in 2011 (it was 39.2 BL in 2006 and 17 BL in 2000), whereas in the same year the production of biodiesel was estimated at 21.4 BL (6.5 BL in 2006 and only 0.8 BL in 2000).[1] The use of fuel bioethanol in 2011 was estimated to be the equivalent of 3% (energy basis) of the gasoline consumption, considering the consumption of light distillates to be approximately 1640 BL in the same year (mainly motor gasoline).[2] World production and consumption of fuel ethanol is dominated by the United States and Brazil, with more than 75 BL of 86 BL

*Correspondence to: awalter@fem.unicamp.br
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[1]Department of Energy, Faculty of Mechanical Energy, University of Campinas, Campinas, Brazil

[2]CTBE/CNPEM – Brazilian Bioethanol Science and Technology Laboratory/National Research Center on Energy and Materials, Campinas, Brazil

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produced in 2011 (approximately 88% of the world production). The United States is by far the main producer (54.2 BL in 2011).[1]

Despite this long-term experience, since 2008–2009 Brazil has had difficulties increasing the production of fuel ethanol (in fact, in 2011 there was a reduction of 18% compared to 2010). In spite of this, Brazil still has the best results in terms of production costs, energy balance, and avoided greenhouse gas (GHG) emissions. Except in 2010–2011, when the United States was a net exporter (surpassing 2 BL in both years), Brazil has been the main exporter of fuel ethanol—in 2011, it exported approximately 2 BL but surpassed 5 BL in 2008—and is one of the few countries capable of being a large exporter in the short to mid term.[3]

Based on recent trends (2000–2009), it was predicted that the production of ethanol should reach 64 BL in 2019, with 52.4 BL for the domestic fuel market, almost 10 BL for export, and less than 2 BL for other uses.[4] However, considering the drawbacks of ethanol production in recent years, but assuming a market recovery after 2012 (22.9 BL was produced in 2011), a production of 50 BL is predicted for 2019 (roughly 53.7 BL in 2020). The International Energy Agency predicts a world market of approximately 200 BL of fuel ethanol in 2020, which highlights the importance of Brazil in this context.[5]

However, the recovery of ethanol production in Brazil poses many challenges, as there are new players in the business, the expansion will mostly occur in less traditional areas, improving sustainability is mandatory and the industry needs to move toward production diversification and the development of second-generation biofuels. The purpose of this paper is to analyze the developments so far achieved and the challenges for keeping the competitiveness of this industry. In the following section, a brief history of ethanol production and the profile of this industry in Brazil are presented. The main developments of agricultural and industrial subsectors and their challenges are presented in the subsequent sections. A further section is devoted to assessing what is already known and the required actions regarding selected sustainability aspects, such as socioeconomic impacts, land use, GHG emissions, impacts on water resources and biodiversity. Finally, the conclusions are presented.

ETHANOL PRODUCTION IN BRAZIL

Historical Perspective

In the early 20th century, there were several attempts by the Brazilian sugar industry to produce fuel ethanol due to the surplus of sugar and to the heavy burden of gasoline imports.[6] In 1931, a 5% blending of ethanol in all imported gasoline was mandated and as consequence, in only 4 years the production increased from almost zero to 51 million liters[7] in 1937.[6–8] The blending amount varied during World War II, after which low oil prices diminished the interest in fuel ethanol, which continued to be blended with the gasoline on an as-available basis.

The impacts of the 1973 oil shock on the balance of payments and on inflation motivated the launch in November 1975 of the National Alcohol Program (Programa Nacional do Álcool—Proalcool). The main events in ethanol production in Brazil since then are presented below.

- The first target set by the government was the substitution of 20% of the gasoline consumed in the country (this target was reached in early 1980s).[6] Production targets were 3.0 BL of anhydrous ethanol in 1980 and 10.7 BL in 1985, which were easily met. The technology of ethanol engines had been developed by Brazilian research centers due to efforts begun in the 1950s.
- In 1979, as a result of the second oil shock, the government pressured the auto industry to produce on a commercial basis vehicles able to run on neat ethanol; shortly after the introduction to the market of the first model made to run on neat hydrated ethanol (by FIAT), the remaining three other automakers operating in the country at that time closely followed the move.[6,9] At the same time, the producers received support for increasing the production of hydrated ethanol.
- In 1985, the oil prices came down causing an increase in the subsidies burden and initiating the process of stagnation of the ethanol program. During the 1990s, partly due to less support from the government, the ethanol market faced difficulties. A shortage of ethanol in 1989/1990 led to a strong drop in sales of neat ethanol cars, and this significantly impacted the consumption of hydrated ethanol during the decade.
- The deregulation of the ethanol market began in 1991, with the government slowly relinquishing control, and the deregulation process was completed in 1999.[10] Currently, the government control of the fuel ethanol market is limited to setting the ethanol blending rate (in the 18–25% range) based on an

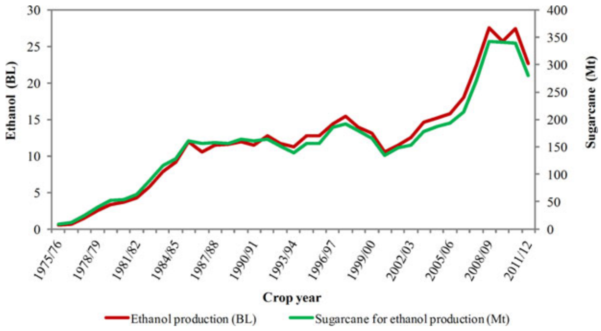

FIGURE 1 | Ethanol and sugarcane production (just for ethanol) in Brazil from 1975 to 2011. Created using data from Ref 10.

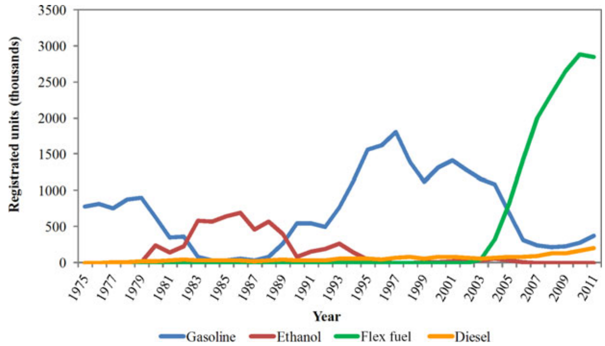

FIGURE 2 | Registration of new light-duty vehicles by fuel type—two-wheel vehicles not included—1975/2011. Created using data from Ref 12.

appraisal of the supply/demand balance. With the deregulation process, the Proalcool program, as initially conceived, was terminated.

- Since 2003, flex-fuel vehicles (FFVs) have been the main driving force of the domestic consumption. In Brazil, FFVs can run with any fuel mix between gasohol (18–25% ethanol, volume basis) and pure hydrated ethanol (100%). Gasohol is a blend of anhydrous ethanol and gasoline, and in Brazil all gasoline is in fact a blend.

Figure 1 shows the evolution of ethanol production in Brazil (hydrated and anhydrous) as well as of sugarcane production (only for ethanol; estimated on average figures of the sucrose content and on the production of sugar and ethanol) from 1975 to 2011. A deep reduction in hydrated ethanol production in the second half of the 1990s can be seen, due to the reduced fleet of ethanol-fueled vehicles. In contrast, the growth rates of ethanol production from 2000 to 2008 were even higher than the rates verified in the early years of the ethanol program; the hydrated ethanol market consolidated primarily because of the success of FFVs. Currently, all car manufacturers in Brazil have at least one FFV model and there are more than 100 models available; FFVs represent more than 90% of the new cars sold. Figure 2 shows the evolution of registered new light-duty vehicles in Brazil from 1975 to 2011, according to the fuel option. It is clear that the sales of neat ethanol cars were deeply reduced after the shortage of fuel ethanol in late 1980s, and they were almost nil during the 1990s. The great success of FFVs after their launch can also be observed in Figure 2.

However, since 2008, the production of ethanol has faced difficulties and it was drastically reduced in 2011 (see Figure 1). The reasons are various, and so far it is not possible to evaluate the impact of a single factor, but there are several important factors:

- The financial crisis after 2008 negatively impacted the traditional entrepreneurs of the ethanol sector that used to finance their activities with short-term loans. Owing to financial constraints, fewer investments were made along the supply chain and sugarcane yields declined.
- As a consequence of the poor financial situation of traditional producers, new players in the sector bought existing assets, who then postponed investments on new industrial plants and also on enlarging the planted area.
- Adverse weather conditions also negatively impacted sugarcane production, first with unusual rains during the harvest season of 2009–2010 and later with a long drought (2010–2011).
- The high sugar prices in the international market (from the second half of 2009 until July 2011) motivated a shift from ethanol to sugar production, further impacting the ethanol supply.
- Simultaneously, since 2008, gasoline prices to the consumers have been nearly constant (i.e., controlled to avoid inflation), reducing the competitiveness of fuel ethanol and the appeal of ethanol production.

Altogether, the supply of ethanol did not grow according to the demand and thus ethanol prices rose. On average, the price ratio between hydrated ethanol and gasoline to the final consumers (volume basis; in the city of São Paulo) that was 53% in 2007 rose to 71% in 2011. In a vicious circle, the investments

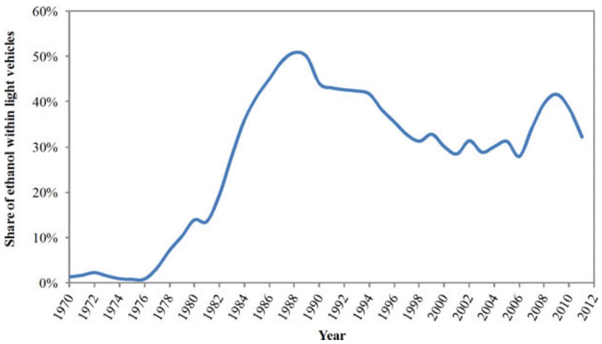

FIGURE 3 | Share of fuel ethanol in light-duty vehicles in Brazil. Diesel oil is not consumed in light-duty vehicles in Brazil. All natural gas used in the transport sector is consumed in light-duty vehicles. Created using data from Ref 13.

for increasing sugarcane supply and producing more ethanol were reduced. Only recently (from 2011 onward), some actions were taken, such as financial credits for the sugarcane suppliers, but the recovery of production will take some years as the production of sugarcane is still inadequate.

Since 2009, the share of fuel ethanol in the energy consumption of light-duty vehicles has been reduced, as seen in Figure 3. The maximum share was in the late 1980s, just before the ethanol shortage crisis in the early 1990s, and the result in 2011 was almost the worst result in the last 20 years.

The negative impacts have also been noticed in the fuel ethanol trade as Brazil lost its leading position as an exporter in 2010. The exports were primarily destined for the United States (a large share via the Caribbean) and the European Union, and they reached an all-time high in 2008 (more than 5 BL); this was primarily supported by high international crude oil prices despite European Union and United States tariffs.[14] In 2010, the United States was the main exporter to Europe (with a large share of ethanol exported as gasoline blends) and this was not only because of the production difficulties in Brazil but also due to the United States surplus and to the financial incentives given in the United States to the producers. Recent ethanol trade figures are very peculiar: in 2011 Brazil imported approximately 1.2 BL (mostly from the United States), due to its lower production and to the lower prices in United States, but exported in the same year almost 2.0 BL, also mostly to the United States. Fuel suppliers in the United States needed ethanol that is classified as advanced from the point of view of the GHG emissions (at least 50% avoided GHG emissions regarding gasoline), and domestic production (from corn) is not classified as such. The market for advanced biofuels was defined as 7.6 BL in 2012 and is predicted to grow to 79.5 BL in 2022.

TABLE 1 | Production and Number of Mills in Brazil, in 2010–2011[1]

Production and Number of Mills	Center-South	North-Northeast	Brazil
Sugarcane crushed (Mt)	560.56	63.27	623.83
Ethanol produced (BL)	25.62	1.99	27.61
Sugar produced (Mt)	33.57	4.61	38.18
Number of mills	349	86	435

[1] Created using data from Ref 15.

Sugarcane Sector

The sugarcane industry in Brazil is divided into two regions based on the harvesting periods: north-northeast, where the cane harvest extends from September to March, and the center-south, which harvests cane from April to November. The center-south region is the most important and was responsible for almost 90% of the cane crushed in the 2010–2011 season; in addition, their processing units are significantly larger than the ones in the north-northeast region. Table 1 shows data from the industrial units under operation in the harvest season 2010–2011. The geographic location of the mills is indicated in Figure 4.

São Paulo, in southeast Brazil, is by far the main producer of sugarcane and ethanol. In 2011, there were 185 mills under operation that crushed 361.7 million tonnes (Mt) of sugarcane (58% of the total), produced 15.5 BL of ethanol (56%) and 23.5 Mt of sugar (62%).

In early 2011, 40 new industrial projects were identified, varying from being almost ready for operation to units in the design stage. All these new mills, except one, would be installed in the center-south region, with half of them predicted to be built in the center region (CW in Figures 4 and 5). Figure 5 shows the distribution of new areas cropped with sugarcane in the center-south region from 2003 to 2012 (the accumulated new area in the period was 4.85 million ha (Mha), to be compared with 5.4 Mha cropped with sugarcane in 2003); 96% of the growth of sugarcane production between 2003 and 2011 was in the center-south region, and for this reason the tiny amount of growth in the northeast is not shown in Figure 5.

According to the production model, there are three different types of sugarcane mills existing in Brazil[18,19]:

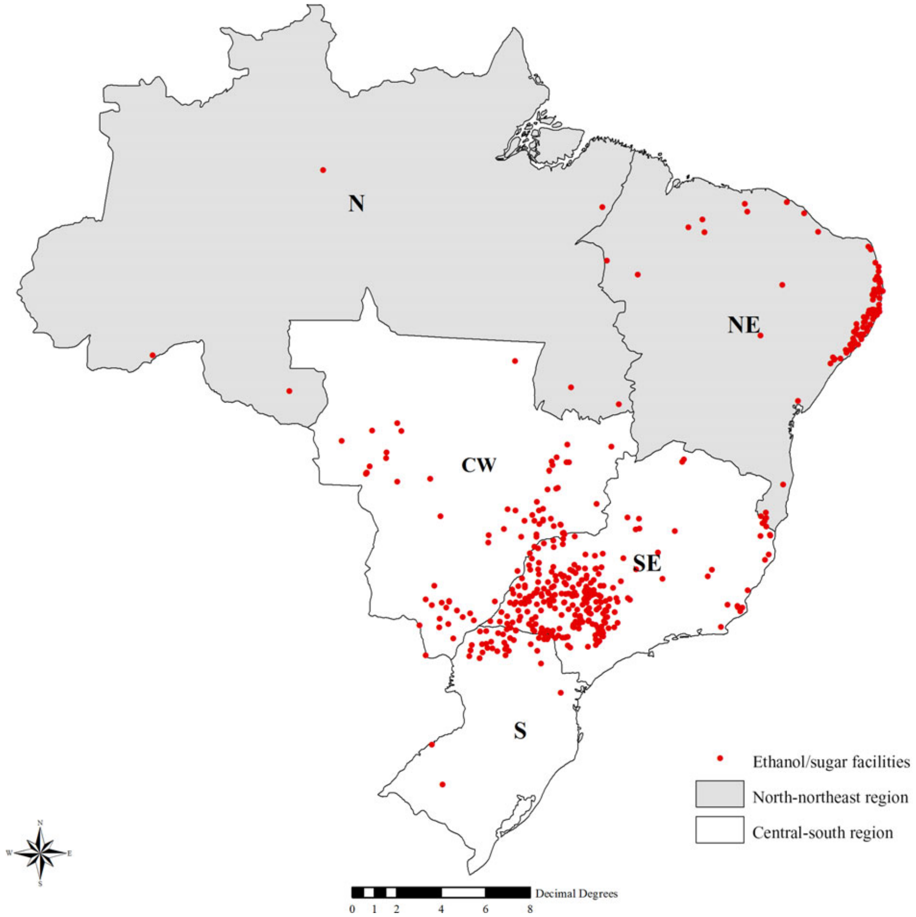

FIGURE 4 | Location of sugarcane processing units in Brazil. Created using data from Ref 16.

- A sugar mill with an annexed ethanol distillery, where both sugar and ethanol are produced in a fully integrated process. The main advantages are the flexibility in production (more sugar or ethanol depending on the market demands), the gains in economies of scale in the common systems (cane preparation, juice extraction, utilities), and the synergisms with the integrated operation of the two facilities. In 2011, there were 253 mills with annexed distilleries in Brazil.
- An autonomous distillery, which only produces ethanol. Many of the new plants (green field) being built in Brazil since 2004–2005 are of this type, and it also predominated in the second phase of the ethanol program, from 1979 to 1985. In 2011, there were 168 mills with autonomous distilleries.
- A sugar mill only produces sugar. They are less important due to the small number (14 in 2011) and to the reduced production capacity. Nevertheless, this is the model prevailing in the sugarcane mills throughout the world.

In the 2010–2011 harvest, the average output of the mills in Brazil, center-south and north-northeast were 1.4, 1.6, and 0.7 Mt of cane crushed per year, respectively; the average output of the mills in the state of São Paulo was 2 Mt year^{-1}. Of the 52 new units built in the 2006–2010 period, based on the projects analyzed by National Bank for Economic and Social Development (BNDES), the majority (62%) had a crushing capacity in the 1.5–2.9 Mt year^{-1} range; mills larger than 3 Mt year^{-1} accounted for 15% of the new projects.[20]

Electricity is rapidly becoming an important third product of the mills, and the projections are that they will tend even more to energy (i.e., ethanol and electricity); the expectation is that the proportion of electricity, ethanol, and sugar in the average gross revenues of the plants will evolve from 2%, 42%, and 56%, respectively, in the 2006–2007 season to 16%, 51%, and 32%, respectively, in the 2015–2016 season. In summary, the energy products of

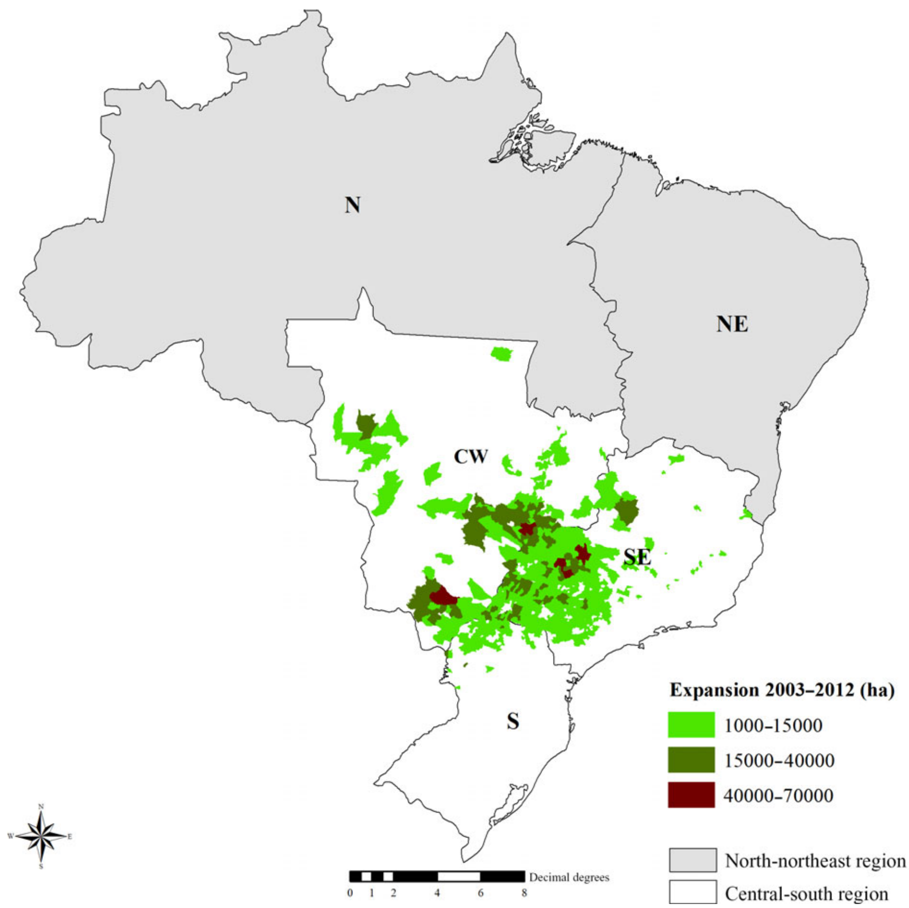

FIGURE 5 | Expansion of sugarcane in center-south Brazil from 2003–2012. Created using data from Ref 17.

sugarcane in the medium term will amount to two thirds of the average gross revenues of the sector.[21] This tendency regarding surplus electricity production is due to a better regulatory environment and the vision of the new investors in the sugarcane sector. Specific regional policies have had a small impact; rather, the costs of interconnecting to the grid have been the primary determinant for the feasibility of such projects.

Despite the difficulties since 2008, it is clear that the sugarcane sector has been reorganized, motivated by the entrance of new stakeholders, many from abroad, including several oil companies.[22] One consequence of that is the increase in the size of the groups. The share of the five largest groups in the total cane production was 5% in 2005, it increased to 27% in 2010, and is expected to reach 40% in 2015. In 2007, there were 22 plants with a total milling capacity of 36 Mt of cane (7% of the total cane) controlled by foreign investors, and this figure is expected to increase to 31 plants with a milling capacity of 83 Mt of cane (12% of total cane) by 2012.[23]

AGRICULTURAL ISSUES

Sugarcane Productivity and Breeding Programs

Over the past 35 years, the average sugarcane yield has increased approximately 68%, from 47 t ha^{-1} in 1975 to 79 t ha^{-1} in 2010; however, owing to the reasons previously mentioned, the average yield dropped to 68 t ha^{-1} in 2011.[24] Technological advances, which include development of new varieties, genetic improvement, and best management practices played an important role in the evolution of the sugarcane crop. The yield increase was approximately 0.91 t ha^{-1} $year^{-1}$.[25] Figure 6 shows the evolution of sugarcane yields and of the total harvested area from 1975 to 2011.

The development of high-quality, high-yielding cultivars was critical for the results achieved with ethanol production in Brazil. Breeding success depends on using the genetic diversity conserved in germplasm collections. A new paradigm is emerging with the integration of biotechnology and

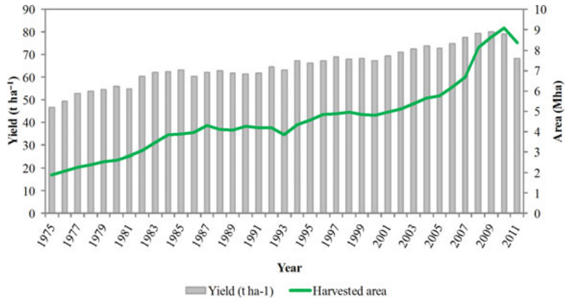

FIGURE 6 | Sugarcane yield (t ha^{-1}) and harvested area (Mha) in Brazil in the 1975–2011 period. Created using data from Ref 24.

genomic sciences for the conservation and use of genetic resources.[26]

Sugarcane varieties need to be periodically replaced as they decay after many years of cultivation. The breeding program that was established intends to adapt sugarcane cultivars for agronomic and industrial interests and to allocate those varieties to the right environment.[27] More than 550 varieties of sugarcane have been developed in the past 80 years, mostly after 1970. At present, there are four Brazilian breeding programs:

- IAC: The Campinas Agronomic Institute (publicly funded) has had a breeding program since 1930.
- CTC: The Sugarcane Technology Centre, formerly Copersucar Technology Centre, started its program in 1969. It is a private company that maintains the world's largest and most complete germplasm bank, consisting of more than 5000 clones of commercial and wild species of sugarcane.
- RIDESA: The Inter University Network of Sugarcane Sector Development, formerly Planalsucar (National Sugarcane Improvement Program), started in 1971 by a government decision. It was initially composed of seven Federal Universities; later, two more universities joined the group. It is the largest genetic improvement program in Brazil.
- CANAVIALIS: It is a private company established in 2003 that has developed a large breeding program dedicated to genetically modified crops.

In the Brazilian southeast region, irrigation in commercial sugarcane fields is generally not used, contributing to low production costs. However, new expansion areas in the central region, predominantly in drier areas with inadequate rainfall, have been used for sugarcane cropping. Therefore, drought tolerance is seen as an increasingly important trait for new sugarcane varieties.[28] Furthermore, sugarcane breeding programs also aim to develop pest and disease resistance and varieties better adapted to the increasingly common mechanical harvest.

The Brazilian sugarcane genome sequence has been in progress since 2000. At the University of São Paulo, a group of scientists linked to FAPESP's (São Paulo Research Foundation) Program for Research on Bioenergy obtained its first reads with a pyrosequencer—a cutting-edge technology used for genetic sequencing. The objective of this experiment is to identify the promoter regions and variants that control gene expression and to recognize patterns of genetic diversity to support the breeding programs of sugarcane.[29]

Regarding genetically modified (GM) sugarcane, the National Biosafety Technical Commission has approved field trials in Brazil, incorporating traits such as increased yield, drought tolerance, insect resistance, and herbicide tolerance. Although there are no sugarcane GM varieties in commercial use today, their introduction is expected to take place in the second half of this decade.[30]

Agricultural Management and Fertilizer Use

In Brazil, sugarcane crops use lower levels of fertilizers than in other countries. The Brazilian technical recommendation for nitrogen (N) application in planted cane is approximately 30 kg ha^{-1} in the furrow at planting with a supplementation of 30–60 kg ha^{-1} after 30–60 days[31], whereas for the ratoon cycle this level increases to 90–120 kg ha^{-1}.[32] For instance, the Australian N application levels for plant and ratoon are 30% and 54% higher, respectively, than in Brazil.[33] Intrinsic aspects, such as the lack of response of the plant cycle of sugarcane and the cost, are responsible for the application of less N in Brazil.[34] Moreover, overapplication of N can also decrease the sugar content of the cane and substantially increase N leaching from the root zone.[35–37] Furthermore, an important specific factor in Brazil's sugarcane crops is the recycling of nutrients by the application of two industrial residues, vinasse and filter cake. Vinasse, or stillage, a by-product of ethanol production, is now managed as a nutrient source (rather than residue), and its application has been optimized within the topographic, soil, and environmental control limits; filter cake is the remaining product of sugar and ethanol production that contains large amounts of nutrients and is filtered out of juice in the sedimentation process.[38]

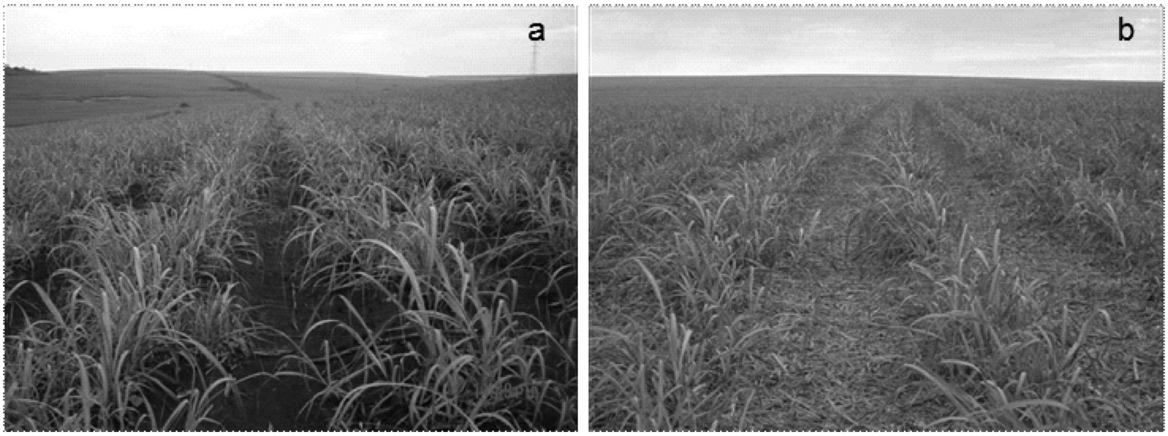

FIGURE 7 | Burnt (a) and unburnt (b) sugarcane areas with similar topography, soils, and climate conditions.

Considering the relatively large amount of N that is exported with the stalks at harvest (80–100 kg N ha^{-1}), a depletion in soil N would be expected in the long term, particularly in regions where N fertilizer application is low.[39] This depletion has not been common, however, which has motivated research on other inputs of N into the sugarcane production system, mainly through biological N fixation.[40] Using natural abundance techniques, Boddey et al.[41] concluded that 60% of the N absorbed by a crop without mineral N fertilizer application was provided by biological fixation, mainly from endophytic and soil associative diazotrophic bacteria. However, more research is needed to understand the role of biological fixation in sugarcane and the role of N cycling in soil organic matter.

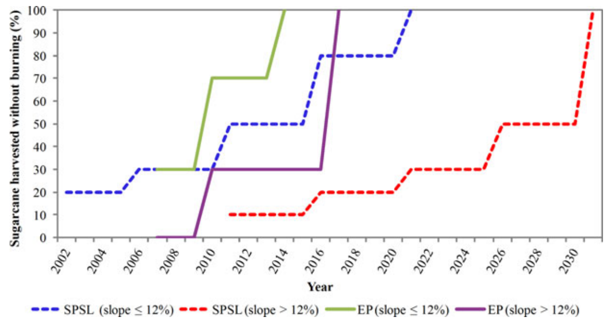

FIGURE 8 | Schedule for phasing our preharvest burning in the São Paulo state. SPSL (São Paulo State Law); EP (Environmental Protocol) in areas with slope up to 12% (currently mechanizable) and above 12% (currently nonmechanizable).

Challenges

Historically, sugarcane has been burnt prior to harvest to reduce the costs of harvesting and cane hauling, whether harvested by hand or by machine. However, in the process of burning, carbon dioxide and other GHG along with soot or ash are released. Several studies have identified a strong correlation between particle emissions from sugarcane burning and hospital admissions for asthma and other respiratory problems in children and the elderly and hypertension.[42–44]

Owing to environmental, agronomic, and economical reasons, the manual harvest of sugarcane with burning (Figure 7(a)) has been gradually replaced by mechanical harvest with maintenance of the dry leaves and tops (straw) on the field (Figure 7(b)) in a system called "green cane management." In the state of São Paulo, preharvest burning was expected to cease in all areas suitable for mechanical harvest by 2021. However, a voluntary sugarcane industry protocol, the "Environmental Protocol," has set 2014 as a target year for phasing out preharvest burning in those areas (Figure 8). Because the slope of the terrain is one of the limiting factors for harvesting sugarcane mechanically, different targets for nonmechanisable areas, that is, with slopes of 12% and higher, have been set for both the São Paulo State Law and the Environmental Protocol. The green management of sugarcane includes the deposition of large amounts of plant litter on the soil (Figure 9) after each harvest, ranging from 10 to 20 t of dry matter per hectare. This crop residue left on the soil surface can cause changes in shoot emergence and growth, soil nitrogen dynamics, soil erosion, soil water content and temperature, soil aggregate stability, and soil carbon sequestration.[45–51]

Therefore, the large areas currently being converted to mechanical harvesting in Brazil will demand significant adjustments in agronomic management, ranging from fertilizer application to cultivar

FIGURE 9 | Straw accumulated on the soil surface under unburnt sugarcane in the southeastern Brazil.

selection. With increased mechanization, one of the potential problems is soil compaction due to the increased traffic of heavy machinery on the field.[52] Compaction can affect soil gas exchanges, soil water dynamics, and ultimately root development and crop productivity. Currently, there are initiatives to decrease traffic from farm machinery.

In this context, the Brazilian Bioethanol Science and Technology Laboratory (CTBE) is implementing a low impact mechanization project, which is based on adopting the no-till farming system in the cane fields, precision agriculture, and the development of controlled traffic machinery. Some of the expected benefits of this project are lower machinery use, a reduction in the cost of the tillage operation, maintenance of straw on the surface, a reduction or elimination of terraces, reduced soil compaction, the possibility of planting during the rainy season, increased productivity, and an increased longevity of ratoons.

Straw represents approximately one third of the total primary energy of sugarcane and its characteristics, similar to those of the widely used bagasse, make it a promising fuel to supplement bagasse for surplus power generation at the mill. In addition, the development of commercially feasible lignocellulosic ethanol, also referred as second-generation ethanol, will generate a demand for sugarcane straw as feedstock. In Brazil, the rapid increase in the implementation of green cane management system will make large amounts of straw available in sugarcane growing regions. Variables such as soil characteristics, climate, local topography, and agricultural practices, as well as sugarcane varieties, will need to be taken into account to define the optimum amount of straw that can be removed from the field in a sustainable manner.

INDUSTRIAL ISSUES

Industrial Conversion Efficiency

During the first phase of the Proalcool program, the priority was increasing ethanol production without due consideration for process efficiencies.[53] However, after 1986 it was necessary to compete with gasoline under adverse conditions (low oil prices and fewer subsidies), and several less efficient mills were pushed out of the market.[54] This led to important improvements in sugar production, and in the 1990s the industry began down the path of becoming the world's primary sugar exporter.

Within the distillery, the largest area of sugar losses was (and still is) the fermentation, where the use of cane juice in the autonomous distilleries was a novelty for most plants. Improvements in juice treatment, beer centrifugation, microbiological control, yeast treatment and recycling, and the use of selected yeasts were important milestones in the improvement of fermentation.[53,55] Even though some continuous fermentation systems are in use, the prevailing system is still the Melle–Boinot fed-batch fermentation with yeast recycling. The distillation and dehydration technologies were imported as integrated systems and adapted to the Brazilian conditions of beer quality and fuel ethanol specifications.

The energy sector also experienced considerable improvement with mills evolving from purchasing electricity from the public grid and using wood to supplement bagasse in the boilers to the present situation with all mills being energy self-sufficient. In fact, on average, the electricity currently produced by sugarcane mills is twofold higher than the consumption. Steam conditions have been consistently increasing from the 10–15 bar range prior to 1975 to the current 65–140 bar range. The boiler technology employed at the mills is also progressing, with the first bubbling fluidized bed boiler due to start operation soon.[56] Table 2 summarizes the results of this technology development.

The strong modernization process of the mill power section has stood out since the late 1990s. All green field (and several brown field) units are already equipped with high-pressure cogeneration systems (e.g., 68 bar/480°C boilers with condensing extraction steam turbines) and feature better process designs to reduce energy consumption. Such configuration enables the generation of more than 60 kWh t^{-1} of cane of surplus electricity using only

TABLE 2 | Some Figures of the Technological Evolution of Brazilian Sugar Mills and Distilleries since 1975[1]

Technological Evolution	1975	2005
Milling capacity of a 6 milling units of 78″ width (tc h^{-1})	5,500	15,000
Sugar extraction efficiency (%)	93	97
Fermentation time (h)	16	8
Fermentation efficiency (%)	82	91
Distillation efficiency (%)	98	99.5
Global distillery efficiency (%)	66	86
Boiler efficiency, lower heating value (%)	66	89
Turbine generator efficiency (%)	50	75

[1] Created using data from Refs 55 and 57.

bagasse as fuel, whereas the implementation and evolution in cane straw recovery will eventually lead to much higher levels.[58,59]

Other Products from Sugarcane

Sucrose is a relatively low-cost, renewable feedstock, which has attracted growing interest as raw material in the synthesis of different chemicals.[60–62] Several other coproducts can be associated with the cane industry using different streams as feedstock, such as vinasse and bagasse. An extensive study published in Brazil in 2005 identified more than 60 technologies in several industries that use sugarcane as a raw material.[62]

In Brazil, molasses is essentially used for ethanol production in distilleries adjacent to sugar mills but it can also be used as animal feedstuff or culture media for bacteria and fungi in other fermentation processes employed in the production of chemical and pharmaceutical products, as well as for the production of baker's yeast. More recently, synthetic biology platforms have been proposed employing genetically modified yeasts, bacteria, and microalgae to produce value-added chemicals and high-energy content hydrocarbon fuels from sugars.[63–65] A pathway based on a fermentation process using genetically engineered yeast strains has been tested in pilot scale in Brazil for some years, and according to the developer production on a commercial scale is expected to start soon.[63]

In addition, in the past few years, the biofuel industry has become interested in alcohol chemistry. In 2010, Braskem inaugurated the world's largest plant producing ethylene from sugarcane ethanol and announced the construction of another unit to produce "green" propylene with a minimum production capacity of 30 kt $year^{-1}$.[66] In addition, the direct production of biodegradable polymers has also been pursued.[67] In 1995, a polyhydroxybutyrate pilot plant was installed attached to a sugarcane mill in the state of São Paulo.[68] Five years later, the plant was remodeled and restarted to operate with a production capacity of 60 t $year^{-1}$, and in 2004 a 2000 t $year^{-1}$ commercial plant was installed.[69,70]

The solid and liquid residues of the cane industry can constitute relevant coproducts, too. As mentioned, vinasse and filter cake are recycled through field application as fertilizers whereas energy applications are expected to be in place through vinasse biodigestion.[69] Bagasse boiler ashes are recycled as a fertilizer, but studies have shown an interesting use as a partial substitute for sand in concrete.[71]

From bagasse, technologies have been developed in Brazil for producing commercial products, such as natural fiber to be used in sanitation tubes and swimming pools. It is also a source of cellulose for the paper and cardboard industries and represents an inexpensive source of raw material that can be converted into several chemical feedstocks through biotechnology.[69] One of the significant applications of bagasse has been the production of protein-enriched cattle feed and enzymes.[72]

Despite the numerous alternatives, practically all the bagasse is combusted in cogeneration systems. Some bagasse surplus is sold to other industries (e.g., ceramic and orange juice industries) to serve as energy sources, though with declining trends due to the progressive adoption of more advanced cogeneration systems at the mills. Alternatively, in the future, more advanced technologies, such as thermochemical or biochemical routes, might be employed to produce chemicals and fuels or even more power from lignocellulosic material from cane.[73–75] Owing to its relatively low cost and high availability, sugarcane residues are likely to be one of the most important feedstocks for conversion as the technologies become commercially available.

Second-Generation Ethanol

Among the diversified advanced options for biomass utilization, the biochemical conversion of cane residues into ethanol may become the principal alternative to the conventional production of bagasse-based electricity in the near term. Although significant progress continues to be made to overcome the technical and economic challenges, second-generation biofuels still face major constraints on their commercial deployment.[76] However, the deployment of bagasse-based technologies in Brazil would be favored because the production process could be attached to the sugar/ethanol units already in place, requiring lower investments, infrastructure, logistics, and energy supply. Furthermore, bagasse is available at the industrial facility and thus is free of transportation costs.[77]

In spite of the relatively limited allotted resources (especially when compared to the investments made in Europe and United States), funding bodies, government, and private companies are financing research on second-generation ethanol from sugarcane biomass in Brazil with special efforts toward the integration of first- and second-generation processes and construction of pilot plants.[78] An enzymatic hydrolysis pilot plant has been operated by Petrobras since 2008, and another plant is expected to start operation at CTBE in 2012.[79] An acid hydrolysis process was also tested in the past by CTC in pilot scale, but since 2007, a new process concept has been developed and the construction of a demonstration plant is planned.

Different levels of process integration, with different impacts on the technoeconomic performance, can be conceived. Seabra et al.[80] calculated the technoeconomic performance for the biochemical conversion of sugarcane residues, considering future stand-alone conversion plants adjacent to sugarcane mills in Brazil. Assuming a complementary use of 40% of the cane straw available in the field, the authors estimate that the adjacent conversion plant would enable an additional ethanol production of 33 L t^{-1} of cane, plus an overall electricity surplus of approximately 50 kWh t^{-1} of cane (mill and conversion plant). For the conditions assumed in the study, the minimum selling price of the second-generation ethanol was evaluated at 318 US\$ m^{-3}. Simulation results indicate that the integrated first- and second-generation processes would lead to better economic results than a stand-alone plant, especially when advanced hydrolysis technologies and pentose fermentation are included.[81] For the advanced scenario, the authors project that the integrated process would produce 116 L t^{-1} of cane (considering a complementary use of 50% of the cane straw), for which an internal rate of return of 16.8% would be verified.

Challenges

Ethanol distilleries have experienced a considerable improvement, which has led to an overall sugar stoichiometric conversion efficiency of 86%.[55,57] Juice extraction and fermentation are the two process steps responsible for most of the sugar losses, but there is very little room for improvement, which could possibly lead to 89–90% overall efficiency in the future. Still, the cogeneration and fermentation sections can present better performances in terms of costs and yields.[82]

For the near term, mills are expected to expand the diversification of sugar-based products, including some production of value-added chemicals and hydrocarbon fuels. Synthetic-biology platforms will start to operate on a commercial scale soon, but further developments are still needed to improve process yields while reducing the energy requirements. These are critical aspects in the pursuit of competitive fuel costs.

Electricity exports are projected to increase progressively, with significant contributions from the sugarcane straw collection. Major technological hurdles are not expected with respect to electricity expansion, except for the implementation of a cost-effective route for cane straw collection. However, alternative bagasse uses should also be in place in the future, especially those aimed at the production of second-generation biofuels. Despite the encouraging projections, to play a significant role in the sugarcane sector, the biochemical conversion must be not only a cost-effective alternative but also competitive with the current commercial steam cogeneration systems.[59] Results from Dias et al.[74] show that second-generation ethanol may compete favorably with electricity when sugarcane straw is used and when low-cost enzyme and improved technologies become commercially available (a major challenge today). However, Seabra and Macedo[59] indicate that the profitability of a biochemical conversion plant would not be favorable in comparison to a power plant for the reference values adopted in the study. Given all the associated uncertainties, at this point it is not clear which option will prevail and a single answer will most likely not exist.

SUSTAINABILITY ASPECTS

Production Cost and Competitiveness

The increase in sugarcane ethanol production and the development of its supply chain resulted in a continuous growth of productivity in the agricultural and industrial phases, as seen in Figure 6 and Table 2, bringing, as a consequence, continuous reductions in the cost of biofuel production, as illustrated in Figure 10.

The reduction of production costs with respect to the cumulative production is known as the experience curve approach. The experience curve of Brazilian sugarcane ethanol was presented by Goldemberg et al.[84] and subsequently evaluated in more detail (considering the agricultural and

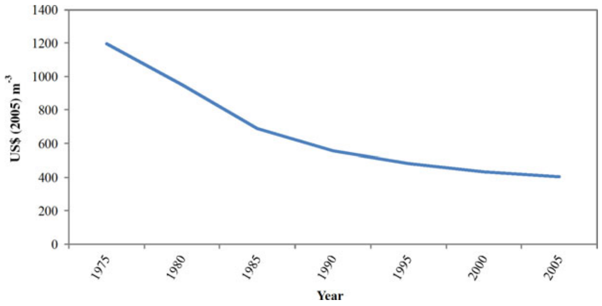

FIGURE 10 | Adjusted Brazilian ethanol production costs. Created using data from Ref 83.

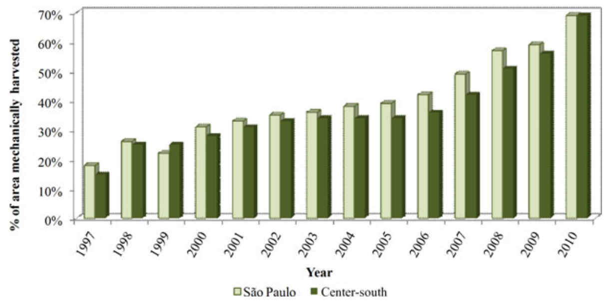

FIGURE 11 | Evolution of the mechanical harvest area in São Paulo and the center-south. Created using data from Refs 93 and 94.

industrial phases) by van den Wall Bake et al.[83] At the time of this evaluation, the break-even point of Brazilian ethanol was estimated at US$ 38 per barrel of crude oil. The authors argued that the main driving forces to reduce sugarcane production costs were the continuous increase in sugarcane yields and, in the industrial phase, the increasing scale of the mills.[83]

First-generation sugarcane ethanol has been recognized as the only cost-competitive biofuel, and worldwide Brazil has the cheapest fuel ethanol.[85] For biofuels, raw material represents the bulk of production costs and in the case of ethanol from sugarcane in Brazil the average cost of sugarcane is approximately 60–65% of the final cost of ethanol.[1] Some of the main aspects that contribute to the low cost of Brazilian sugarcane ethanol are the joint production of sugar (currently, 85% of the cane crushed is processed in annexed ethanol distilleries), bringing the benefits of common industrial processes for both products; and the use of bagasse already available at the mill (as a result of crushing sugarcane) as a primary energy source to meet the plant's full energy demand and, more recently, to generate surplus electricity. However, this trend of reducing costs was interrupted between 2008 and 2011 due to lower yields and higher costs of inputs such as fertilizers.[86] The recovery of earlier productivities and the expected cost reduction will depend on retaining investments both in the agricultural (mainly) and the industrial phases. If these goals are realized, positive results could be noticed in just a few years.

Social and Economic Impacts

Sugarcane production grew sevenfold between 1975 and 2010.[24] Even considering all the incentives and subsidies for ethanol production in Brazil—which lasted until 1999—it is estimated that production and use of sugarcane ethanol in the country avoided US$ 100 billion (in 2000 U.S. dollars) of external debt.[87] Since 1975, the sugarcane supply chain has experienced intense development, resulting in positive side effects for the capital goods industry.

The sugar and ethanol sector directly employed 1 million workers in 2009.[88] Sugarcane production in the center-south region especially in state of São Paulo (the most developed state of the country) has been characterized as using unskilled migrant workers from less developed regions of the country, primarily for manual harvesting. This aspect is very contentious, due to the tough working conditions, but the tendency of mechanized harvesting to drastically reduce job opportunities for these workers has also been presented as a negative effect. It will be difficult to allocate so many unskilled workers (it is estimated that approximately 250,000 sugarcane cutters will lose their jobs) to other economic activities.[89]

Some authors emphasize the inadequate conditions of the sugarcane cutters, including labor exploitation; however, it is important to emphasize that sugarcane workers earn the second best wages in Brazilian agriculture.[90–92] Even considering the harsh conditions faced by manual sugarcane cutters, some evolution in labor aspects—such as wages and educational level—have been occurring since 1975, which is explained mainly by the increase in mechanical harvesting during recent years, as shown in Figure 11.

The increase in mechanically harvested sugarcane has reduced the need for sugarcane cutters, requiring, at the same time, better qualified and schooled workers.[95] There has also been an increase in job formalization in sugarcane production; in 1981, for the entire country, only 37.2% of sugarcane jobs were formal, whereas in 2008 this share was 81.4%. In the state of São Paulo, in 2008, the share of formal jobs reached 94.5% and it is currently even higher.[96]

This change in the profile of agricultural workers is a clear trend in the Brazilian sugar and ethanol industry, explained by the higher cost of manual harvesting and by the environmental protocols requiring the suppression of pre-harvest sugarcane burning.[89]

Land Use, Land Use Change, and Impacts on Food Supply

The debate regarding the advantages of biofuels replacing fossil fuels in terms of reducing GHG emissions went along another dimension from the studies conducted by Searchinger et al.[97] and Fargione et al.,[98] which tried to take into account land use changes (LUC) induced by the expansion of agricultural-based biofuels, causing the so-called indirect land use change (ILUC). Since then, the discussion over environmental and socioeconomic impacts due to the rise of using biofuels have included the need to take into consideration the direct LUC for this purpose, as well as the consequences of possible induced expansion of nonbiofuel crops elsewhere.[99]

The area cropped with sugarcane in 2011 accounted for 1.1% of the total area of Brazil, or 3.3% of the total current agricultural area. Sugarcane dedicated to ethanol production corresponds to approximately half of all sugarcane harvested.[24] Studies based on satellite images covering the center-south region (close to 90% of the sugarcane production) show that between 2000 and 2010 sugarcane expansion occurred mostly over pastures (69.7%), followed by annual crops (25%), citrus (1.3%), forest (0.6%), and sugarcane land under crop rotation (3.4%).[100]

The production of ethanol from sugarcane in Brazil was included in the debate about the indirect effects of land use change (ILUC), and the hypothesis most frequently mentioned is that the expansion of sugarcane could indirectly cause deforestation in the Amazon forest. This contention is based on the fact that sugarcane has displaced pastures and annual crops such as soybean, and the first economic activity after deforestation is livestock production, followed by soy cropping after a few years. The dynamics of deforestation is very complex, and the hypothesis that the agronomic activities displaced by sugarcane are causing deforestation is clearly a simplification.[24,101,102]

Global economic models have been used to evaluate and to predict LUC in response to price changes, primarily taking into consideration different crop yields and price elasticities. Typically, general equilibrium models and partial equilibrium models are used for such purposes.[103] These models are more or less simplified and have significant differences in their theoretical frameworks and in their databases, leading to different results. As a consequence, the results

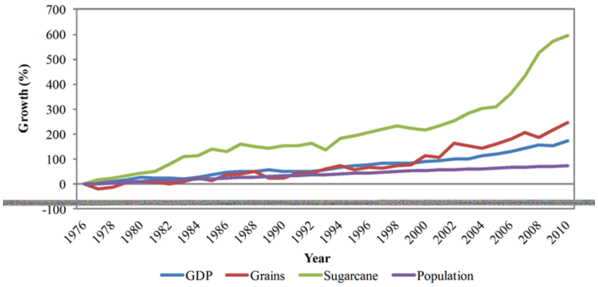

FIGURE 12 | Growth of sugarcane, grains, GDP (in real terms), and population in Brazil from 1976 to 2010. Created using data from Refs 24 and 106.

reached with different models that consider the same scenarios can be significantly different.[104]

Supported by the use of satellite images and by the development of a partial equilibrium model builtup specifically to evaluate LUC in Brazil (Brazilian land use model), Moreira et al.[105] estimated that the deforestation caused by indirect effects due to the sugarcane expansion from 2005 to 2008 (2.395 Mha) was 7.6%, that is, slightly more than 180,000 ha. This relatively small indirect impact due to the increase in sugarcane for ethanol production in Brazil can be explained by a variety of reasons, such as the expansion over pasture areas, considerable livestock intensification, the large amount of land available, and the continuous improvement of yields of different crops.

According to the Brazilian sugarcane Agroecological Zoning[102], there are 64 Mha suitable for sugarcane production, of which 34 Mha correspond to abandoned areas or degraded pastures. In this sense, it is not expected that the forecasted increase of ethanol production in the country in the coming 10–15 years, which will require no more than 4–5 Mha,[4] will cause considerable indirect effects of deforestation on native vegetation.

Over the past three decades, the increase in sugarcane production in Brazil has occurred in parallel with a large growth in food production. Figure 12 shows the growth of sugarcane production, grain production, gross domestic product (GDP) (in real terms), and population from 1976 to 2010. It can be seen that the increase in grain production is greater than the increases in GDP and population. The large amount of land available for agricultural expansion, as well as the trend in livestock intensification, indicates that sugarcane ethanol will most likely not cause negative impacts on food production in Brazil, even considering the large expansion predicted.[108] In Brazil, the cattle herd is about 200 million head, occupying 200 million hectares—a population density of just one head per hectare; a 10% improvement in livestock intensification would potentially make 20 million hectares available, more than twice the area cropped with sugarcane in 2011.[108,109] In contrast, some authors argue that the expansion of crops dedicated to biofuels may displace other crops dedicated to food production at the local level.[110] These undesirable effects should be avoided as many benefits to society can accrue if bioenergy is produced in a sustainable way.[111]

Energy Balance and GHG Emissions

The environmental advantages of sugarcane ethanol for gasoline substitution and the mitigation of GHG emissions have been known since the first comprehensive analyses of energy balance and GHG emissions in the ethanol life cycle.[112–114] Updated studies have been published subsequently following the evolution of agricultural practices in the sugarcane sector and the scientific advances relating to environmental concerns.[115,116]

In the past decade, a number of studies have estimated the energy use and GHG emissions from sugarcane ethanol in Brazil using life cycle assessment (LCA) methods.[117–121] In general, these studies indicate that ethanol leads to net energy savings and emission reductions compared to gasoline but the magnitude of the benefits varies considerably among the analyses. However, direct comparisons are difficult to make on a consistent basis. Triana[122] standardized the results of four different studies on the ethanol energy balance and found recalculated energy ratios varying from 2.63 to 8.84. In addition to the methodological differences, the database used in each study contributes to the discrepancies between the results. Significant differences exist, for instance, between the Brazilian center-south and northeast regions in terms of the technology level employed in the sugarcane sector, which can lead to very different environmental performances.[123]

In a recent study covering the current conditions of the center-south region, ethanol life cycle emissions were estimated at 21.3 g CO_2eq MJ^{-1} (Table 3), with the 90% confidence interval lying between 12 g CO_2eq MJ^{-1} and 35 g CO_2eq MJ^{-1}.[75] Despite the relatively high uncertainty, the authors emphasize that there is a clear trend for the next decade, with a significant reduction in GHG emissions.

However, nitrous oxide emissions from soils and LUC emissions are key GHG emission sources and could potentially negate the environmental benefits of substituting biofuels for fossil fuels.[97,98,124] The magnitude of the flux between soil and atmosphere depends largely on soil temperature, soil water content, oxygen availability, N substrate (nitrate and ammonium) availability, and organic carbon. In addition, these regulators are strongly influenced by weather, vegetation, soil properties (bulk density, organic matter, pH and clay content), and land management.[125]

TABLE 3 | Fossil Energy Use and GHG Emissions in the Anhydrous Ethanol Life Cycle in 2008[1]

Emissions and Credits	Fossil Energy Use (kJ MJ^{-1})	GHG Emission (g CO_2eq MJ^{-1})
Sugarcane farming	88	6.8
Straw burning		3.8
Field emissions[2]		6.7
Agricultural inputs production	40	3.8
Sugarcane transportation	19	1.4
Sugarcane processing	4	2.6
Ethanol transport and distribution[3]	22	1.8
Tailpipe emissions		0.8
Electricity[4] (credits)	−60	−3.7
Bagasse[5] (credits)	−33	−2.7
Total	80	21.3

[1] Created using data from Ref 75.
[2] Includes emissions from the soil due to fertilizers, residues, and limestone application.
[3] It was considered road transportation using heavy-duty trucks and a total transportation distance (including distribution) of approximately 340 km.
[4] 10.7 kWh t^{-1} cane displacing natural gas thermoelectricity generation.
[5] 3.3% of surplus bagasse displacing fuel oil fired boilers. It was assumed 10% bagasse losses in handling and storage.

Experiments in Australia comparing burnt and unburnt harvesting systems indicate that the maintenance of sugarcane straw on the field increases soil N_2O. These results have been recently corroborated by field experiments conducted in Brazil, but with an even more marked increase when vinasse is applied. Because the soil–atmosphere exchange of N_2O depends on complex interactions, more regional and site-specific data are needed to evaluate the impact of this source on the overall GHG balance of biofuels.[126–130]

When other land uses are converted to biofuel crops, there can be either GHG emissions or removals, considering biomass burning and decomposition and soil carbon losses and sequestration processes. For the expansion that occurred in the 2002–2008 period, direct LUC emissions have been considered a carbon sink in Brazil, which could possibly be sustained in the future as the growth scenarios for 2020, indicating a progressive use of pasture lands (many with relatively low levels of carbon stocks) in the expansion.[131]

Regarding the indirect LUC effects, previous studies for specific Brazilian conditions indicate that they may be very small.[132] The Californian Air Resources Board[133] initially estimated LUC emissions for ethanol as 46 g CO_2eq MJ^{-1} (including direct and indirect effects), which is now under revision, and significantly lower values have already been proposed. Small contributions from LUC were estimated by the U.S. Environmental Protection Agency[134], which concluded that sugarcane ethanol would be able to mitigate from 59% to 91% of gasoline emissions. As a consequence, ethanol from Brazil was classified as advanced biofuel according to the RFS2 (Renewable Fuel Standard 2).

Relevant impacts may also be expected from the soil carbon stock change due to alterations in cane cultivation management. Studies have indicated the trend for carbon sequestration under green cane management, though it is conditioned by factors such as climate, soil texture, nitrogen fertilizer management, time since the adoption of the unburnt harvest, initial carbon stocks, and the level of soil disturbance during the replanting operation.[135–144] Estimates from 12 sites indicated a mean annual C accumulation rate of 1.5 Mg ha^{-1} $year^{-1}$.[145] Soil carbon can represent a significant sink of carbon dioxide at the national scale in sugarcane production if best practices are adopted in land use and management.[146]

Despite the enormous attention that has been given to the energy balance and GHG emissions, other environmental categories can also play important roles in an ethanol–gasoline trade-off analysis. However, comprehensive LCA studies of cane ethanol are relatively sparse. In addition to global warming, the life cycle impact assessment performed by Ometto et al.[147] covered ozone formation, acidification, nutrient enrichment, ecotoxicity, and human toxicity, but comparisons with counterpart fuels were not part of the study. A direct comparison between gasoline, ethanol, and blends is presented by Luo et al.[148] focused on seven impact categories. The authors concluded that in terms of abiotic depletion, GHG emissions, ozone layer depletion, and photochemical oxidation ethanol fuels are better options than gasoline, whereas gasoline is a better fuel where human toxicity, ecotoxicity, acidification, and eutrophication are concerned.

Impacts on Water Resources

Considering the availability of water resources, Brazil's location is privileged both on the surface and in water tables. The surface fresh water (rivers and lakes) covers 50,000 km^2, whereas the main water table, the Guarani Aquifer, extends for 1.2 million km^2, 70% of which is in center-west and south of Brazil. This aquifer stores approximately 40,000 km^3 of water (which is equivalent to the world's total annual runoff).[29]

For agricultural use, water consumption may vary depending on the leaf area and root density, phenological stage, cycle (plant or ratoon cane), climatic condition, and soil water content.[149] Water deficit is one of the major factors limiting the production of sugarcane, especially in areas where there is a prolonged dry period, such as in the northeast and center-west Brazilian regions.[150]

In Brazil, sugarcane is widely grown under rainfed conditions. In the state of São Paulo, sugarcane growers consider water availability to be the major cause of interannual yield variation and yield differences among soil types. Farmers apply modern management, but irrigation is not normally used because the average annual rainfall exceeds 1300 mm. In this region, the major yield reduction is blamed on dry spells of more than 2 weeks during the hot rainy season, November–March.[151]

In some sugarcane expansion regions in the Cerrado (the Brazilian Savannah) "salvage irrigation" is normally required. In this kind of irrigation, which is normally performed after planting or harvesting time, waste water and vinasse from the ethanol industrial process is normally used.[150] In contrast, in the northeast region, supplementary irrigation with different amounts of water at the most critical development stages is required to mitigate water shortages.

In addition to yield increase, irrigation provides some other benefits, such as crop longevity; however, some environmental problems, such as fresh water resource depletion, may emerge. In some countries, including Bangladesh, India, and Pakistan, the massive expansion of private sector tube well irrigation schemes has led to the rapid depletion of groundwater.[152] In Brazil, the ratio of total water supply to water use (withdrawal of water for irrigation, industry and households) was calculated to be 1% in 1995, and this figure is projected to increase from 3% to 5% in 2075, depending on the irrigation scenario.[153] A ratio of 25% or higher is generally an indication of water stress.

The vinasse produced in ethanol production is rich in organic matter and nutrients, and if released into streams it can increase the biochemical oxygen demand and promote eutrophication of surface waters.[154] However, as already mentioned, vinasse is currently recycled back to sugarcane fields as organic fertilizer.

In the industrial phase, approximately 21 m^3 of water t^{-1} of cane are used during the conversion of cane to ethanol, of which 87% is used in four processes: cane washing, juice evaporation, fermentation cooling, and ethanol condenser cooling. Catchment water in cane processing has been reduced over the past 20 years to approximately 1 m^3 t^{-1} of cane by optimization, water reuse and recycling.[29,155]

Biodiversity Impacts

LUC is a key driver of changes in biodiversity due to its effects on habitat.[156] The magnitude of the ecological impacts of habitat loss can be exacerbated by the spatial fragmentation of remaining habitat as the surviving species are confronted with a modified environment and reduced area, increased isolation, and novel ecological boundaries.[157]

The production of biofuels can cause direct LUC and, possibly, indirect impacts. In Brazil, the impact of large-scale ethanol (and sugarcane) production on biodiversity is a relatively new issue and this feature is reflected in the limited number of detailed studies so far available. However, a common argument is that the direct impacts of sugarcane cropping on biodiversity have been limited because most plantations are in areas previously used for extensive cattle raising and annual crops. These croplands are also far away from important biomes such as the Amazon rain forest and the Pantanal.[158]

Sugarcane cropping in Brazil occurs primarily in regions where the predominant biome in the past was the Atlantic Forest and tends to expand in areas where the main biome is the Cerrado. Logging and the introduction of crops and cattle raising in the former Atlantic Forest area was disastrous, and currently less than 7% of the original area remains. Worldwide the Atlantic Forest is one of the most threatened tropical biomes with much of the standing forest in small, disturbed, and isolated patches.[159]

In most of the areas of consolidated production of sugarcane, the current forest code requires farmers to keep 20% of the agricultural land as biodiversity reserve, as well as to preserve natural vegetation to protect riparian areas. Unfortunately, law enforcement has not been effective throughout the country despite a reasonable effort (at least in some states). A good example of these efforts is described by Rodrigues et al.[160] who for many years have developed large-scale ecological restoration projects of riparian areas on private lands in the state of São Paulo. The authors describe 32 projects covering almost 530,000 ha, a reasonable proportion in large sugarcane farms. These restoration projects were developed using different methods. In the case of large sugarcane farms, the principal action was planting native tree species because of the low resilience of the target sites, reduced forest cover, and high fragmentation. The authors mention that, in general, large sugarcane farms had high portions of riparian areas occupied by highly mechanized agriculture, abandoned fields, and anthropogenic wet fields created by siltation in water courses. These projects have been developed with a close follow-up of natural vegetation restoration but without a proper study of the impacts on biodiversity and ecosystem services. It is well known that forested riparian zones may regulate energy and material transfer between terrestrial and aquatic ecosystems (e.g., providing shade and organic matter, retaining sediments, and filtering chemicals) and they are also important for maintaining habitat structure, water clarity, and food web structure.[161] In addition, well-preserved riparian zones serve as wildlife habitats and ecological corridors and help to stabilize stream banks.[162]

The impact of sugarcane cropping on fauna biodiversity has also been examined. Chiarello[163] reports a survey of mammals and birds in a forest fragment close to Ribeirão Preto, in the state of São Paulo, where there is a large concentration of sugarcane cropping. Twenty mammal species were confirmed in the area, and 49 bird species were recorded. At that time, few fragments remained and, besides being isolated from each other, they were disturbed by selective logging, hunting, and intrusion of fires. The results demonstrate that forest fragments are refuges for native fauna and the restoration of natural vegetation would be important for preserving species even in areas close to extensive sugarcane cropping. In contrast, Lyra-Jorge et al.[164] report a survey of existing species in fragments at the boarder of the Cerrado biome in the central-north portion of the state of São Paulo surrounded by eucalyptus plantations and sugarcane. The authors report that the remaining natural vegetation still shelters large mammals, including species locally threatened by extinction. However, some carnivore species expected in the region could not be detected. The authors concluded that species more vulnerable to habitat fragmentation may not have been able to adapt.

Challenges

Taking into account the international sustainability agenda of biofuels, the production of ethanol from sugarcane in Brazil has presented reasonable to good results, especially with regard to the concerns previously mentioned in this section. These results were achieved while ethanol competitiveness with gasoline was enhanced, even without subsidies. The existing disadvantages have been reduced due to factors that include strict legislation and adequate control, more consciousness and higher pressure from consumers, and concerns about corporate image.

However, a significant increase in ethanol production will require expansion of sugarcane cropping to new regions and this will bring challenges for sustainability. First, because water availability in the center-west region is less than in the southeast, local resources can be potentially impacted. Second, because the bulk of the expansion will occur in a biome (the Cerrado) with limited knowledge available and where the anthropogenic impacts have so far been minor. Third, because agricultural productivity tends to be low, at least initially, due to the availability of few varieties appropriate for the local conditions and, in general, lower soil quality and poor rain distribution. In addition, new technologies, such as intensive mechanization and new agronomic practices, including straw disposal in the soil and no-tillage practices, will be in use in the future, and their impacts are not well known.

From a socioeconomic perspective, it is necessary to investigate more thoroughly the impacts on the people directly involved in ethanol production, especially at a time that combines profound changes in the governance, intensive mechanization, introduction of new technologies and agricultural practices, and diversification of the production.

Overall, the challenge in the coming years will be reviving production and increasing it in new regions while retaining the targets of reduced costs and improved sustainability.

CONCLUSIONS

Brazil has produced fuel ethanol on a large scale for more than three decades. Despite such experience and the results of the ethanol share in the transport sector, relatively low production costs, good energy balance, and lower GHG emissions, production has been stable during the past few years and even declined in 2011. The challenge of reviving the ethanol production in Brazil is even more complex, as there are new players in the business, the expansion will mostly occur in new production areas, costs need to be reduced, and sustainability must be improved.

In the agricultural stage, the main challenge is the transition to the mechanized harvest without burning and, as a consequence, the disposal of crop litter on the soil surface and/or its use in industry. The large areas currently being converted to mechanical harvesting in Brazil will demand significant adjustments in agronomic management ranging from cultivar selection to fertilizer application. On the other hand, straw is a promising fuel to supplement bagasse for surplus power generation at the mill or even as raw material for lignocellulosic ethanol production.

There is a clear trend for product diversification in the sugarcane industry, including value-added chemicals and high-energy content hydrocarbon fuels. Electricity exports are projected to rise, possibly with significant contributions from sugarcane straw collection. Preliminary results show that second-generation ethanol may favorably compete with electricity when sugarcane straw is used and when low-cost enzyme and improved technologies become commercially available.

From the point of view of sustainability, ethanol from sugarcane in Brazil has delivered reasonable to good results despite persistent difficulties. Generally, the difficulties have been reduced steadily due to factors that vary from more pressure from consumers to stricter regulation and control. A major challenge in the coming years is that a significant increase in ethanol production will occur in new regions, and issues such as water availability, impacts on biodiversity and agricultural productivity need to be faced.

Despite the long experience and the relative success achieved, much effort will be necessary to expand the sugarcane industry in Brazil, intensifying the activities in new production areas, changing the agronomical practices and diversifying the production methods.

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