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Review

Land Use and Management Effects on Sustainable Sugarcane-Derived Bioenergy

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Abstract: Bioenergy is an important and feasible option for mitigating global warming and climate change. However, large-scale land-use change (LUC) to expand bioenergy crops, such as sugarcane, raises concerns about the potential negative environmental and socioeconomic side effects. Such effects are context-specific, and depending on the LUC scenario and management practices, several co-benefits can be attained. We reviewed the literature and discussed how LUC and best management practices affect key components of sustainability (e.g., soil health, soil carbon (C) sequestration, greenhouse gas emissions (GHG) emissions, nutrient cycling, water quality, among others) of sugarcane-derived bioenergy production in Brazil. Sugarcane expansion has occurred predominantly over pasture areas, although converting croplands could be also an environmentally feasible option. The land transition from low-productivity pastures to sugarcane cultivation seems to be a sustainable pathway to increase bioenergy production. This LUC scenario enhances soil health and soil C sequestration over time, although soil compaction, biodiversity loss, and erosion are still challenging. Besides, adopting best management practices, such as conservation tillage, sustainable crop residue management, rational fertilization, and recycling by-products, has been fundamental to ensuring sustainable bioenergy production. Public policies and well-designed legal frameworks and regulations, such as the Forest Code and the RenovaBio legislations in Brazil, are necessary to make bioenergy production compatible with rational land use and protection. Lastly, our analysis provided insights into sugarcane expansion over a small proportion (1%) of pasture areas in Latin American and Caribbean (LAC) and sub-Saharan African (SSA) countries, which may result in a substantial impact on global bioenergy supply. We concluded that sugarcane-derived bioenergy is a sustainable option to tackle climate change while provisioning other key ecosystem services and promoting socioeconomic development.

Keywords: soil carbon sequestration; soil health; ecosystem services; ethanol; bioelectricity; RenovaBio; land-use change; Brazil

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1. Introduction

Most climate change mitigation pathways that limit global warming to 1.5 °C or 2 °C rely on bioenergy production to reduce greenhouse gas (GHG) emissions and also store carbon (C) in the soil [1,2]. Among the bioenergy crops, sugarcane (*Saccharum* spp.) stands out due to its proven potential to produce high yields of food (sugar and by-products) and bioenergy (first- and second-generation ethanol, and bioelectricity). Sugarcane-derived bioethanol is a well-established renewable energy alternative to fossil fuels [3] recognized for the low C emissions in its life cycle that, if properly done, can avoid negative impacts on food security and biodiversity [4]. Global projections have indicated that annual ethanol production will expand from about 100 billion L to nearly 134.5 billion L by 2028 [5]. Two-thirds of this increase is expected to originate from Brazilian sugarcane.

Brazil is the world's largest sugarcane producer, responsible for 40% of global production [6]. Due to sugarcane, Brazil became the second largest producer of bioethanol (28 billion L) in the world [7], and stands out with the largest fleet of flex-fuel vehicles (~ 30 million) [8]. In the past decades, Brazil has been increasing not only the area under sugarcane cultivation (Figure 1A), but also the production of sugar (Figure 1A), ethanol (Figure 1A), and bioelectricity (Figure 1B). In 2019, cogeneration power plants fed with [sugarcane] bagasse and straw generated about 36.8 TWh, supplying the mills' needs of steam and power, and delivered a surplus of 22.6 TWh to the national grid (Figure 1B), which represented 5.9% of total electricity production in Brazil this year [9]. The sugarcane sector has become increasingly more efficient (Figure 1C), since the cultivated area has grown at a lower rate (+1.5 times since 1985) than the stalk production (+1.8 times), and especially at a much lower rate than the production of derived products, such as sugar, ethanol, and bioelectricity (+5.0 times), thanks not only to improved crop yield and juice quality, but also to substantial increases in industrial efficiency in the last decades. Moreover, the sugarcane area likely will keep increasing in near future, in response to growing domestic and international market demand and support provided by national public policies (e.g., RenovaBio–[10]) and international commitments to achieve the Nationally Determined Contributions (NDC) of the 2015 Paris Agreement [11]. However, it must do so in sustainable ways through both enhanced field and industrial productivity. A recent example of intensification is the growing industry's interest in producing bioenergy (second-generation ethanol and bioelectricity) by using sugarcane crop residue (named straw) [12].

Globally, the expansion of the area dedicated to the production of bioenergy is a cause of concern. The production and use of biomass for bioenergy can have co-benefits, adverse side-effects, and risks, including land degradation, water scarcity, food insecurity, GHG emissions, and impinging on sustainable development goals [2,13]. These impacts are context-specific and depend on the scale of deployment, previous land use, bioenergy crop, soil health, regional climate, and management practices [2]. For example, limiting bioenergy expansion to marginal or degraded lands, such as extensive and low-productivity pastures in Brazil, would benefit the environment [4,14] and have interesting synergies with food security with little or no negative impact on food availability, including food export [4,15]. In addition, several co-benefits can be achieved, such as enhanced soil fertility [16,17], biodiversity [18,19], and soil C sequestration [20,21], when land conversion for bioenergy production is associated with best management practices and implementation at appropriate scales [2].

Therefore, one must seek lower impact land-use change strategies for sugarcane expansion (Section 2 of this paper) and best management practices (Section 3) to ensure the sustainability of the entire production system. Based on this scenario, the main objective of this review paper was to gather consistent and up to date information on the effects of land use and management practices on the sustainability of sugarcane-derived bioenergy production in Brazil, as well as to evaluate the feasibility of sugarcane expansion in other potential regions, such as Latin American and Caribbean and sub-Saharan African countries.

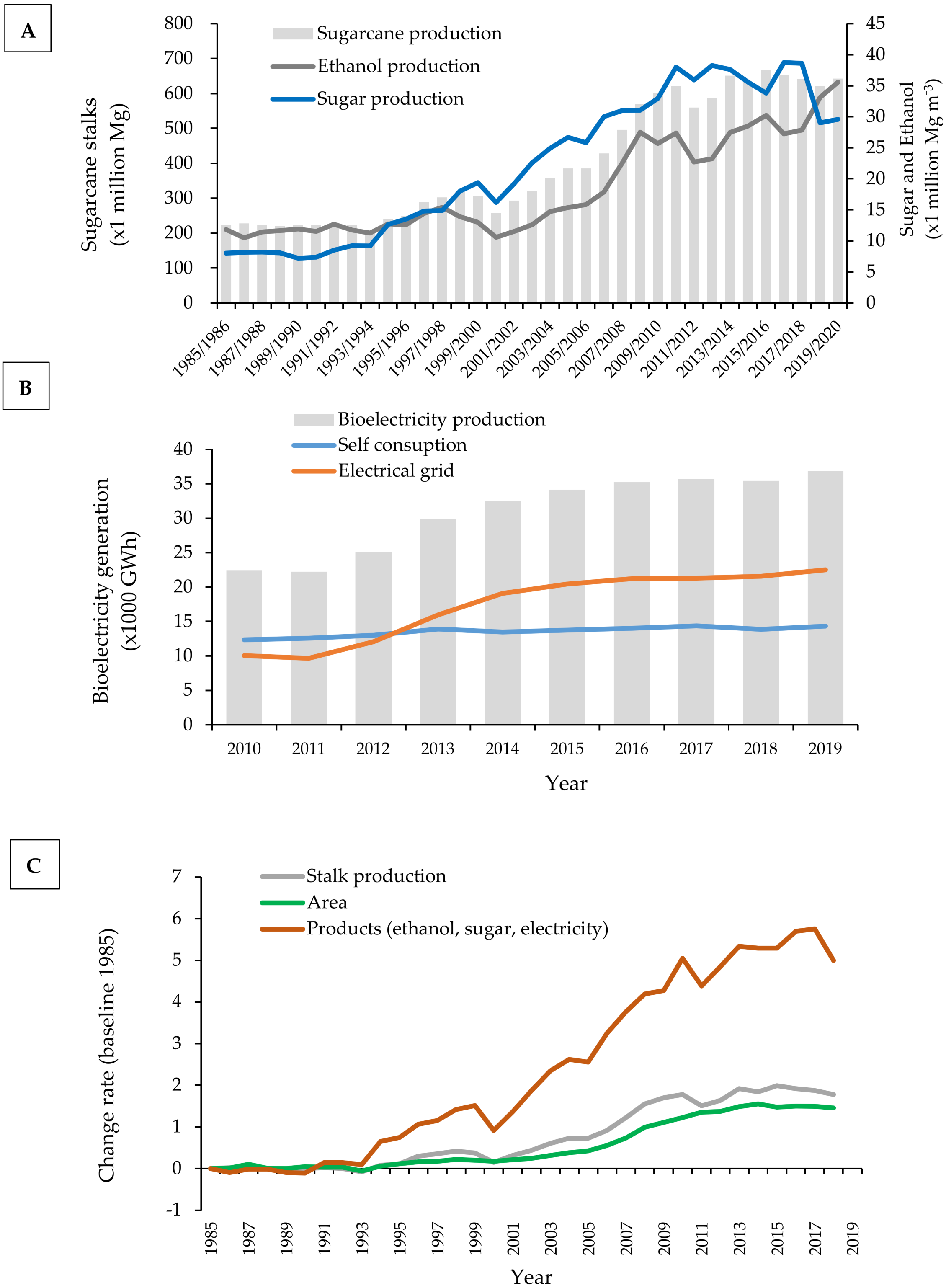

Figure 1. Sugarcane-derived bioenergy production in Brazil. (**A**) Sugarcane stalk, ethanol, and sugar production. (**B**) Bioelectricity generation. (**C**) Change rate of the area, stalk production, and sugarcane products (sugar + ethanol + bioelectricity) using 1985 as a baseline. **Source:** UNICA [22].

2. Land Use Change for Sugarcane Production in Brazil

Sugarcane cultivation in Brazil started in the early XVI century in the northeast coastal region for sugar production, establishing the first agricultural commodity produced in the country. Later, due to the more favorable climate and soil conditions [23] and socioeconomic and political issues, sugarcane cultivation expanded to the southeastern region, particularly to the São Paulo state, which became the core region of production.

Since the 1980s, the area dedicated to sugarcane in Brazil has increased by 150%, from 4 to 10 million ha (Figure 2). An important landmark that drove the sugarcane expansion in Brazil was *Proálcool*, the National Fuel Alcohol Program created in 1975 to reduce Brazilian dependency on imported oil. The expansion increased slowly (~1.0 million ha or 20%) up to the early 2000s. However, in the following 15 years (2000–2015), there was a fast growth, doubling the sugarcane area from 5 to 10 million ha. This rapid expansion was driven by several factors, such as attractive domestic and international markets for sugar and ethanol, higher industrial efficiency, and the introduction of unburned mechanical harvesting gradually replacing the old burning and manual harvest system, among others. Sugarcane expansion has occurred in the central-south region (Figure 2), predominantly over pasture areas, which contains the most extensive agricultural land use in Brazil (~170 million ha). Most of the pasture areas are cultivated with African grasses (mainly *Urochloa* genus). They are under some degree of degradation due to absence or poor management (e.g., liming, fertilization, grazing control, irrigation) and low production of biomass [24]. According to Adami et al. [25], more than 99% of direct land-use change (LUC) of sugarcane expansion (2000 to 2009) in central-south Brazil occurred on either pasture or agricultural land. More specifically, the authors observed that sugarcane expanded 69.7% on pasture land, 25.0% on annual crops, 1.3% on citrus, and 0.6% on native vegetation (mainly Cerrado), while 3.4% was sugarcane land under crop rotation during planting renovation. This advance of sugarcane over pastures was also reported by Dias et al. [26]. They observed that pasture (natural and planted) area decreased, while sugarcane expanded in the central-south region, mainly in the central and northern São Paulo state (Figure 2a′), which was responsible for approximately 65% of the total national expansion since 1985 [27]. Annual spatial distribution changes of sugarcane, pasture, and other land uses in Brazil are available in the MapBiome project [28]. In the last five years (2015–2020), the sugarcane area has remained practically unchanged, covering around 10 million ha. Currently, the central-south region accounts for 91% of the national area, predominantly in the state of São Paulo (55.3%), Goiás (9.4%), Minas Gerais (9.1%), Mato Grosso do Sul (6.8%), Paraná (6.1%), and Mato Grosso (2.8%) [27]. The last four states, which border São Paulo state, were and will continue to be the most important hotspots of sugarcane expansion in Brazil. The remaining 9% of the sugarcane area is in the northeast region, predominantly in Alagoas (2.8%), Pernambuco (2.4%), Paraíba (1.0%), and Bahia (0.7%) [27], which tends to maintain or even reduce the area dedicated to sugarcane cultivation for the next years. In terms of available land to expand sugarcane cultivation in the future, a recent study conducted by Hernandes et al. [29] updated the Sugarcane Agroecological Zoning for the central-south region of Brazil and revealed that even applying a more conservative approach by excluding environmentally relevant areas, 33.7 million ha are suitable for sugarcane expansion, of which 20 million ha are currently occupied with pastures and 13.7 million ha with annual crops.

The available data provided by Adami et al. [25] indicate that sugarcane expansion has little or no role as a driver of direct deforestation in Brazil. Total sugarcane plantation covers only 3.6% of Brazilian agricultural land (agriculture + pasture), and 15.7% of total cropland of country [28]. If only ethanol production is considered, that sugarcane area halves. Due to the vast area of low-productivity and poorly managed pasture in Brazil, it has been estimated that if the productivity of the pastures increases from the current 32–34% to 49–52% of its potential, the freed pastureland would be enough to meet the food and biofuel demands by 2040 without further conversion of native vegetation areas into agriculture [24]. The most promising strategies to promote pasture intensification in Brazil are direct recovery/replanting of the grasses and, particularly, by adopting integrated agricultural systems, such as crop–livestock, livestock–forest, and crop–livestock–forest systems, which already account for more than 15 million hectares across the country [30,31]. Finally, indirect LUC due to sugarcane expansion over pasture and then the advance of pasture over natural ecosystems elsewhere (mainly the Amazon region) is still a controversial issue. Empirical evidence suggests that expansion of agricultural production is disconnected from deforestation in developing economies, such as Brazil [32]. Nevertheless, further scientific efforts need to be undertaken to reduce the modelling uncertainties [33] and then, to simulate realistic scenarios to evaluate the potential indirect effects of sugarcane expansion in Brazil.

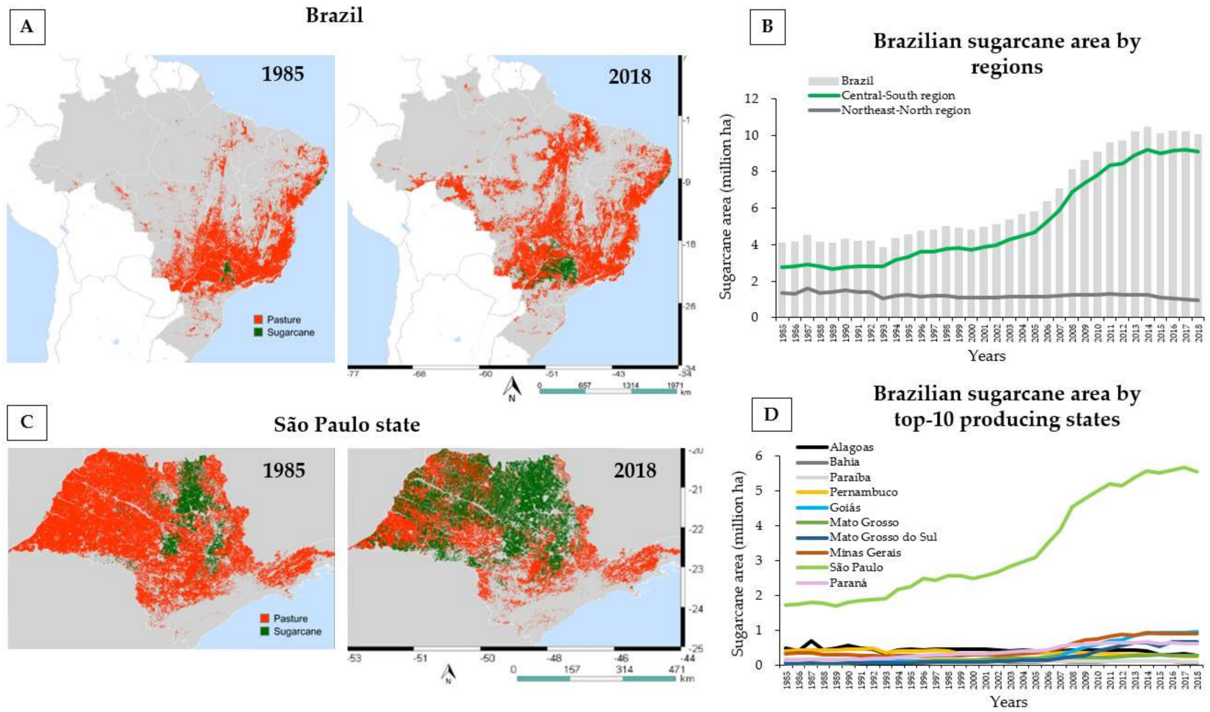

Figure 2. Spatial distribution of sugarcane and pasture areas in Brazil (**A**) and São Paulo state (**C**) in 1985 and 2018; and sugarcane production area from 1985 to 2018 in two main production regions in Brazil (**B**) and in top 10 producing states (**D**). **Source**: (**A** and **C**) MapBiomes [28] and (**B** and **D**) UNICA [22].

Despite the large area suitable for sugarcane cultivation in Brazil [29], it is fundamental to evaluate how sustainable is the large-scale LUC for sugarcane expansion and bioenergy production. Therefore, in the next subsections, we detail the LUC effects on soil C sequestration (Section 2.1), soil health, and soil-related ecosystem services (Section 2.2).

2.1. Soil C Sequestration in Land-Use Change Scenarios for Sugarcane Expansion

Soil C changes induced by LUC must be taken into account in calculating the CO_2 savings attributed to bioenergy crops [34–38]. In this literature review, we have examined the few available studies that reported (by direct field measurement or modelling) soil C responses to the most common land-use transitions into sugarcane in Brazil (e.g., [37,39–42]).

The most comprehensive study was conducted by Mello et al. [37], who investigated soil C stocks up to 1 m depth after LUC across a total of 135 sites to determine the C debt/credit and the payback time for sugarcane ethanol production. They quantified the soil C stock changes due to LUC as a net loss (C debt) or gain in soil C (C credit) for sugarcane expansion in Brazil considering three LUC scenarios. Sugarcane expansion over Cerrado vegetation and pastures reduces soil C stocks, while soil C gains occur where cropland is converted to sugarcane (Figure 3). The payback time for the soil C debt was 8 years for Cerrado and 2–3 years for pastures, but no payback was needed when sugarcane replaced annual crops. The Cerrado biome has a huge diversity of soil conditions and weather, resulting in diverse native vegetation phytophysiognomies (e.g., grasslands, shrublands, typical savannas, and woodland savannas) that differ in grass cover, percentage of canopy cover, and dominant plant species [43]. However, the most common native vegetation type in the Cerrado biome is called Cerrado *stricto-sensu*, which is characterized by a sparse tree-shrub stratum with tortuous trunks, irregular branches, and the presence of native grass. The substitution of Cerrado vegetation by sugarcane decreases soil C stocks, with losses of up to 26% (0–0.3 m). The land-use change factors (LUC-F) calculated for Cerrado to sugarcane, after 20 years, were 0.74 (±0.03), 0.80 (±0.03), and 0.93 (±0.04) for 0–0.3 m, 0–0.5 m, and 0–1 m layers, respectively, indicating C losses following Cerrado conversion.

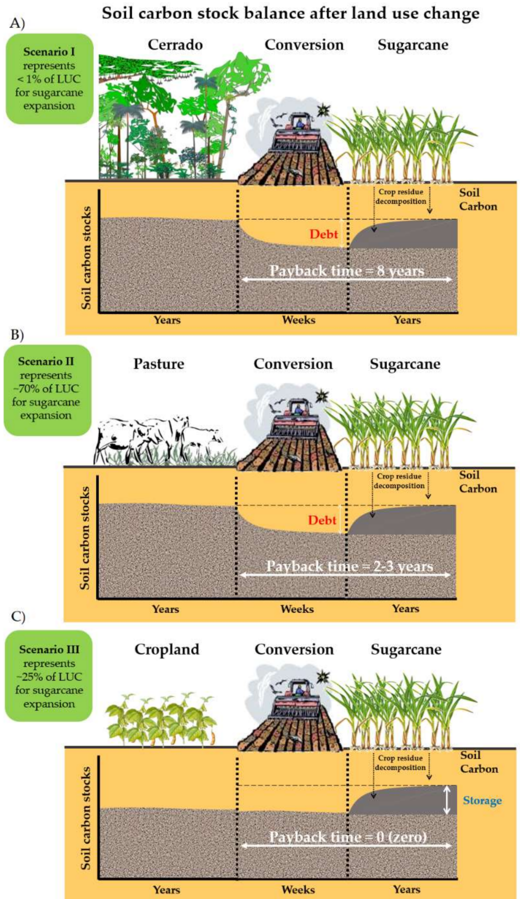

Figure 3. Soil carbon stock changes and payback time under different scenarios of land-use change for sugarcane expansion in Brazil, (**A**) Cerrado (Brazilian Savanah) to sugarcane; (**B**) pasture to sugarcane; (**C**) cropland to sugarcane. Payback by conversion to sugarcane takes into account soil C derived from sugarcane cultivation and the avoided CO_2 emission by replacing fossil fuels with ethanol. Data of payback time were based on Mello et al. [37]. The representation (%) of each land-use change (LUC) scenario for sugarcane expansion (green boxes) was based on data provided by Adami et al. [25].

Including other LUC scenarios, Bordonal et al. [40] showed that conversions from perennial crops, such as coffee and citrus, to sugarcane significantly depleted soil C stock for the 0–1 m layer in the short term (3 and 4 years), by 8.2 Mg ha^{-1} year^{-1} (LUC-F~0.80) and 8.7 Mg ha^{-1} year^{-1} (LUC-F~0.76), respectively, in the northeast region of São Paulo state, Brazil. Therefore, the authors concluded that conversion from citrus or coffee to sugarcane should be avoided [40]; even more studies are necessary since this evaluation was limited to two paired areas. In fact, only 1.3% of sugarcane expansion occurred over citrus areas from 2000–2009 in central-south Brazil [25], suggesting that sugarcane expansion was restricted to sites where farmers left the citrus activity or planted the orchard in other areas.

For the long-term soil C stock prediction using the CENTURY ecosystem model, Silva-Olaya et al. [42] reported that conversion from native vegetation to pastures (including pasture areas under different levels of productivity) resulted in a mean rate of C loss of 0.19 Mg ha^{-1} $year^{-1}$ (0–0.2 m layer). This value was lower than that found when annual crops were established after clearing native vegetation (1.14 Mg ha^{-1} $year^{-1}$). With secondary land-use conversions to sugarcane, the model predicted that conversion from pasture would result a mean soil C loss rate of 0.49 Mg ha^{-1} $year^{-1}$. On the other hand, Silva-Olaya et al. [42] observed soil C gains (average increase of 0.10 Mg ha^{-1} $year^{-1}$) when sugarcane was established on land used to produce annual crops. Conversely, using the DayCent model, Oliveira et al. [41] found that conversion from low-productivity pasture to sugarcane resulted in soil C gains of 0.16 Mg ha^{-1} $year^{-1}$ (0–0.3 m layer). The main discrepancies between these estimates of soil C changes involving pasture areas were associated with the degree of degradation of pastures, and consequently, the initial soil C stocks when land conversion occurred. In general, compared to sugarcane fields, well-managed pastures act as a sink of soil C, while degraded pastures generally are C sources to the atmosphere [44]. However, it is worth mentioning that LUC from pasture to sugarcane occurred predominantly in low-productivity pastures, in which sugarcane became a feasible option to increase soil C stocks [41], return the land to a productive system, and increase the economic gains of landowners [14].

Thus, the shift from low-productivity (and mostly degraded) pastures or croplands to high-productivity bioenergy crops may reduce the payback time of the C debt incurred from LUC or even result in a positive soil C balance or a biofuel C credit [37,38]. These soil C gains may be magnified with proper soil management (described in Section 3) and high organic matter input rates from the plant material and agroindustrial residues in sugarcane fields, allowing soils to contribute to C sequestration of biofuel-related land use and land-use change [45,46]. It is important to mention that previous studies presented in this section analyzed only the effects of LUC on soil C stocks. Therefore, they did not include information regarding other GHGs, like N_2O and CH_4. We advocate that further comprehensive studies, including field GHG measurements, modelling, and life cycle analyses, should be performed to evaluate the effects of sugarcane expansion on overall GHG emissions in different edaphoclimatic conditions. With an increasing need for biofuels and Brazil's potential to help meet global demand, GHG emission balance results are essential for guiding expansion policies of sugarcane production and land-use decisions towards greater sustainability.

2.2. Effects of LUC for Sugarcane Expansion on Soil Health and Soil-Related Ecosystem Services

Land-use change for agricultural purposes affects soil health, and consequently, its capacity to perform key functions and provide multiple ecosystem services [47,48]. However, land transition impacts are not always adverse to the soil. Depending on previous land use and management practices adopted in the "new" agricultural system, soil health can be reduced, sustained, or even enhanced. Several studies have investigated the impacts of LUC for sugarcane expansion in Brazil on multiple soil health indicators. Overall, low-productivity pastures are in a continuum of soil health decline due to poor grass and soil management and low investments [49,50]. Compared to native vegetation, long-term use with pasture (mostly that which is low productivity and/or degraded) leads to soil acidification, depletion of soil macronutrients [17], reduced soil C stocks [21,39], severe soil compaction (which reduces soil porosity, aeration, and water conductivity, and increases mechanical resistance to root growth [51,52]), and reduced soil macrofauna diversity [53,54], microbial biomass, and enzymatic activity [49]. Conversion of low-productivity pasture to sugarcane, which requires liming and fertilization, enhances soil chemical quality by reducing soil acidity and increasing macronutrient levels [17], but may have negative impacts on soil physical attributes compared to pasture soils [51,52]. Although tillage performed just before sugarcane planting reduces soil compaction, its effects tend to be short-lived, reoccurring soil compaction that increases erosion risk over time [55]. To synthesize the

LUC effects on individual soil health indicators under different climate and soil conditions, Cherubin et al. [48] integrated soil chemical, physical, and biological indicators into an overall soil health index (SHI), as shown in Figure 4. While soils under native vegetation were functioning at 87% of their potential capacity, the soil functioning decreased to 70% in pasture areas. Conversion from pasture to sugarcane slightly enhanced soil health and its functioning to 74%, due mainly to improvements in soil chemical attributes. Thus, sugarcane expansion over pastures not only prevents further overall soil degradation but also can restore specific soil functions and land productivity.

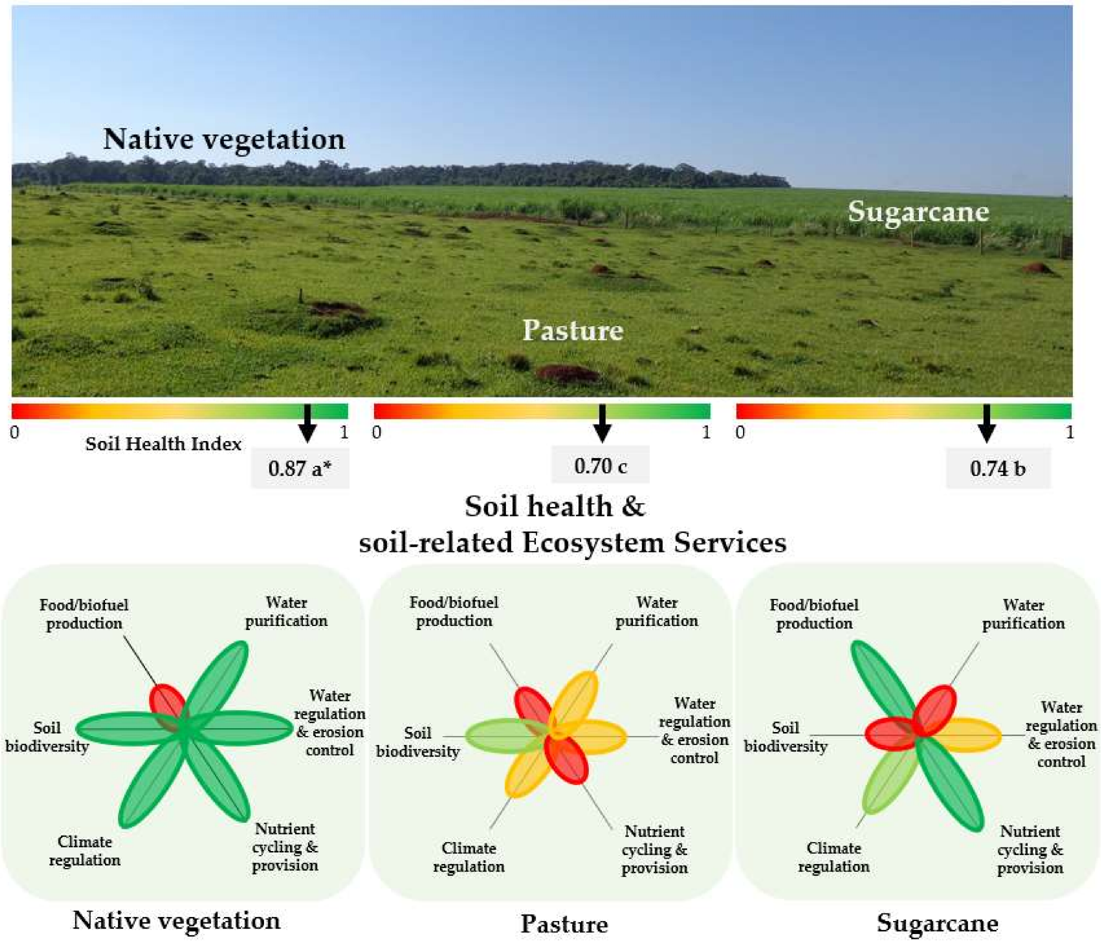

Figure 4. Soil health and soil-related ecosystem service responses to land-use change for sugarcane expansion in Brazil. * Mean soil health index scores followed by the same uppercase letter did not differ according to Tukey's test ($p < 0.05$). Soil health index scores are based on Cherubin et al. [50]. The provision of soil-related ecosystem services of each land use was ranked qualitatively, from poor (red petal), moderate (orange petal), good (light green petal), to optimum (dark green petal), based on the papers cited in the Section 2.2. The criteria used for ranking were the frequency of studies reporting positive or negative LUC effects on each soil-related ecosystem service and the statistical significance of those changes.

Changes in soil health are closely linked with changes in soil-related ecosystem services (ES) and, in a broad context, with sustainability goals and human well-being [56]. A comprehensive evaluation of LUC impacts on soil-related ES is presented in Figure 4. Native ecosystems are generally in a steady state, providing and supporting multiple ES, but obviously are limited food or energy sources. The land transition from pasture to sugarcane enhances primarily provisioning ES (e.g., food and bioenergy). However, sugarcane cultivation systems also synergically produce other ES, such as climate regulation and nutrient cycling [14]. Nevertheless, maximizing provisioning services from agroecosystems can result in trade-offs with other ecosystem services [57]. Depending on management practices, sugarcane cultivation can also be the source of numerous disservices [57,58].

Indeed, intensified sugarcane systems are highly mechanized, causing soil compaction [51], which triggers several additional disservices, such as reduced water infiltration, increased runoff and erosion risks, losses of habitat for soil biota, and crop yield decline. Sugarcane farmers adopt conventional tillage during field reforming every five years to overcome soil compaction, incorporate lime and fertilizer, and control weeds and pests, but soil disturbance causes significant soil C losses and GHG emissions [59–61]. Pesticides used during the sugarcane cycle to control weeds, pests, and diseases, and mineral fertilizers also impair soil biodiversity [53] and threaten downstream water quality [62,63]. Losses of soil biodiversity are detrimental to multiple soil functions and services [64]. Recently, Franco et al. [54] revealed that the negative effects of LUC (native vegetation–pasture–sugarcane) on populations of some macrofauna groups (known as soil engineers) weaken soil functioning and its capacity to store C. Finally, if not properly managed, sugarcane fields are more prone to degradation by soil erosion [65–67]. To understand the effects of sugarcane expansion and cultivation in a broader context of sustainability, we recommend consulting Filoso et al. [58], Bordonal et al. [4], and Oliveira et al. [14]. We also encourage future studies to evaluate soil-related ES changes quantitatively, reducing the subjectivity of qualitative approaches.

Based on this LUC scenario, the land transition from low-productivity pasture to sugarcane can sustain or even enhance the soil's capacity to provide essential soil-related ESs. In addition, compared to ranching activity, sugarcane increases land productivity, bringing socioeconomic benefits to landowners, workers, and the community [14]. Nevertheless, we also identified relevant tradeoffs associated with sugarcane cultivation, such as GHG emissions, biodiversity loss, soil erosion, and water contamination. Therefore, the adoption of best management practices is crucial to reduce or even eliminate these tradeoffs (see Section 3) and the preservation of headwater forest and riparian zones near sugarcane fields helps to mitigate negative effects on the water quality [63] and other ES [58]. Furthermore, soil-related ES tradeoffs associated with LUC for sugarcane cultivation should be evaluated in terms of their spatial and temporal scales to design sustainable management systems and offer public policy recommendations.

3. Best Management Practices towards Sustainable Sugarcane-Derived Bioenergy Production

Minimizing the negative effects of the cultivation of bioenergy crops or even bringing benefits to soils and the environment depends on the adoption of adequate management practices, including conservation tillage and crop rotation, management of crop residues and fertilization, and recycling sugarcane by-products for soil C sequestration and the promotion of a circular economy.

3.1. Conservation Tillage and Crop Rotation

In the last decades, the sugarcane production system has undergone profound changes, chiefly the gradual conversion of manual harvesting of burned sugarcane to a green mechanized harvesting system. The adoption of the green harvesting system is recognized as a win–win strategy because of its benefits involving agronomic and environmental aspects [68]. However, the heavy and intense machinery traffic, especially during mechanized harvesting and transportation operations [49,55], that occurs in this new system, leads to high levels of soil compaction, which has been recognized as central issue in sugarcane cropping systems.

Historically, soil tillage is performed before sugarcane planting to reduce soil compaction. Tillage disrupts soil aggregates and exposes the soil organic matter to microbial respiration, and consequently increases soil C losses by CO_2 emissions to the atmosphere [59–61]. However, recent studies indicate that the benefits of soil tillage are of little persistence and are no longer detected after one or two years of sugarcane cultivation [55]. Conversely, the adoption of conservation tillage (e.g., reduced tillage) in substitution to conventional tillage preserves soil physical quality in annual crops [69] because soil disturbance is confined only in the planting row and most of the soil surface remains covered with crop residues.

Several studies worldwide have indicated that the adoption of conservation tillage results in greater nutrient cycling and soil C sequestration [70–74], soil biological activity [75], soil protection against erosion [76], and crop yield gains [72,74]. However, the magnitude of these effects, particularly soil C sequestration and crop yield, depend on climate and soil conditions, as well as adoption of other best management practices (e.g., crop residue retention, cover crops, crop rotation) [73,74].

Despite the recognized benefits of conservation tillage systems, conventional tillage operations (i.e., plowing, harrowing, and subsoiling) are still predominantly used in Brazilian sugarcane fields [72]. The main challenge for adopting conservation tillage in sugarcane is to overcome the problems caused by soil compaction, subsoil acidity, and specific soil pests (e.g., *Sphenophorus levis*) and weeds (e.g., *Cynodon* spp). Under Brazilian conditions, recent studies have indicated that most soil C accumulated during the sugarcane cycle in green cane areas is lost after tillage operations in the replanting period [59,71,72,77]. For instance, Silva-Olaya et al. [59] reported that 3.5 Mg CO_2 ha^{-1} was lost after soil tillage for reforming sugarcane fields. Conversely, the adoption of conservation tillage practices resulted in a soil C accumulation rate of 0.96 Mg ha^{-1} $year^{-1}$, indicating that this practice can be a feasible strategy to increase C sequestration in sugarcane soils [71]. However, conservation tillage in sugarcane fields is a type of reduced tillage because around 13% of the soil layer (until 40 cm) is disturbed by the planting furrow made once every five years [72]. In the future, with the adoption of new technologies, such as controlled traffic systems and transplanting pre-sprouted seedlings, the soil disturbance in sugarcane planting should be considerably reduced, improving the potential for soil C accumulation and contributing to mitigate GHG emissions. Additionally, the elimination of tillage practices in sugarcane planting reduces fossil fuel consumption and indirectly mitigates GHG emissions [78].

Crop rotation is another agricultural practice to reduce GHG emissions, break the monoculture cycle, and improve soil health [79–81]. Since sugarcane is a semi perennial crop, annual crop rotation cannot be easily implemented, but, at least, different crops can be cultivated during the sugarcane replanting time every five years. Green manure legumes (e.g., sunn hemp—*Crotalaria* sp.) are preferred due to their well-known abilities to establish a symbiotic association with N-fixing bacteria. Legume cover crops enhance other components of soil health [82] and provide relevant soil-related ES, including a reduction in pest infestation, control of soil erosion, and the supply of N through biological N fixation, which reduces the N-fertilizer demand for the subsequent crop [83,84], decreasing the associated nitrous oxide (N_2O) emissions and nitrate leaching.

Sugarcane is responsive to legumes cultivated in rotation, resulting in yield gains ranging from 15% to 25% in Australia [85] and around 30% in Brazil [83]. In combination with the adoption of conservation tillage and maintenance of soil covered with crop residues during the sugarcane cycle, the use of a cover crop is an important step to improve the sustainability of the soil–plant system.

3.2. Rational Crop Residue Management

Currently, 94% of the sugarcane areas in central-southern Brazil make use of the green sugarcane system [7], in which large amounts of harvest straw residues (ranging from 10 to 20 Mg ha^{-1}) are maintained in the fields [86]. The thick layer of straw has influenced the dynamics of soil–plant–atmosphere system in several ways, including benefits such as: increasing crop yields [87–89], soil C stocks [90,91], nutrient recycling [16], regulation of soil temperature and moisture [92,93], soil structure quality [94], soil erosion control [95], soil biodiversity [96,97], and weed control [98]; however, negative effects have also been found, such as higher pest infestation [99] and GHG emissions [100,101]. However, despite the agronomic and environmental effects of maintaining straw in the field [68,102], this residue contains one-third of the energy potential of the sugarcane crop [103]. Therefore, sugarcane straw is a valuable feedstock for bioenergy production (cellulosic ethanol, electricity, and other bioproducts), enabling new opportunities for the sugarcane industry. Based on this dual purpose, several studies were performed to estimate the amounts of straw that could be removed from the field without jeopardizing soil health and sugarcane yield and maximizing economic gains [12].

The benefits of straw maintenance to soil health indicators are not proportional to the amounts of straw left over the soil. Such benefits tend to level off with 7 to 10 Mg ha^{-1} of straw [93,94,96,101,104] and no extra gains are observed at higher rates of straw. Indeed, Silva et al. [104] reported that full soil coverage is reached when at least 7 Mg ha^{-1} of straw is retained on the field. Considering the average of 14 Mg ha^{-1} of straw produced annually [86], removing part of the straw (ranging from 4 to 7 Mg ha^{-1}) should increase the availability of biomass for bioenergy production without negative impacts on soil health indicators.

Sugarcane straw is the main C input in sugarcane soils [105] and indiscriminate removal of this crop residue for industrial purposes tends to reduce soil C stocks [90,91,106]. Tenelli et al. [72] concluded that 55 and 95 kg C ha^{-1} was retained for each megagram of sugarcane straw returned to sandy and clayey soils, respectively, in the short-term basis. These findings are in line with modeling studies, which reported that long-term straw inputs on soil surface positively effect soil C stocks [41,105,107]. However, soil C increments are decreasing over time as the amount of straw left on the soil surface increases [72,105].

Straw mulching increases N_2O emissions in sugarcane soils [100,108,109], and consequently, the removal of this crop residue could be a mitigation strategy. Straw preservation recycles several nutrients in the soil [16] and acts as a physical barrier to preserve soil moisture [92], and thus, favors soil microbiota activity and N_2O emissions. Gonzaga et al. [100] synthesized the literature data on the effect of sugarcane straw removal on N_2O emissions and derived regional N_2O-N emission factors of 0.28%, 0.44%, 0.70%, and 0.56%, respectively for total, high, low, and no removal scenarios. Despite the higher N_2O emissions observed when more straw was left on soil, it is important to highlight that in all cases, the N_2O emission factors obtained under Brazilian conditions were lower than the 1%, used as a default for Tier 1 by the Intergovernmental Panel on Climate Change (IPCC) [110].

The effects of straw removal on soil indicators are clear, but the same pattern has not always been observed for sugarcane yield. A comprehensive study by Carvalho et al. [89], encompassing 28 field experiments, concluded that the effect of straw removal depends on regional climate conditions, soil texture, harvesting season, and crop age. This study showed that the higher yield losses induced by straw removal occur in regions where sugarcane undergoes longer periods of water deficit throughout the year, such as in important areas of sugarcane expansion in southern Goiás and western São Paulo. Therefore, straw removal recommendations should not be based on isolated factors but rather on holistic and integrated knowledge to ensure that enough straw is left to sustain crop yield and other multiple soil-related ES.

3.3. Fertilization Management and GHG Emissions in Sugarcane Fields

Fertilizers, especially N, have a relevant impact on the energy and GHG emissions balance of bioenergy crops because of the embedded energy in the manufacturing of the fertilizers and the GHG emissions arising from their application in the fields, mostly as N_2O [111]. Nitrogen fertilizers may account for up to 40% to 50% of the GHG emitted to produce ethanol from sugarcane [4,112] and approximately 25% of the energy spent to grow sugarcane in the field [113].

The IPCC uses an N_2O-N fertilizer emission factor of 1% as a default for Tier 1 [110], expressed as the proportion of the N fertilizers applied that is emitted as N_2O. The default value has been employed to estimate the GHG emitted for bioenergy from sugarcane in Brazil [4,110] as regional emission factors were scarce. However, recent data indicate that N_2O emissions from N fertilizers applied to sugarcane are lower than the IPCC values. Analyzing the data of 44 independent field observations conducted in Brazil with several fertilizer sources, we estimated an average N_2O-N fertilizer emission factor of 0.60. Low emission factors have been reported for other crops, being attributed to the good drainage of the deep Oxisols that predominate in most agricultural areas in Brazil [113], which does not favor anaerobic conditions that stimulate N_2O emissions via denitrification. In fact, nitrification, which prevails in well-aerated soils, seems to be the dominant pathway for N_2O formation in sugarcane soils [114].

The relatively low N_2O emissions from N fertilizer in sugarcane soil are partially reverted when the sugarcane industry by-products, such as vinasse, are recycled in the fields. Vinasse is a liquid residue of the must distillation to produce ethanol and is generated in large quantities (i.e., 10 to 13 L/L^{-1} of ethanol). It is applied in amounts that vary from 50 to 150 m^3/ha^{-1} and is a source of K and other nutrients [115]. While the N_2O emission factor of the N contained in vinasse is close to or below the IPPC default value, when vinasse is applied with N fertilizers or shortly after or before fertilization, the emission factor of N fertilizers may double [116,117]. Good management practices, such as the separation of vinasse and fertilizer application in space or time, or the use of nitrification inhibitors can reduce such emissions [116,118,119], which is desired to maintain a favorable GHG balance in the production of biofuels.

Despite the important contribution of N fertilizer to the overall GHG emissions for biofuels from sugarcane, recent studies outlined here indicate that emissions in sugarcane production are generally lower than the default values used in many life cycle analysis assessments. In addition, there are practical solutions for situations where emissions may be high. The fact that the amounts of N fertilizer applied to sugarcane in Brazil are usually 20% to 30% lower than in most important producing countries [120] also contributes to the favorable GHG balance of bioenergy from sugarcane. This is further evidence of the good environmental performance of ethanol from sugarcane produced in Brazil.

3.4. Recycling Sugarcane by-Products: Nutrient Savings and Promotion of the Circular Economy

The exported material by the sugarcane industry—mostly sugar and ethanol—is composed of C, O, and H; therefore, mineral nutrients can be recycled. Most mills in Brazil crush 2 million megagrams of sugarcane or more per year. Thus, large amounts of biomass are transported to the mills where they are processed in centralized facilities, making it easy to organize the recycling of by-products. Each megagram of sugarcane stalk generates approximately 125 kg of bagasse dry matter (i.e., the residue after the juice is removed by crushing). There are several uses for bagasse, but the most common is to produce steam and electricity to supply energy for the mill. Burning bagasse results in the production of approximately 6 kg of ashes Mg^{-1} of sugarcane [121]. Ashes, with high contents of silicate and oxides of K, Ca, Mg and other metals [122], return to the sugarcane fields usually mixed with other by-products such as filter cake.

The filter cake, or press mud, comprises small pieces of bagasse and sludge retained during vacuum filtration of sugarcane juice clarification to produce sugar. Nowadays, many ethanol distilleries also clarify the juice; therefore, filter cake can be generated from both sugar and ethanol processes [121]. The filter cake yield (70% moisture) is approximately 35 kg/Mg^{-1} sugarcane. In addition to organic matter, filter cake contains small amounts of mineral nutrients present in the sugarcane biomass and those added to help juice clarification, including phosphate, making phosphorus the nutrient in the highest concentration in this by-product (i.e., 5.7 to 9.2 kg P Mg^{-1}) [121]. Filter cake is recycled in sugarcane fields fresh or composted with other by-products of sugarcane processing, such as ash, vinasse, and, eventually, bagasse.

A typical mill produces both sugar and ethanol, in proportions that vary from 40% to 60% of each. If the sugarcane is processed for sugar, the resulting molasses are fermented to produce ethanol at a rate of 13 L Mg^{-1} of sugarcane. When the sugarcane syrup is directly fermented, the ethanol yield is approximately 85 L Mg^{-1} of stalk [115,121]. The primary use of vinasse is as fertilizer, distributed in the fields through special channels or trucks. The allowed application rates are regulated by environmental legislation to prevent excess salts in soils [123]. Whenever vinasse is used, K fertilization is unnecessary, and the rates of other nutrients are also adjusted.

The recycling of nutrients by the by-products in the sugarcane industry is part of a circular economy. It brings agronomic, environmental, and economic advantages, as sizeable amounts of nutrients return to the fields (Table 1). The organic matter and the nutrients in these by-products provide well-documented benefits for both soil fertility and crop yields [120,121] and promising effects on soil C stocks [42,124,125]. Considering the average annual fertilization of 50, 65, 120 kg ha^{-1} of N, P, and K, respectively, in plant cane and 100, 13, 100 kg ha^{-1} of N, P, and K, respectively, in the ratoon cycles [126], and that 20% of the sugarcane fields are plant cane and 80% are ratoon crops, the annual consumption of fertilizers for a 25,000 ha plantation would be 2250 Mg N, 585 Mg P, and 2600 Mg K. Therefore, the potential amounts of nutrients recycled with by-products (data of Table 1) represent 23%, 40%, and 87% of the necessary fertilization for N, P, and K, respectively. Despite that, not all nutrients will be available for the crop in the short term due to slow straw decomposition and eventual nutrient losses in the system. The need for external sources of nutrients may be further reduced with other practices such as straw preservation, which also allows for nutrient cycling and better fertilizer management [127].

Table 1. Nutrients and organic matter recycled in a mill processing 2 million Mg of sugarcane per year (approximately 25,000 ha).

By-Product (*)	Amount Recycled	Recycled Nutrients and Organic Matter (**)			
		N	P	K	Organic Matter
	Mg or m^3	Mg year^{-1}			
Filter cake	10,500	15	89	4	3150
Ash	12,000	0	36	132	0
Vinasse	1,274,000	510	111	2123	35,672
Total	-	524	235	2259	38,822

(*) Filter cake: 35 kg Mg^{-1} sugarcane stalk (70% moisture), assuming that only the sugarcane used for sugar generates filter cake; Ash: 6 kg Mg^{-1} sugarcane stalk; Vinasse (m^3): 13 L L^{-1} of ethanol produced. Ethanol yield: 85 L Mg^{-1} (ethanol from juice) and 13 L Mg^{-1} (ethanol from molasses). It was assumed that half of the sugarcane is used for ethanol and half for sugar. (**) Data of composition of filter cake, ash, and vinasse were compiled from Mutton, Rossetto, and Mutton [115]; Câmara et al. [122]; and Rossetto et al. [121].

In terms of soil C, if the 38,822 Mg of high-quality organic matter is evenly distributed in the 25,000 ha of sugarcane fields that supply feedstock to the mill (data of Table 1), the C input will be of approximately 0.9 Mg ha^{-1} year^{-1}. Soil C gains induced by vinasse and filter cake were predicted by Silva-Olaya et al. [42] using the Century model. Simulations suggested that changes from burning to green harvesting would increase soil C stocks by an average of 0.21 Mg ha^{-1} year^{-1}, but soil C gain can be higher, an average of 0.37 Mg ha^{-1} year^{-1} when vinasse and filter cake are added to the soil. Similar soil C gains were also reported in simulations performed by Brandani et al. [124] and Zani et al. [125].

However, because of economics and logistics, the application of sugarcane by-products (especially vinasse) in many sugarcane companies occurs mostly in areas closer to the mill. In this scenario, nutrients are recycled only in a portion of the cultivated area, resulting in excess nutrients in some areas and, consequently, environmental drawbacks, such as the intensification of GHG emissions and nutrient leaching. More recently, to expand the area where vinasse can be economically applied, new technologies, such as vinasse concentration and the production of liquid biofertilizer, have been adopted. In addition, the amounts of vinasse that can be added to a field are regulated to prevent nutrient overload and leaching losses [123].

More recently, the use of biochar from sugarcane residues has been considered a feasible strategy to improve the circular economy [127]. Biochar is the product of biomass pyrolysis and has been applied to the soil to improve soil health, increase soil C stocks, and reduce N_2O emissions [128–131]. Several studies worldwide have shown the benefits of biochar application on soil attributes and crop yields. However, although the high potential of biochar use, little information is available on the effects of sugarcane-based biochar on soil GHG emissions in Brazil (e.g., [132]). It is relevant to mention that biochar produced from different feedstocks may have distinct characteristics and should result in different effects on agricultural soils. More studies are needed to understand the pros and cons of using sugarcane biochar as a strategy to increase soil C stocks and mitigate N_2O emissions.

Nonetheless, the proper management of sugarcane by-products can positively impact the sustainability of bioenergy from sugarcane.

4. Public Policies for Promoting Sustainable Bioenergy Production and Land Preservation

The sustainability of bioenergy must be assured, among other things, by legal frameworks and regulations. There are two legislations in place in Brazil that go in that direction: the Forest Code [133] and the Renovabio law [10].

The Forest Code, approved in the Brazilian Congress in 2012 [133], is a very restrictive law that establishes rules for Permanent Protected Areas (high slope fields, areas around water bodies, etc.), as well as Legal Reservations in private lands. The proportion of legal reservations in private lands varies from 80% of the farm area in the Amazon biome to 35% in the Cerrado biome and 20% in the Atlantic Forest biome. This means that at least 20% and 35% of the farmland must be covered with native vegetation in Atlantic Forest and Cerrado biomes, respectively, where most sugarcane production occurs in Brazil. Although there is a deficit of legal reservations in some regions of Brazil due to the previous deforestation (before the Forest Code was established), especially in the old farming areas [134,135], farmers have an obligation to offset the legal deficits. This is progressively being done by many sugarcane mills [136], which may bring both environmental and socioeconomic returns [137].

Legislation to promote sustainable bioenergy production, the New National Biofuels Plan, or RenovaBio, was passed in 2017 and has already been implemented [10]. Renovabio is a modern legislation that is part of the strategy to achieve the commitments to the Paris Agreement on Climate Change and is in accordance with the Declaration of Vision issued at COP-23 (Bonn, Germany) in 2017. Producers that register at Renovabio will be rewarded for proven reduction of GHG emissions of their biofuels when replacing fossil fuels, through independent certification agencies, based on the cradle-to-wheel life cycle analysis. Decarbonization certificates, or CBios, are issued by financial institutions depending on the individual biofuel producer's performance in volume and efficiency. One CBio is equivalent to 1 Mg CO_{2eq} of avoided emission. Thus, the RenovaBio legislation will stimulate biofuel producers to improve practices to decrease GHG emissions and foster innovation in this sector [138].

RenovaBio is a market-driven scheme involving no subsidies. Since June 2020, CBios are negotiated at the Brazilian Stock Exchange, in amounts linked to decarbonization goals in Brazil, established by the government for a 10-year period. Such goals for 2019–2029 were published in a government resolution, which established the transport sector's annual decarbonization targets, including subtargets for fuel distributors, to be compensated with CBios [139]. Bioenergy producers must comply with some rules to benefit from RenovaBio: (a) zero deforestation (biofuels cannot come from areas that have been deforested, even legally, after December 2017, when the Renovabio law was approved); (b) be within the zoning areas allowed for the specific feedstock production; and (c) producers must abide by the Forest Code. So far, more than 200 bioenergy producers have already been admitted to Renovabio, and 33% of the CBios issued in 2020 have already been traded up to September 2020, worth approximately USD 60 million, at approximately US$10 per CBio [140], evidence that this legislation is reaching is objectives.

These are examples of how proper rules and governance can drive the bioenergy sector to improve sustainability indicators toward achieving the objective of mitigating global warming, in accordance to the Declaration of Vision issued at COP-23, and efforts supported by organizations such as the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA).

5. Sugarcane Potential for Bioenergy Production in Latin America and Africa

Since colonial times, sugarcane has been cultivated in practically all wet tropical countries of Latin America and the Caribbean (LAC) and sub-Saharan Africa (SSA), mostly to produce sugar, where it represents a relevant commercial crop. In some countries, such as Angola, Colombia, Ecuador, Guatemala, and Paraguay, sugarcane is also a feedstock for ethanol and electricity production, adopting the Brazilian combined model of associating bioenergy production to sugar mills. An increasing number of other countries are planning or already deploying sugarcane bioenergy projects, aiming to reduce gasoline imports, achieve local and global environmental benefits and stimulate local agroindustry, creating jobs and generating income [141].

The favorable conditions in LAC and SSA for promoting sugarcane bioenergy, such as appropriate climate and land availability, associated with the need for economic development and the existence of local expertise in this agroindustry, justify and reinforce this potential, which has been identified and assessed by several independent studies during recent decades (e.g., [142–151]). Modern sugarcane breeding programs and world-class mills can be found in these regions, presenting high yields and processing efficiencies. However, at the same time, there are also inefficient mills, much room for improvement, many prospects for product diversification, and the possibility of adopting sustainable bioenergy schemes.

To highlight the potential of sugarcane as a bioenergy resource in LAC and SSA regions, without harming the natural environment or affecting other agricultural production, we assumed that sugarcane is cultivated on only 1% of the current pasture land, in the FAO land use classification "Land under permanent meadows and pastures" [6]. In general, this type of land is underutilized and has low productivity. Adopting better management practices, such as fertilization, rotational grazing, and integrated livestock–forestry or crop–livestock–forestry systems, can increase these lands' productivity without impairing ranching or other activities [152]. We assumed the adoption of proper practices and the conventional technologies currently available, sugarcane with an average yield of 85 Mg ha^{-1} and ethanol produced directly from sugarcane juice with a productivity of 85 L Mg^{-1}. It was also assumed a cogeneration system in sugar mills operating at 65 bar and 480 °C and generating 110 kWh Mg^{-1} of electricity [153]. Under these conditions, a set of countries of LAC (18 countries) and SSA (20 countries) was selected, considering a minimum area of pastures (>500,000 ha) and, for African countries, the availability of a relevant area with a minimum mean rainfall >800 mm $year^{-1}$ (based on Masih et al. [154], to evaluate the land available and the amount of ethanol and electricity potentially produced using 1% of pasture areas. The results are presented in Table 2 for LAC and SSA as a whole. LAC results are also presented without the Brazilian data since sugarcane is already largely used for energy production in this country.

Table 2. Potential of bioenergy production from sugarcane in selected countries of Latin America and the Caribbean (LAC) and sub-Saharan Africa (SSA).

Region	Land under Permanent Meadows and Pastures (2018) (FAO, [6])		Sugarcane Production (2018) [A] (FAO, [6])	Sugarcane Potential Production on 1% of Pasture Land [B]		Potential Annual Bioenergy Production	
						Ethanol	Electricity
	1000 ha	% Country Area	1000 Mg	1000 Mg	% Increase (A/B)	1000 m³	MWh
SSA (20 countries) (*)	331,227	33%	43,217	281,543	651%	23,931	30,970
LAC (18 countries) (**)	499,931	28%	975,640	424,941	44%	36,120	46,744
LAC w/o Brazil (17 countries)	326,570	34%	228,812	277,584	121%	23,595	30,534

* sub-Saharan Africa countries: Angola, Cameroon, Congo, Côte d'Ivoire, Eswatini, Ethiopia, Ghana, Guinea, Kenya, Liberia, Madagascar, Malawi, Mozambique, Nigeria, Sierra Leone, South Sudan, Uganda, Tanzania, Zambia, and Zimbabwe. ** Latin America and Caribbean countries: Argentina, Bolivia, Brazil, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Guyana, Honduras, Mexico, Nicaragua, Panama, Paraguay, Uruguay, and Venezuela. Data at the country level are provided in Appendix A (Table A1).

As can be observed in Table 2, the area occupied by pastures in SSA and LAC represents about one-third of the whole national area, and excluding Brazil, both regions have approximately the same area with this type of vegetation, about 330 Mha. Thus, assuming that 1% of these areas (3.3 Mha in each case) would be cultivated with sugarcane, processed for energy under the above productivities, with an energy equivalence of one cubic meter of ethanol per 3.57 barrel of oil equivalent (boe), the bioenergy production potential as ethanol is, respectively, 80.4 Mboe year^{-1} and 79.3 Mboe year^{-1} in SSA and LAC (without Brazil). For comparison, with about 5 Mha of sugarcane fields used for bioenergy, Brazil produced 127 Mboe year^{-1} or 350 kboe day^{-1} in 2019 [7]. As an exercise, joining the potential ethanol production in SSA and LAC (including Brazil), 60 Mm^3 year^{-1}, and adopting the Renovabio's mitigation GHG factor (700 L of ethanol per megagram of avoided CO_2 emission) observed in typical Brazilian mills, the emission of 85.7 Mton of CO_2 could be mitigated annually. This is equivalent to the C stored in 110 thousand hectares of the Amazon forest (standing trees, dead wood, litter, and soil organic C at the 0–30 cm layer) [155].

This assessment of the land potential assumes a small share of pasture (1%). It does not include sustainability aspects, which require a detailed evaluation of the implementation of actual bioenergy projects.

6. Final Remarks and Future Perspectives

The production of renewable and sustainable sugarcane-derived bioenergy is a worldwide recognized option to reduce GHG emissions and mitigate climate changes. However, decisions on land use change, management practices, and use of agroindustry by-products directly impact critical aspects of the sustainability of the bioenergy production system. In the last two decades, the sucroenergy sector in Brazil doubled the area of sugarcane production, eliminated the preharvest burning in most areas, and increased the production of sugar, ethanol, and electricity. Several advances have been observed on the use of sugarcane by-products to maximize the bioenergy produced and nutrient recycling, the basis for a circular economy.

Our literature review shows that LUC from native vegetation and perennial crops (coffee and citrus) to sugarcane results in soil C losses, while conversion from cropland to sugarcane induces soil C gains. The effects of sugarcane expansion over pasture areas on soil C stocks are dependent on the productive capacity and/or degree of pasture degradation. Nevertheless, this study highlights, from a comprehensive evaluation of soil health and soil-related ecosystem services, that land use change from low-productivity (or degraded) pasture to sugarcane cultivation is a promising scenario for expanding bioenergy production in Brazil and other Latin American, the Caribbean, and sub-Saharan African countries. The expansion of sugarcane production in those countries could be an important strategy for economic development and climate change mitigation. It is important to note that sugarcane is not the only option to produce bioenergy; therefore, detailed environmental, socioeconomic, and cultural assessments are necessary to design the best bioenergy crop and management options adapted to each reality. Although sugarcane-derived products have shown good economic and environmental indicators, we advocate that the adoption of best agricultural practices (e.g., reduced tillage, crop rotation, crop residue maintenance, and fertilization management) and improvements in by-product (e.g., vinasse, filter cake, and biochar) use and management should be a priority in order to increase soil C sequestration and reduce soil GHG emissions, thus improving soil health and the sustainability of the bioenergy. In addition, new technologies of by-product use, such as the production of biomethane from vinasse biodigestion and biochar from lignocellulosic residues may represent promising opportunities to increase the efficiency and profitability of the sector and reduce GHG emissions. The implementation of recent government regulations and incentives, such as the RenovaBio program, should catalyze the adoption of best management practices and the production of cleaner bioenergy options, improving economic and environmental indicators. Finally, we encourage further comprehensive life cycle analyses and integrated sustainability assessments to check whether the policies are being implemented correctly and are efficient to guarantee that sugarcane-derived bioenergy is produced sustainably and in ways compatible with other land uses and ecosystem services.

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Appendix A

Table A1. Potential of bioenergy production from sugarcane, by country, in Latin America and the Caribbean (LAC) and sub-Saharan Africa (SSA). Gray background means average values for relative proportion of the country land and percentage of sugarcane increase, and sum values for area, and production of sugarcane, ethanol and electricity.

Country	Land under Permanent Meadows and Pastures (2018) (FAO, [6])		Sugarcane Production (2018) [A] (FAO, [6])	Sugarcane Potential Production on 1% of Pasture Land [B]		Potential Annual Bioenergy Production	
						Ethanol	Electricity
	1000 ha	% Country Area	1000 Mg	1000 Mg	% Increase (A/B)	1000 m^3	MWh
Angola	51,737	41.5%	573	43,977	7676%	3738	4837
Cameroon	2000	4.2%	1287	1700	132%	145	187
Congo	10,000	29.2%	718	8500	1183%	723	935
Côte d'Ivoire	13,200	40.9%	1948	11,220	576%	954	1234

Table A1. *Cont.*

Country	Land under Permanent Meadows and Pastures (2018) (FAO, [6])		Sugarcane Production (2018) [A] (FAO, [6])	Sugarcane Potential Production on 1% of Pasture Land [B]		Potential Annual Bioenergy Production	
						Ethanol	Electricity
	1000 ha	% Country Area	1000 Mg	1000 Mg	% Increase (A/B)	1000 m^3	MWh
Eswatini	1032	59.4%	5596	877	16%	75	96
Ethiopia	20,000	17.6%	1475	17,000	1153%	1445	1870
Ghana	7383	30.9%	152	6275	4115%	533	690
Guinea	10,700	43.5%	312	9095	2919%	773	1000
Kenya	21,300	36.7%	5262	18,105	344%	1539	1992
Liberia	1254	11.3%	275	1066	387%	91	117
Madagascar	37,295	63.5%	3143	31,701	1009%	2695	3487
Malawi	1850	15.6%	3025	1573	52%	134	173
Mozambique	35,464	44.4%	3155	30,144	956%	2562	3316
Nigeria	28,623	31.0%	1423	24,330	1710%	2068	2676
Sierra Leone	2200	30.4%	78	1870	2384%	159	206
South Sudan	25,773	40.7%	nad *	21,907		1862	2410
Uganda	5315	22.0%	3977	4518	114%	384	497
Tanzania	24,000	25.3%	3052	20,400	668%	1734	2244
Zambia	20,000	26.6%	4461	17,000	381%	1445	1870
Zimbabwe	12,100	31.0%	3305	10,285	311%	874	1131
SSA	331,227	33.0%	43,217	281,543	651%	23,931	30,970
Argentina	108,500	39.0%	19,040	92,225	484%	7839	10,145
Bolivia	33,000	30.0%	9616	28,050	292%	2384	3086
Brazil	173,361	20.4%	746,828	147,357	20%	12,525	16,209
Colombia	39,600	34.7%	36,277	33,660	93%	2861	3703
Costa Rica	1200	23.5%	4421	1020	23%	87	112
Cuba	2738	24.9%	19,648	2328	12%	198	256
Dominican Republic	1197	24.6%	5278	1017	19%	86	112
Ecuador	3094	12.1%	7502	2630	35%	224	289
El Salvador	625	29.7%	7046	531	8%	45	58
Guatemala	1811	16.6%	35,568	1539	4%	131	169
Guyana	781	3.6%	1214	664	55%	56	73
Honduras	1760	15.6%	5526	1496	27%	127	165
Mexico	80,279	40.9%	56,842	68,237	120%	5800	7506
Nicaragua	3275	25.1%	7224	2784	39%	237	306
Panama	1509	20.0%	2931	1283	44%	109	141
Paraguay	17,000	41.8%	6160	14,450	235%	1228	1590
Uruguay	12,000	68.1%	351	10,200	2910%	867	1122
Venezuela	18,200	20.0%	4167	15,470	371%	1315	1702
LAC	499,931	28%	975,640	424,941	44%	36,120	46,744
LAC w/o Brazil	326,570	34%	228812	277,584	121%	23,595	30,534

* nad: non-available data.

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