RESEARCH REVIEW

Agronomic and environmental implications of sugarcane straw removal: a major review

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Abstract

Large-scale bioenergy demand has triggered new approaches to straw management in Brazilian sugarcane fields. With the progressive shift from a burned to a nonburned harvest system, most of the straw presently retained on the soil surface has become economically viable feedstock for bioenergy production. The trade-offs between the need to preserve soil quality and produce more bioenergy have been the subject of intense discussion. This study presents a synthesis of available information on the magnitude of the main impacts of straw removal from sugarcane fields for bioenergy production and therefore represents an easily available resource to guide management decisions on the recommended amount of straw to be maintained on the field to take advantage of the agronomic, environmental, and industrial benefits. Crop residues remaining on sugarcane fields provide numerous ecosystem services including nutrient recycling, soil biodiversity, water storage, carbon accumulation, control of soil erosion, and weed infestation. Furthermore, several studies reported higher sugarcane production under straw retention on the field, while few suggest that straw may jeopardize biomass production in cold regions and under some specific soil conditions. Pest control is among the parameters favored by straw removal, while N₂O emissions are increased only if straw is associated with the application of N fertilizer and vinasse. An appropriate recommendation, which is clearly site specific, should be based on a minimum mass of straw on the field to provide those benefits. Overall, this review indicates that most of the agronomic and environmental benefits are achieved when at least 7 Mg ha⁻¹ of dry straw is maintained on the soil surface. However, modeling efforts are of paramount importance to assess the magnitude and rates of straw removal considering the several indicators involved in this complex equation, so that an accurate straw recovery rate could be provided to producers and industry toward greater sustainability.

Keywords: 2G bioethanol, bioelectricity, bioenergy, Saccharum spp., soil management, soil quality, sugarcane trash, sugarcane yield, sustainability

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Introduction

Global demand for food, energy, and water is putting pressure on the sustainability of the ‘planetary boundaries’, requiring actions for sustainable production across all sectors (Rockstrom et al., 2009). Many advocates of biofuels have vested their hopes on producing bioenergy as a ‘green’ alternative to fossil fuels, especially because of its competitiveness concerning the environmental and economic aspects (Goldemberg & Guardabassi, 2010; Buckeridge et al., 2012). Replacing fossil fuels with sugarcane-based ethanol has been reported to reduce emissions of greenhouse gas (GHG) by around 85% (Macedo et al., 2008; Cavalett et al., 2013).

Brazil is the world’s largest sugarcane (Saccharum spp.) producer, with a 691-million-ton yield achieved from a cultivated area of 9.1 million hectares in the 2016/2017 harvest season, 90% of which was concentrated within a production region in the south-central part of the country (CONAB, 2016). To meet the global demand for biofuels, the leading ethanol producers (e.g., Brazil and United States) will need to increase their production from the current 80 to approximately 200 billion liters by 2021 (Goldemberg et al., 2014). Such future demand is likely to result in a substantial increase in the area of sugarcane cultivation in Brazil,
and subsequently raise questions about the true sustainability of ethanol (Lapola et al., 2010; Tsao et al., 2011).

Recently, there has been a concerted effort to minimize the negative environmental and human health impacts associated with burned harvest systems, through the establishment of green harvest practices that now predominate as a management system. Particularly in São Paulo State, sugarcane harvest systems are also under increasing pressure to meet State Law No. 11.241/2002 (São Paulo 2002), which mandates that burned harvest be completely phased out by 2021 in areas with a terrain slope of up 12%. Additionally, a significant push for the mechanization of sugarcane harvest has been triggered by the Green Ethanol Protocol agreement, which was signed by the Environmental State Secretariat of São Paulo and the sugarcane sector in order to anticipate the phase out of burned harvest systems by 2014. Therefore, the previously employed manual harvest system with preliminary burning of residues is now performed mechanically without burning in the most cultivated sugarcane region.

Such transition over recent years has resulted in the deposition of large amounts of straw on sugarcane fields, forming a straw mulching on the soil surface (Oliveira et al., 1999; Robertson & Thorburn, 2007a,b; Fortes et al., 2012; Carvalho et al., 2013). Legal restrictions regarding preharvest burning and the consequent increase in straw deposition on the soil surface have influenced the dynamics of sugarcane production in several aspects, including yields (Aquino et al., 2015), nutrient recycling (Fortes et al., 2012), soil C stocks (Galdos et al., 2009a), GHG emissions (Carmo et al., 2013), soil erosion (Martins Filho et al., 2009), soil biology (Souza et al., 2012), pest infestation (Dinardo-Miranda & Fracasso, 2013), weed control (Hassuani et al., 2005), among others. While straw mulching may benefit the long-term soil quality and crop productivity, such residue also represents a valuable feedstock for second-generation ethanol production and bioelectricity cogeneration and enables new opportunities for the Brazilian sugarcane industry. There is, however, a current lack of data informing the recommendable amount of straw that should be removed from the fields taking into consideration all these aspects. The balanced combination of these aspects will surely help to promote a more profitable and sustainable sugarcane production chain.

The aim of this study was to synthesize the existing knowledge from current literature, with an emphasis on the agronomic and environmental implications of sugarcane straw removal for bioenergy production in Brazil. Our approach was to perform a comprehensive literature review, including all data available from international literature, as well as those published in Portuguese, which are typically inaccessible to international readers. The study includes the following sections: (i) assessment of sugarcane straw and potential for use in industry; (ii) implications of sugarcane straw removal for nutrient recycling, soil erosion losses, soil biology attributes, soil GHG emissions; and (iii) implications of straw removal for rates of pest infestation, weed control, and sugarcane development and yields. The ultimate goal of the study was to develop recommendations for an optimal amount of straw to be maintained on the field to balance agronomic and industrial benefits while improving the sustainability of sugarcane production chains in Brazil.

Assessment of sugarcane straw and potential use in industry

Sugarcane straw, also known as sugarcane trash, is a fibrous and heterogeneous residue comprising mostly of plant tops (the green plant tips) and dry leaves (older senescent leaves) (Franco et al., 2013). Several studies indicate that sugarcane fields contain an average of 8–30 Mg ha\(^{-1}\) dry mass of straw (Trivelin et al., 1995; Hassuani et al., 2005; Vitti et al., 2008; Carvalho et al., 2013), and its production varies according to crop variety, vegetative stage, edaphoclimatic conditions, and management practices (Hames et al., 2003; Santos et al., 2014). Typically, straw is composed by 54% dry leaves and 46% tops (Franco et al., 2013), and moisture content after harvest is around 30–60% (Paes & Oliveira, 2005; Michelazzo & Braunbeck, 2008). In the harvest time, in general, tops present moisture ranging from 60% to 70%, while dry leaves present moisture content of around ~10% (Franco et al., 2013).

On average, sugarcane straw presents N, P, and K nutrient concentrations ranging from 4.4 to 5.4, 0.1 to 0.7, and 2.8 to 10.8 g kg\(^{-1}\), respectively (Oliveira et al., 1999, 2002; Fortes et al., 2012; Trivelin et al., 2013; Andreotti et al., 2015). With regard to lignocellulosic composition, straw contains about 19.0–34.4% lignin, 29–44% cellulose, 27–31% hemicelluloses, in addition to 2.4–7.9% ash (Barros et al., 2013; Costa et al., 2013; Landell et al., 2013; Oliveira et al., 2013; Moutta et al., 2014; Santos et al., 2014; Szczepkowski et al., 2014). Since the widespread adoption of mechanized harvesting in sugarcane fields, straw has generally been maintained on the soil surface, which has significantly altered crop management. However, increasing demand for cleaner sources of energy required process optimization and provided an opportunity to utilize these sugarcane residues for bioenergy production. Sugarcane is a versatile crop that can be used to produce sugar, ethanol by first- and second-generation routes and surplus electricity by cogeneration. It is estimated that only one-third of the
energy potential of sugarcane is derived from its juice, which has been used efficiently in the production of sugar and first-generation ethanol. The remainder of the energy potential is associated with the sugarcane bagasse and straw, which represent approximately two-thirds of the crop energy potential (Leal et al., 2013). Traditionally, this compartment has not been used efficiently in the Brazilian sugarcane sector over the last decades.

In this context, Brazil is a world leader in renewable electricity generation. It supplies about 40% of the country’s electricity needs and 16% of this total is derived from sugarcane biomass (EPE, 2015). In this scenario, Brazil increased the focus on electricity generation from sugarcane biomass over the last few decades, driven especially by the increasing price of electricity sold to the grid, public–private initiatives and specific policies for incentivizing sales of surplus electricity (Hofsetz & Silva, 2012; Gonçalves et al., 2015). Initially, electricity was generated only to meet the self-consumption supply of the sugarcane mills, but with a modernization of cogeneration systems and the growing use of bagasse and, in some cases straw, many sugarcane mills have become net exporters of electricity (UNICA, 2016). Thus, since 2013, surplus electricity offered to the grid by the sugarcane sector has been greater than that used for self-consumption (i.e., in 2015, about 60% exported to the grid versus 40% for self-consumption; Fig. 1).

In Brazil, it is estimated that 394 sugarcane mills generate electricity from bagasse and straw (smaller proportion). Of these, only 177 exported surplus power to the grid, that is, more than half are still merely producing electricity for self-supply (ANEEL, 2015). The industrial use of straw is a key issue to address this underutilization of power generation by the Brazilian sugarcane sector. Concerning second-generation (2G) ethanol production, Goldemberg et al. (2014) have shown a huge potential to increase the biofuel production in the country. Presently, two commercial 2G ethanol production plants have begun operation in Brazil using sugarcane bagasse and straw, although not at full scale. However, the economic viability of such processes is still questionable (Zhao et al., 2008; Zheng et al., 2009; Santos et al., 2012). Other studies have shown that after this period of the learning curve, the 2G technologies will be competitive even at relatively low oil prices (Wang et al., 2014; Milanez et al., 2015).

Despite evidence that sugarcane straw is a particularly viable feedstock for bioenergy production in the sugarcane industry, the process of decision-making about its optimal utilization should be offset with the implications of straw removal on soil quality, sugarcane yield, as well as several other factors. The indiscriminate removal of sugarcane straw may reduce the benefits of sugarcane-based products. Therefore, the impacts of straw removal on soil quality and several other aspects related to sugarcane production will be addressed in the following sections.

**Impacts of straw removal on nutrient recycling**

Nutrient recycling is one of the main reasons for maintaining straw in the field. There are several studies that have approached this issue, either in relation to nutrient release from straw or in terms of decomposition dynamics (Abramo Filho et al., 1993; Oliveira et al., 1999; Gava et al., 2001; Robertson & Thorburn, 2007a; Fortes et al., 2012; Thorburn et al., 2012; Trivelin et al., 2013). In a
pioneering study from Brazil, Abramo Filho et al. (1993)
verified that only 60% of the initial volume of straw was
decomposed throughout the same crop season. Higher
annual decomposition rates, ranging from 70% to 98%,
have been reported for other studies in Brazil (Oliveira
et al., 1999, 2002; Fortes et al., 2012) and Australia
(Robertson & Thorburn, 2007a). In general, sugarcane
straw is characterized by a slow rate of decomposition,
which is related to its high concentrations of lignin and
polyphenols (Abiven et al., 2005) and high C : N ratio
which can vary from 70 : 1 to 120 : 1 (Gava et al., 2005;
Meier et al., 2006; Robertson & Thorburn, 2007a,b).

However, the recycling of nutrients contained in
straw does not occur in the same proportion to its
decomposition. In a long-term study, Fortes et al. (2012)
observed that the amounts of straw nutrients released
to the soil–plant system (in kg ha⁻¹ and in percentage
of initial content) after the three crop cycles were as
follows: N – 12.7 (31%), P – 0.7 (23%), K – 43.1 (92%),
Ca – 18.2 (54%), Mg – 8 (70%), and S – 4.6 (65%). Other
studies in Brazil, Australia, and Thailand have observed
similar trends in the proportional release of nutrients
from decomposing sugarcane straw (Oliveira et al.,
2002; Meier et al., 2006; Hemwong et al., 2009).

With respect to potassium (K), Oliveira et al. (1999)
observed that 85% of the total quantity of this nutrient
was released after a period of 1 year, which was equiv-
alent to the application of 56 kg ha⁻¹ of potassium fertil-
izer. In a similar way, Vitti et al. (2010) observed that
approximately 40–60 kg ha⁻¹ of K₂O can be reduced
from the K fertilizer applied in areas under straw
mulching. Franco et al. (2013) evaluated eight sugarcane
varieties and indicated that such reductions in K fertil-
izer usage could be even higher because, on average,
sugarcane straw accumulates around 80 kg ha⁻¹ of K
(equivalent to 96 kg ha⁻¹ K₂O). Potassium does not con-
stitute part of the structural components of the sugarcane
plant cell wall, nor does it form organic compounds
within the plant (Epstein & Bloom, 2006). Therefore,
it is easily released to the soil in an ionic form that contributes to the short-term plant nutrition.
However, according to Sordi & Manechini (2013) special
attention should be given regarding the environmental
impacts of increased levels of soil K under straw mulch-
ing in areas where vinasse is also applied for fertigation.
As K is rapidly released from straw, its accumulation
and leaching, coupled with the application of vinasse,
may cause or aggravate K saturation in the soil.

With respect to nitrogen (N), one of the most vital
nutrients demanded by the sugarcane crop, a number of
studies indicate that only a small proportion, ranging
from 3% to 30%, is mineralized over 1 year (Oliveira
et al., 2002; Basanta et al., 2003; Gava et al., 2005;
Robertson & Thorburn, 2007a; Fortes et al., 2013; Ferreira et al.,
2015). According to Ferreira et al. (2015), only 16.2% of
the N content of straw was recovered by sugarcane after
three crop years, which amounts to only a small contrib-
ution to crop nutrition (2.1% of total N requirement).
The high C : N ratio of straw results in significant N
immobilization due to the increased microbiological
activity driven by energy inputs to soil, leading to sub-
sequently slow rates of N release over the short term
(Meier et al., 2006). Such N immobilization persists until
soil organic matter (SOM) reaches a new equilibrium
(Trivelin et al., 2013). Despite the fact that N originating
from crop residue is not nutritionally important in
short-term evaluations, its contribution to the mainte-
nance of SOM can be twice as much as the N derived
from fertilizer over a long-term perspective, suggesting
that overall maintenance of straw on the field can be
beneficial to the crop in the long term (Dourado-Neto
et al., 2010). Corroborating these findings, Trivelin et al.
(2013) used a modeling approach to show that maintain-
ing all of the straw on sugarcane fields over a 30-
year period would result in a reduction in N fertilizer
inputs equivalent to 36 kg ha⁻¹ yr⁻¹. Similar modeling
results were observed in sugarcane fields in Australia
(Vallis et al., 1996; Robertson & Thorburn, 2007a).
Together, these studies suggest that the indiscriminate
removal of straw may increase N fertilizer require-
ments in a long-term perspective. Therefore, it is likely that the
removal of sugarcane straw for bioenergy production
would result in higher demand for fertilizer, which
would potentially increase biomass production costs
and environmental impacts.

Only comprehensive assessment approaches that take
into consideration the entire sugarcane chain will be
able to balance these costs and benefits and thereby sug-
gest optimal strategies for the removal of sugarcane
straw for bioenergy purposes.

Impacts of straw removal on soil conservation
The growing global demand for sugarcane-based prod-
ucts promotes an intensification of land use, which
raises concerns about soil physical quality and the nega-
tive implications to ecosystems functioning (Gasparatos
et al., 2011; Fu et al., 2015). Compared with other crops,
sugarcane production requires intensive mechanization,
which may cause physical soil degradation, increasing
soil density and soil resistance to penetration (Souza
et al., 2014; de Souza et al., 2015). These factors are asso-
ciated with lower soil porosity, lower soil aggregation,
and consequently, reduced water infiltration rates and
lower water availability for plant growth (Castro et al.,
2013; Hunke et al., 2015). Reduced soil water infiltration
increases runoff and erosion losses, which in turn result
in greater transport of sediments, nutrients, and/or
chemical products used in crop management (Gücker et al., 2009). Erosion losses are a very important issue in sugarcane fields. For instance, Hartemink (2008) observed that soil erosion losses can range from 16 to 150 Mg ha\(^{-1}\) yr\(^{-1}\) and are strongly dependent on the terrain slope, rainfall, soil type, and soil coverage.

The maintenance of crop residues that act to cover the soil dissipates the energy of raindrops as well as prevents soil disaggregation and surface sealing, thereby improving the water infiltration capacity (Brady & Weil, 2002). Peres et al. (2010) observed that sugarcane straw preservation on the field was able to reduce water losses by almost half of those observed under conditions without straw. In this context, the removal of inadvisably high rates of sugarcane straw for bioenergy production may intensify erosion losses and compromise soil quality. Figure 2 illustrates the soil erosion losses of a sandy soil in São Paulo State, southern Brazil, where sugarcane straw was previously removed for bioenergy production.

In a rainfall simulation study, Silva et al. (2012) observed that in sugarcane plots where the full soil coverage was maintained, the interrill erosion was reduced by 92% compared with a control situation where all the straw was removed. Using the same approach, Sousa et al. (2012) pointed out that maintaining straw covers of 7 Mg ha\(^{-1}\) could potentially reduce soil losses by an average of 85% (Fig. 3). According to this study, higher interrill soil losses were also evident in areas with higher terrain slope up until a point where straw coverage reached 7 Mg ha\(^{-1}\). Maintaining levels of straw higher than this, however, did not lead to any significant difference in soil losses across different slopes (ns results in Fig. 3). Additionally, Martins Filho et al. (2009) found that erosion losses may decrease exponentially with increasing soil cover, especially in treatments with straw coverage equal or above 7 Mg ha\(^{-1}\). However, it is important to highlight that these studies were performed using rainfall simulation approach and present a qualitative analysis and further research evaluating the total soil losses in Brazilian sugarcane fields under real conditions of rainfall is needed.

The loss of soil nutrients can occur through leaching, runoff, and sediment transport, all of which can be directly influenced by sugarcane straw cover (Silva et al., 2012). Garbiate et al. (2011) suggested that straw-covered soils result in lower rates of nutrient loss when compared to areas without straw. Martins Filho et al. (2009) analyzed the nutrient losses through erosion of an Alfisol covered with sugarcane straw and observed that P and K were the elements with highest losses. These authors observed that losses of K were exponentially reduced with increasing soil cover, but this was less pronounced proportionally than the rates of soil loss per se. Currently in Brazil, special attention should be given to sugarcane areas under vinasse fertigation, where large amount of K is applied and this may represent a high risk of K losses through erosion or runoff because of the highly mobile characteristics of this nutrient in the soil.

**Impacts of straw removal on soil biological attributes**

Soil biological attributes are sensitive to changes in management and may serve as indicators of soil quality (Souza et al., 2012). The degree of sugarcane straw coverage can influence the abundance and diversity of macrofauna (Cerri et al., 2004), as well as soil microbial biomass (Souza et al., 2012). Soil fauna typically benefit from greater soil cover which can enhance biodiversity and facilitate the activity of organisms considered as

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**Fig. 2** Example of soil erosion losses in a sandy soil in São Paulo State, southern Brazil, where sugarcane straw was removed for bioenergy production. (a) Represent the initial topsoil losses influenced by reduced soil coverage when straw is removed; (b) represent the loss of topsoil caused by interrill erosion.
soil engineers (Aquino et al., 2008; Portilho et al., 2011). Many of the soil invertebrates are responsible for breaking down and incorporating organic material in the soil layer, which are key mediators of ecosystem processes such as soil structure, porosity, and aggregation (Lavelle et al., 2006), and may positively affect the microbiological soil properties. Soil microbiota is responsible for the further decomposition and cycling of straw nutrients making it available to plants. Because of their sensitivity to environmental stress, evaluating soil microbiota can provide information about changes to agricultural management practices as better indicator of soil quality in comparison with current soil chemical and physical parameters (Hungria et al., 2009; Kaschuk et al., 2010).

The cultivation of sugarcane in areas previously occupied by pastures reduced by 39% the diversity of soil macrofauna (Franco et al., 2016). However, the magnitude of such changes to soil biota is highly reliant of the management practices or types of crops. A number of studies have indicated an increase in the abundance of macrofauna in areas covered with sugarcane straw, and conclude that these animals prefer an environment characterized by low amplitude changes to temperature and soil moisture, as well as food abundance (Portilho et al., 2011; Pasqualin et al., 2012). Abrão (2012) found that soil macrofauna were strongly influenced by the amount of straw present, demonstrating greater density, richness, and diversity when soil was covered by more than 50% straw (i.e., 7.6 Mg ha⁻¹). Similar results were reported by Abreu et al. (2014), who observed a greater density of individuals when more than 50% of straw (equivalent to 5.1 Mg ha⁻¹ of dry basis) was maintained on the soil surface. The increased diversity of soil macrofauna may be attributed to high levels of nutrients in soil under sugarcane cultivation (Franco et al., 2016). Many groups of soil macrofauna are therefore recognized as key mediators of nutrients cycling that can improve soil fertility. This topic is appropriate for further research.

Souza et al. (2012) showed that the C and N microbial biomass of areas covered with sugarcane straw were 102% and 34% higher than those with no straw coverage, respectively. In agreement with these findings, Paredes Junior et al. (2015) observed similar or higher microbial activity in areas where straw was maintained on the soil. These results indicate that straw mulching creates an improved environment for soil biological communities and serves as food for microbial and soil invertebrate communities.

Recently, there have been efforts to characterize the microbial groups responsible for the soil activities under various management practices in sugarcane cropping areas (Navarrete et al., 2015a; Pitombo et al., 2016; Rachid et al., 2016). Rachid et al. (2016) observed that straw removal modified the fungal communities present in soil, but did not affect bacterial communities. However, other studies have shown that microbial communities can be shaped by straw management as well as through the addition of organic or mineral fertilizers (Rachid et al., 2013; Navarrete et al., 2015b; Pitombo et al., 2016). All these studies have shown that individuals within the phylum Verrucomicrobia often benefit and become more abundant in areas that lack a straw covering. Members of this phylum have been described as highly selective for areas of low soil fertility and poor soil quality (Navarrete et al., 2015b). It is therefore likely that this taxonomic group might be effectively used to monitor the biological depletion of soil quality in sugarcane fields. Overall, synthesizing the information presented in literature suggests that maintaining a reasonable amount of straw on the field is likely to improve the biological quality of soil, and consequently, the sustainability of sugarcane-based products.

Impacts of straw removal on soil greenhouse gas emissions

A wide range of studies have shown that the removal of crop residues for biofuel production worldwide may result in the depletion of soil organic carbon and increase greenhouse gas (GHG) emissions to the atmosphere (Sheehan et al., 2003; Blanco-Canqui, 2012; Liska et al., 2014; De Figueiredo et al., 2015). Several factors can affect GHG exchanges between the soil and atmosphere, including land use, weather conditions, N fertilizer use, and soil mulching (Aulakh et al., 2001; Schaufler et al., 2010). Soil CO₂ emissions are directly related to biological process, including root respiration and decomposition of SOM through microbial activity, which are influenced mostly by temperature, soil
moisture, and oxygenation (Epron et al., 2006; Concilio et al., 2009; Ryu et al., 2009). The volume and distribution of straw on the soil surface can influence soil temperature, with reported reductions of up to 5 °C when straw covers are present (Abramo Filho et al., 1993). Similarly, the rate of soil water evaporation can be reduced by 25% in areas that have 75% straw coverage (Tominaga et al., 2002).

In Brazil, short-term studies have demonstrated that the removal of sugarcane straw increases soil CO2 emissions (Corradi et al., 2013; Teixeira et al., 2013; De Figueiredo et al., 2015). Such emissions respond to exponential increases in soil temperature (Davidson et al., 2000), which in turn have a remarkable effect on the microbial activity that induces the decomposition of SOM and roots (Silva-Olaya et al., 2013). The presence of residues on the soil may also contribute to decreased O2 concentration in the soil, resulting in lower CO2 emissions (De Figueiredo et al., 2015). Corradi et al. (2013) evaluated the effect of straw removal on soil CO2 emissions. This study observed emissions of 4.1, 3.8, and 5.5 Mg CO2 ha⁻¹ for areas with 0%, 50%, and 100% straw removal, respectively. Similarly, Moitinho et al. (2013) and De Figueiredo et al. (2015) reported that total removal of straw resulted in additional emissions of 33–37 kg CO2 ha⁻¹ day⁻¹, respectively.

Conversely, CO2 emissions induced by tillage can be higher in the presence of straw (De Figueiredo et al., 2015). Teixeira et al. (2013) observed that the association between straw mulching and tillage operations increased CO2 emissions by 36% when compared to similar tillage practices without straw mulching. Soil tillage practices increase the surface contact between soil and straw (also decrease the size of particles). This, combined with higher aeration and temperature, increases microbial activity (La Scala et al., 2006; Silva-Olaya et al., 2013; Teixeira et al., 2013).

Numerous studies worldwide have found that retaining sugarcane straw as a mulch can increase soil C stocks (Blair, 2000; Graham et al., 2002; Canellas et al., 2003; Galdos et al., 2009a; Thorburn et al., 2012). In this sense, Cerri et al. (2011) compiled data from the literature and obtained an average C accumulation rate of 1.50 Mg C ha⁻¹ yr⁻¹ (ranging from -0.12 to 2.38 Mg C ha⁻¹ yr⁻¹), when areas under burned cane were converted to green cane in São Paulo State. Corroborating these findings, Galdos et al. (2009b) using the CENTURY ecosystem model observed that soil C stocks were higher in the long term at all sites when sugarcane straw was maintained on the soil. In a 100-year simulation, the authors obtained a rate of soil C accumulation ranging from 0.023 to 0.228 Mg ha⁻¹ yr⁻¹ in the unburned scenario. According to the authors, these huge differences in C accumulation rates are associated with soil attributes, time of green cane adoption, tillage practices, and initial soil C content under a baseline scenario.

It is important to highlight that all cited studies evaluated only the presence or absence of straw (in most of the cases associated with fire) and did not include the impacts of partial removal of straw on soil C stocks. For example, Robertson & Thorburn (2007b) evaluated the effects of maintaining straw on the surface of soils under Australian conditions and concluded that 13% of the C input was retained in the SOM pools, which indicates that removing straw for bioenergy production might potentially reduce soil C accumulation rates. However, no empirical information for Brazilian conditions was obtained in literature, highlighting the need for more research to confirm this hypothesis.

Regarding nitrous oxide (N2O), besides several studies examining the N2O emissions as a function of straw management in several crops (Baggs et al., 2000; Muhammad et al., 2011; Wang et al., 2016), the effect of sugarcane straw on N2O emissions remains uncertain due to the small number of studies and the high discrepancies among them (Carmo et al., 2013; Vargas et al., 2013; Siqueira Neto et al., 2015; Pitombo et al., 2016). Through a meta-analysis, Shan & Yan (2013) reported that the maintenance of several crop residues had no significant effects on N2O emissions. Similar results were observed by Siqueira Neto et al. (2015) within sugarcane areas of Brazil, indicating that straw coverage by itself did not increase N2O emissions. The interactions between soil moisture, straw coverage, and availability of C and N are complex and make it difficult to establish predictable relationships between these parameters and GHG emissions under field conditions (Malhi & Lemke, 2007; Vargas et al., 2013). Assessing the influence of diverse crop residues containing a range of C : N ratios (including those of sugarcane straw) on the rates of N2O emissions, Huang et al. (2004) concluded that increasing C : N ratios resulted in decreased N2O emissions. Shan & Yan (2013) also pointed to higher N2O emissions when depositing straw with a low C : N ratio on the soil surface. Thus, it may be inferred that sugarcane straw, which has a high C : N ratio (i.e., range 70-130) and a large fraction of lignin and polyphenols, would result in a slower rate of decomposition, and subsequently, lower N availability (Fortes et al., 2012) and lower N2O emission factor (Siqueira Neto et al., 2015).

However, when straw mulching is combined with application of N fertilizer and vinasse, which is common practice in Brazil, several studies have observed a significant increase in N2O emissions (Carmo et al., 2013; Oliveira et al., 2013; Siqueira Neto et al., 2015; Pitombo et al., 2016). The application of N fertilizer and
vinasse provides readily available N that, when associated with increased soil moisture induced by straw, increases the availability of labile forms of C and N to microorganisms, one of the main agents controlling the denitrification processes (Carmo et al., 2013; Siqueira Neto et al., 2015). Further, the application of fresh vinasse reduces soil aeration and increases the availability of dissolved labile organic C for microorganisms, thereby leading to higher microbial activity in anaerobic sites with consequent production of N₂O.

Carmo et al. (2013) and Pitombo et al. (2016) observed that N₂O emissions from sugarcane fields may vary significantly with the application of N fertilizer, vinasse, and under varying amount of straw (Fig. 4). Therefore, based on data from these papers, it is possible to conclude that straw mulching directly influences N₂O emissions, for example, as the application of 100 m³ of vinasse increased N₂O emissions by more than 2.5 times. However, it should be highlighted that straw volumes up to 14 Mg ha⁻¹ are not common to Brazilian sugarcane fields, and the emission factor obtained for the highest straw deposition rate (21 Mg ha⁻¹) should be viewed as a theoretical benchmark. On the other hand, it appears that the N₂O emissions from N fertilizers plus vinasse might be substantially reduced if mitigation strategies are implemented, such as application at different times and/or the use of nitrification inhibitors. In this context, Soares et al. (2015) tested a nitrification inhibitor and reported a reduction in N₂O emissions ranging from 81% to 100%. Additionally, Pitombo et al. (2016) observed that applying concentrated rather than fresh vinasse reduced N₂O emissions and it may therefore be an effective strategy to mitigate GHG emissions in the Brazilian sugarcane sector.

**Impacts of straw removal on weed control**

The presence of sugarcane straw can influence the dormancy, germination, and mortality of weed seeds, leading to changes in the composition of weed communities. Such changes are difficult to predict because they depend on the thickness of the layer of straw on the soil and on the species of weed affected by soil cover (Correia & Durigan, 2004). Species considered major competitors of sugarcane, including Brachiaria decumbens, Brachiaria plantaginea, Panicum maximum, and Digitaria horizontalis, are effectively controlled by a thick layer of straw (Martins et al., 1999; Correia & Durigan, 2004; Monquero et al., 2008). The effect of straw is especially relevant in weeds that have photoblastic seeds (i.e., requiring large temperature variation) and those with a small amount of energy reserve (Ferreira et al., 2010). In addition, relating to the physical effects (sunlight and temperature), straw can also cause suppression of weeds by releasing allelopathic compounds (Silva et al., 2003).

The most prevalent weed species affecting sugarcane crops have different dynamics depending on the amount of straw left on the soil. Correia & Durigan (2004) evaluated the effectiveness of straw as a means of controlling weeds that have economic implications for sugarcane. The study showed that straw was able to inhibit the emergence of Brachiaria decumbens and Sida espinosa seedling and that this was independent of varying amounts of straw (Fig. 5). A similar effect was shown for Digitaria horizontalis, but only at higher doses of straw (i.e., 10 and 15 Mg ha⁻¹) that resulted in a profound reduction in the level of infestation. Although these results are positive, a concerning trend is that some weed species uncommon to burned sugarcane fields have increased their dominance under green cane management. For instance, Ipomoea grandifolia, which has now become one of the main weeds affecting the cultivation of sugarcane, is not significantly affected by the maintenance of different amounts of straw (Correia & Durigan, 2004). The microclimate induced by straw mulching can stimulate seed germination and growth of some weed species, such as Ipomoea spp., Merremia spp. (Correia & Kronka, 2010) and Euphorbia heterophylla (Monquero et al., 2007), as these species do not require direct sunlight to germinate and have sufficient reserves to ensure emergence from layers of straw (Azania et al., 2002; Correia & Durigan, 2004).

Hassuani et al. (2005) analyzed the results of an experimental network of 56 sugarcane harvests in São Paulo State and found that the presence of a straw layer promotes an important herbicidal effect (Fig. 6), most noticeably for monocots that have small seeds and lower reserves. This study revealed that maintaining amounts of straw equal to, or higher than, 8 Mg ha⁻¹...
(dry basis) caused an average efficiency in weed control of 87% (ranging from 56% to 98%), while amounts lower than 8 Mg ha\(^{-1}\) reduced the average efficiency to 56% (ranging from 0 to 96%). Straw amounts lower than 8 Mg ha\(^{-1}\) resulted in high variability in weed control efficiency, which is probably associated with the seed bank of the specific areas, as these straw layers are not always uniformly distributed on the soil.

Despite the potential for straw to act as a natural herbicide for most weeds of economic significance to sugarcane crops, the presence of this mulch greatly reduces herbicide efficiency, particularly those that are applied preemergence (Rossi et al., 2013). Several studies have shown that straw retains herbicides applied preemergence, thereby affecting their mobility and efficiency in weed control (Monquero et al., 2007, 2009; Rossi et al., 2013). Toledo et al. (2009) concluded that even small amounts of straw (between 1 and 2.5 Mg ha\(^{-1}\) yr\(^{-1}\)) may be enough to reduce the effectiveness of preemergent herbicides. When viewed from an overall perspective however, maintaining an optimal quantity of straw (i.e., greater than 8 Mg ha\(^{-1}\)) can lead to a more effective (and sustainable) control of the main weeds of economic significance to the sugarcane crop.

**Impacts of straw removal on pest infestation**

The significant reduction of burned harvesting systems affected pest populations in sugarcane fields (Dinardo-Miranda & Fracasso, 2013). The synergistic effects of the absence of fire and increased straw on the soil surface have increased populations of the spittlebug (Mahanarva fimbriolata), sugarcane borer (Diatrea saccharalis), and sphenophorus (Sphenophorus levis), with significant implications for crop yield (Macedo & Macedo, 2004; Macedo, 2005; Arrigoni, 2011) and quality of feedstock (Rossato et al., 2011, 2013). On the other hand, parasitic nematodes and beetles, such as Migdolus fryanus, which are important pests in sugarcane plantations, were apparently not affected by straw mulching (Dinardo-Miranda & Fracasso, 2013).

Prior to the phasing out of fire-based harvesting, spittlebug had little impact in São Paulo State, as an absence of straw is not beneficial to its development, and eggs were destroyed by fire. Declines in spittlebug populations are pronounced in areas with sparse or no straw cover, as the soil tends to be dryer (Campos et al., 2010). Dinardo-Miranda (2002) reported that the removal of straw can trigger reductions of up to 85% in infestation rates by spittlebug through direct exposure to solar radiation and lower soil moisture content. Several methods for spittlebug control have been adopted, including the use of more tolerant sugarcane varieties (which have not been very effective so far), as well as chemical and biological control, which have been described as efficient in most cases. For instance, use of
the fungus *Metarhizium anisopliae* has been proven to be a highly effective, low-cost method that also shows minimal environmental impacts (Filho *et al.*, 2003; Loureiro *et al.*, 2005). However, this control has proven unsatisfactory under high initial pest infestation conditions, when the use of chemical control is generally necessary (Dinardo-Miranda, 2005). Aiming to suppress attack by spittlebug, the impact of partial removal of straw or piling the straw in the mid row away from the sugarcane stools is not fully known and further research is required.

Another pest that has increased in recent years is *Sphenophorus levis*, which is spread primarily through the transport of infested stalks to new planting areas. In some regions, sugarcane fields have been decimated through attack by this pest (Dinardo-Miranda, 2000, 2011; Arrigoni, 2011). Direct correlations between the adoption of mechanical harvesting and an increase in this pest have been well reported in the literature (Dinardo-Miranda, 2000). While previous fire-based harvesting destroys adult *Sphenophorus levis*, straw maintenance on the soil provides a shelter for this insect. However, uncertainties remain about whether insect populations are enhanced by the presence of straw *per se* or because of the synergistic effects of straw and an absence of fire. Similar observations have been reported for sugarcane borer populations, as straw covers can facilitate its survival. Higher borer population densities have been demonstrated in areas where straw is maintained on the soil (Arrigoni, 2011). Given the management perspectives of straw and its relationship with the prevalence of sugarcane pests, there is a clear need for further studies to qualify and quantify the impact of straw removal on the population dynamics of the main pests of sugarcane plantations.

**Impacts of straw removal for sugarcane growth and biomass production**

The sugarcane crop cycle typically lasts 5–6 years, which includes the first year plant–cane cycle and the ratoons that grow subsequently. Ratoons are harvested annually until the sugarcane yield becomes uneconomical and a new planting is required. The effects of straw on crop yield are very complex and have shown divergent results (Hassuani *et al.*, 2005). Hassuani *et al.* (2005) observed that the removal of straw can increase, decrease, or have no net effect on sugarcane yields and that factors such as annual weather conditions, crop variety, soil conditions, and harvest period are more important to determine yield. In some cases, especially in cold regions, maintaining straw on the soil can hinder the regrowth of sugarcane, resulting in gaps in the stand and reducing the sugarcane yield (Campos *et al.*, 2010). Problems with regrowth usually occur in sugarcane harvested early in the cycle when temperatures are low, because the maintenance of straw reduces soil temperature (Awe *et al.*, 2015) and therefore results in slower crop regrowth at the initial stage. Furthermore, the straw layer acts as a physical barrier to sugarcane sprouting, which may interfere in crop development and result in a reduction in the initial tillering. One option used in Brazilian sugarcane fields to avoid the slower crop development in such regions is to move the straw away from crop rows and piling it between rows (Campos *et al.*, 2010), but the practical outcomes of this practice is not yet clear.

The climatic conditions of the south-central region of Brazil, which are characterized by rainy summers and dry winters, make straw maintenance an important practice for conserving soil moisture, and consequently result in better water conservation and increased water-use efficiency. Resende *et al.* (2006) found that sugarcane yields increased by 25% in response to the maintenance of straw on the soil surface, especially under drought conditions, which highlights the value of these residues as a means of preserving soil moisture. Following the initial cane regrowth stage, crop development is enhanced through the presence of straw, as the mulch layer enhances water infiltration and retention in the soil, and reduces soil temperature (Awe *et al.*, 2015), which in turn is an important factor that benefits the crop during periods of low water availability.

In a recent study, Aquino *et al.* (2015) concluded that the removal of large amounts of straw reduced sugarcane yield, indicating a higher root:shoot ratio in treatments under straw maintenance above 10 Mg ha\(^{-1}\). The sugarcane root system plays a fundamental role in the regeneration of ratoons after harvesting and thus directly influences the uptake of water and nutrients, in addition to determining drought tolerance and the incidence of pests attacks (Aquino *et al.*, 2015). Most of the sugarcane root system (60–70%) is concentrated in the top 20 cm of topsoil (Costa *et al.*, 2007) and this surface layer is vulnerable to weather conditions, which have a marked effect on sugarcane yields under adverse conditions.

Using the APSIM model, Marin *et al.* (2014) observed that sugarcane crops in Brazil have the potential to respond negatively to straw removal, and such yield losses will be accentuated in regions with higher water deficits. Corroborating those findings, Oliveira *et al.* (2016) using the same approach pointed out that the removal of straw for bioenergy production can result in sugarcane yield reductions of around 5 Mg ha\(^{-1}\) yr\(^{-1}\). The lack of consensus regarding the effects of straw removal on crop yield highlights the emergent need for long-term studies under contrasting edaphoclimatic conditions.
Conclusions

The transition from a burned to a green cane harvesting system has led to many adjustments to sugarcane management practices. Furthermore, the imminent removal of sugarcane straw for bioenergy production has driven the demand for additional studies to better comprehend the implications of straw management to avoid negative impacts. Most of the existing studies have been designed to understand isolated or specific impacts of straw mulching on soil indicators, biomass production, and the incidence of pests and weeds. None of them have considered the full suite of ecosystems services derived from maintaining straw mulch on the soil as a whole, including soil C storage, nutrient cycling, soil biodiversity, water storage, soil erosion, biomass production, weed control, among others.

The long-term sustainability of sugarcane ethanol production may depend on several indicators, and among these are soil quality, feedstock production and bioenergy production. It is apparent that there are negative agronomic implications of straw removal for nutrient cycling, soil erosion control, soil biodiversity, soil water storage, soil C accumulation, and weed control. The latter, however, seems to be transitory because weed populations are dynamic and will change regardless of the straw management control strategy. The majority of studies have shown higher yields under straw maintenance, but very few have found that straw hampers biomass production and these tend to be restricted to cold regions and/or under some specific soil conditions. It is necessary to be cautious regarding the uncertainties associated with N2O emissions. Sugarcane straw by itself does not increase N2O emissions, but when it is combined with the application of N fertilizer and vinasse, which are very common practices in Brazilian sugarcane fields, significant increases in N2O emissions have been reported. Pest control is among the parameters that are favored by straw removal.

The establishment of recommendable levels of straw maintenance on the field should be based on several benefits that this feedstock provides to the sugarcane sector, and the trade-offs of straw removal that are clearly site specific. Regions with climate regimes or soil types that are less sensitive to erosion, water deficit, and loss of soil C would be less affected by the removal of straw for bioenergy production. Therefore, the recommendable soil cover or amount of straw to be maintained in the field versus that collected for bioenergy production cannot be determined without taking into account specific local factors. This approach is associated with an ongoing debate with regard to other crops whose harvest residues are potential feedstock for bioenergy (Gollany et al., 2011; Huggins et al., 2011; Karlen et al., 2011, 2012; Tarkalson et al., 2011; Clay et al., 2012; English et al., 2013; Muth et al., 2013; Liska et al., 2014; Zhao et al., 2015).

The data show that an appropriate recommendation should be based on a minimum mass of straw left on the field to ensure the continued provision of ecosystem services such as nutrient cycling, water storage, soil protection, biomass production, among others. These are unlikely to be maintained if straw is removed at excessive rates. For example, Hassuani et al. (2005) and Martins Filho et al. (2009) suggested that at least 7 Mg ha⁻¹ of dry mass (50% of the total) should be maintained on the field to suppress weeds and control soil erosion, respectively.

Several authors have assumed that 50% of the straw could be collected from fields for industrial use when studying sugarcane biorefinery alternatives (Walter & Ensinas, 2010; Cavallett et al., 2012; Dias et al., 2012, 2013). It seems therefore that 50% sugarcane straw removal has become a default value for practical reasons of assessment. However, we advocate this figure should be avoided as sugarcane fields under different soil types and climate conditions produce variable amounts of straw (ranging from 8 to 30 Mg ha⁻¹), and thus, this figure may be inadequate. In general, our review indicates that most of the agronomic benefits are preserved when at least 7 Mg ha⁻¹ of dry straw is kept on the soil surface. We suggest that efforts should be targeted on understanding soil erosion, soil C dynamics, and soil water storage, as they are fully integrated with economic and environmental factors related to bioenergy production.

This review provides easily available information to guide decision-making on the optimum amount of straw to maintain in the field to take advantage of the agronomic and environmental aspects. There exists a need for more comprehensive assessment approaches that take into consideration the entire sugarcane chain and have the capability of capturing the costs and benefits of these complex systems. With this comprehensive evaluation based on a set of empirical studies, it will be possible to suggest proper strategies for the current and future removal of sugarcane straw for industrial use. In addition, long-term field research and modeling efforts are of paramount importance to assess the magnitude and rates at which straw can be removed taking into account all of the various indicators involved in this complex equation.

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