Greenhouse gas mitigation potential from green harvested sugarcane scenarios in São Paulo State, Brazil

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Abstract
Brazil is a major sugarcane producer and São Paulo State cultivates 5.5 million hectares, close to 50% of Brazil’s sugarcane area. The rapid increase in production has brought into question the sustainability of biofuels, especially considering the greenhouse gas (GHG) emissions associated to the agricultural sector. Despite the significant progress towards the green harvest practices, 1.67 million hectares were still burned in São Paulo State during the 2011 harvest season. Here an emissions inventory for the life cycle of sugarcane agricultural production is estimated using IPCC methodologies, according to the agriculture survey data and remote sensing database. Our hypothesis is that 1.67 million hectares shall be converted from burned to green harvest scenarios up to years 2021 (rate 1), 2014 (rate 2) or 2029 (rate 3). Those conversions would represent a significant GHG mitigation, ranging from 50.5 to 70.9 megatons of carbon dioxide equivalent (Mt CO2eq) up to 2050, depending on the conversion rate and the green harvest systems adopted: conventional (scenario S1) or conservationist management (scenario S2). We show that a green harvest scenario where crop rotation and reduced soil tillage are practiced has a higher mitigation potential (70.9 Mt CO2eq), which is already practiced in some of the sugarcane areas. Here we support the decision to not just stop burning prior to harvest, but also to consider other better practices in sugarcane areas to have a more sustainable sugarcane based ethanol production in the most dense cultivated sugarcane region in Brazil.

1. Introduction

The National Alcohol Program (Proálcool) was established in Brazil in 1975 with the purpose of reducing petroleum imports through the production of ethanol from sugarcane. Most recently, the scientific community has recognized the environmental benefits of replacing fossil fuels with ethanol from sugarcane [1]. It is estimated that ethanol derived from 1 ha of...
Sugarcane avoids the emission of about 14 tons (t) CO$_2$eq yr$^{-1}$ relative to the use of fossil fuels [2]. Furthermore, when compared to ethanol derived from other feedstocks (such as sugar beet, maize and sorghum), sugarcane is the most effective option in mitigating emissions of greenhouse gases (GHG) [3].

The rapid expansion of the cultivated sugarcane area in Brazil, mainly in São Paulo State [4], has left many unanswered questions about the true sustainability of biofuels [5], especially in relation to GHG emissions from the agricultural sector, which accounts for nearly 90% of the GHG footprint of sugarcane ethanol [6]. Normally, the sugarcane harvest is performed manually with preliminary burning (burned harvest), or mechanically without burning (green harvest). The burning practice aims to facilitate manual harvesting through the removal of leaves and poisonous animals. However, resultant emissions of greenhouse gases cause harm to the environment [5] and human health [7]. GHG emission from pre-harvest burning has been estimated as 941 kg CO$_2$eq ha$^{-1}$ yr$^{-1}$, which corresponds to 30% of the total GHG emission in sugarcane production [8]; these emissions are essential in assessing the sustainability of ethanol production.

Remote sensing satellite images are an effective tool in monitoring the cultivated sugarcane area [4], and also the sugarcane harvest practice [9], allowing the generation of accurate information that can serve as a basis for studies on GHG emissions and energy balance. Since 2006, the National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais; INPE) monitors the sugarcane harvesting practice in São Paulo State and generates monthly and annual maps of the sugarcane areas harvested with and without the pre-harvest burning. These maps have served as support for public policies on the control, supervision and cessation of burning, and can be viewed on the website www.dsr.inpe.br/laf/canasat.

Legal restrictions regarding the sugarcane pre-harvest burning, and the consequent increase of mechanical harvesting without burning influence the GHG emissions balance in agricultural areas in various forms, since the quantities of diesel and agricultural inputs (nitrogen fertilizer, vinasse, filter cake, limestone and pesticide) consumed in the crop production vary according to the management system adopted, namely with or without the burning practice. De Figueiredo and La Scala [8] reported that conversion from burned to green plot could save from 310.7 (not considering soil carbon sequestration) to 1484.0 kg CO$_2$eq ha$^{-1}$ yr$^{-1}$ (considering soil carbon sequestration).

Several agricultural management alternatives have been proposed to mitigate GHG emissions associated with the sugarcane production [10]. For this analysis, we have focused on the potential of GHG mitigation simulating the non-burning of harvest residues, as well as avoiding emissions as a result of changes in tillage practices and introducing crop rotation in all production areas where sugarcane is still harvested with burning. To reduce the negative environmental impacts of biofuels production in Brazil, and taking into account the sources and sinks of carbon in the sugarcane production process, this study aimed to estimate the potential for GHG mitigation in the agricultural sector from the year of 2012 until 2050, in response to the conversion from burning to green harvested management scenarios (conventional or conservationist), based on three conversion rates, in São Paulo State.

2. Material and methods

2.1. Sugarcane production and management scenarios for 2050

Sugarcane crop yield is related to edaphoclimatic conditions, cultural practices and adopted varieties, corresponding to approximately 82 t of cane per hectare in São Paulo State [11]. On average, sugarcane has a full crop cycle of six years, during which five harvests, four ratoon treatments, and one field renovation are performed. The first harvest is usually done 15–18 months after planting. The harvest of the ratoon is done once a year for four consecutive years, on average. After the first harvest, yield tends to reduce from year to year, making the renovation of the sugarcane field with a new planting necessary after a typical frequency of four harvests [12].

Traditionally, conventional soil tillage is adopted during sugarcane field renovation, which consists of the mechanical removal of ratoon, followed by the operations of subsoiling, heavy harrow, medium harrow, and grader harrow. Recently, conventional tillage has been replaced by reduced tillage in some regions in Brazil, where the soil is lightly tilled in the planting row [13]. To improve fertility and physical properties of the soil, the introduction of crop rotation with leguminous is an agricultural practice widely used during sugarcane field renovation [14].

This study was based on an estimate of the potential mitigation of greenhouse gases (GHG) emissions in São Paulo State during the period from 2012 to 2050, in sugarcane areas where manual harvesting with burning and conventional soil tillage are still practiced (scenario S0). The management scenarios proposed in this study take into account the conversion of the system of manual harvesting with burning for mechanized harvesting without burning (green harvest), including the adoption of conservationist management practices in the sugarcane agricultural production.

The scenario S1 refers to the system of green mechanized harvesting that uses conventional soil tillage during sugarcane field renovation, and the scenario S2 corresponds to the system of green mechanized harvesting that uses reduced soil tillage plus the introduction of a crop rotation (Crotalaria juncea L.) during sugarcane field renovation. We assumed a crop cycle of six years, so that in scenarios S0 and S1, the soil remained in fallow until the new sugarcane is planted (six months), and in scenario S2, crop rotation with C. juncea L. was introduced in the same period. The estimates of the GHG emissions for production scenarios were calculated in accordance with the IPCC methodologies [15] and expressed in kg CO$_2$eq ha$^{-1}$ yr$^{-1}$ following the global warming potential (GWP) of each gas for a period of 100 years, which is 1 for CO$_2$, 25 for CH$_4$ and 298 for N$_2$O [16].

2.2. Remote sensing data and harvest conversion rates

The calculation of GHG mitigation potential of converting the type of sugarcane harvest in São Paulo State was based on the area harvested with burning during the 2011 harvest season that was mapped based on visual interpretation of Landsat type satellite images acquired from April to December of each
crop, according to the methodology proposed by Aguiar et al. [9]. The Canasat Project generated the harvest maps by monitoring the areas available for harvest at the beginning of the season (Table 1). These maps are made available at: www.dsr.inpe.br/laf/canasat (Fig. 1).

The conversion rate of the harvest practice type adopted in this study was based on the hypothesis that the entire sugarcane area harvested with burning in 2011 will be converted to green harvest scenarios according to three periods, despite the expansion of the new sugarcane areas arising in the period from 2012 to 2050 that are all supposed to be green harvested.

The three periods (number of years, $T$) for the cessation of burning were established under the following considerations:

1. The State Law No. 11,241/2002 (rate 1) [17], which provides for the cessation of sugarcane burning by 2021 in mechanized areas (with slope $\leq 12\%$);
2. the Green Ethanol Protocol (rate 2; Protocolo Etanol Verde), signed by the sugarcane sector and the state government to anticipate the cessation of burning in most areas by 2014 (for details see: http://www.ambiente.sp.gov.br/etanolverde/#); and
3. the amount of sugarcane area observed on satellite images that was converted from burning to green harvest from 2006 to 2011 (rate 3). The conversion rates were calculated according to equations (1)–(3), respectively:

$$
\text{Rate 1} = \frac{A_{2011}}{T_L},
$$

$$
\text{Rate 2} = \frac{A_{2011}}{T_P},
$$

$$
\text{Rate 3} = \frac{A_{2011}}{T_R^{2006-2011}},
$$

where $A_{2011}$ is the area in hectares of sugarcane harvested with burning in the 2011 harvest season, and $T$ is the time in years required for the cessation of burning in accordance with: 1) State Law ($T_L$); 2) Protocol ($T_P$); and 3) the actual conversion observed from 2006 to 2011 on the satellite images ($T_R^{2006-2011}$). Both rate 1 and rate 2 are partially overestimated since $A_{2011}$ includes not only the sugarcane cultivated on slope $>12\%$ but also the sugarcane from farmers that have not signed the Green Ethanol Protocol. Burning of sugarcane cultivated on slope $>12\%$ should be banished by 2017 under

### Table 1 – Sugarcane areas harvested with and without the burning practice during the 2006–2011 harvest seasons.

<table>
<thead>
<tr>
<th>Harvest season</th>
<th>GH$^a$ (ha)</th>
<th>GH$^a$ (%)</th>
<th>BH$^b$ (ha)</th>
<th>BH$^b$ (%)</th>
<th>Total (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>1,110,120</td>
<td>34.2</td>
<td>2,131,990</td>
<td>65.8</td>
<td>3,242,110</td>
</tr>
<tr>
<td>2007</td>
<td>1,764,992</td>
<td>46.6</td>
<td>2,025,448</td>
<td>53.4</td>
<td>3,790,440</td>
</tr>
<tr>
<td>2008</td>
<td>1,924,075</td>
<td>49.1</td>
<td>1,997,630</td>
<td>50.9</td>
<td>3,921,705</td>
</tr>
<tr>
<td>2009</td>
<td>2,266,403</td>
<td>55.6</td>
<td>1,810,531</td>
<td>44.4</td>
<td>4,076,934</td>
</tr>
<tr>
<td>2010</td>
<td>2,627,025</td>
<td>55.6</td>
<td>2,101,110</td>
<td>44.4</td>
<td>4,728,135</td>
</tr>
<tr>
<td>2011</td>
<td>3,125,619</td>
<td>65.2</td>
<td>1,670,521</td>
<td>34.8</td>
<td>4,796,140</td>
</tr>
</tbody>
</table>

$^a$ GH: green mechanized harvesting (without burning). $^b$ BH: manual harvesting with previous burning.

![Fig. 1 – Map of the sugarcane areas harvested with and without the burning practice in São Paulo State – 2011 harvest season, and evolution of the total area available for sugarcane harvest in the past six years (Source: www.dsr.inpe.br/laf/canasat).](image-url)
the Green Ethanol Protocol and by 2031 under the State Law considerations. Farmers that have not agreed on the Protocol have to follow the rules established by the State Law.

2.2.1. Conversion rates between practices of harvest
The conversion rates from pre-harvest burning to green harvest adopted in this study are as follow: rate 1 = 167,062 ha\textsuperscript{-1} yr\textsuperscript{-1}; rate 2 = 556,840 ha\textsuperscript{-1} yr\textsuperscript{-1}; and rate 3 = 92,294 ha\textsuperscript{-1} yr\textsuperscript{-1}. Based on the conversion rate observed on the satellite images (rate 3) the burning practice would be banished in 2029, two years earlier than the deadline set by the State Law (2031 for slope > 12%) and 15 or 12 years after the deadline set by the Green Ethanol Protocol (2014 for slope ≤ 12% and 2017 for slope > 12%). To phase out the sugarcane burning within the period prescribed by the State Law (2021 for slope ≤ 12%), it is necessary to adopt a conversion rate of 167,062 ha\textsuperscript{-1} yr\textsuperscript{-1}. On the other hand, to phase out the burning within the deadline set by the Protocol (2014 for slope ≤ 12%), a conversion rate of 556,840 ha\textsuperscript{-1} yr\textsuperscript{-1} is necessary (Fig. 2). According to the remote sensing imagery evaluation, the conversion from burning to green harvest during the period from 2006 to 2010 has been relatively stable; however, 430,589 ha during the 2011 harvest season were converted from burning to green harvest when compared to the period from 2006 to 2010 (Table 1), which demonstrates the willingness of the sugarcane sector to achieve the goals set by the Green Ethanol Protocol.

2.3. Sources of GHG emissions and soil carbon accumulation
The methodological approach of this work is similar to the ones applied by Bordonal et al. [10] to quantify the agricultural inputs applied for different production scenarios, which are characterized by contrasting management practices. The sources of GHG emissions considered in the calculations of the estimates were related to the following practices and inputs shown in Table 2 [8]. In addition, we considered the potential for soil carbon accumulation caused by the change in the agricultural management system, such as mechanical harvesting without burning and reduced soil tillage during sugarcane field renovation. The GHG emissions related to the production phases of agricultural inputs (synthetic N fertilizer, pesticides, and limestone), and to the extraction, processing, and transportation of diesel were also considered in the estimates.

2.3.1. N\textsubscript{2}O emissions from managed soils
The increase in the availability of N in the soil can occur through the application of synthetic N fertilizers, organic composts applied as fertilizers (vinasse and filter cake), and crop residues that return to the soil after harvest; this inevitably leads to the emission of nitrous oxide (N\textsubscript{2}O), which is a by-product of the processes of nitrification and denitrification in the soil [15].

Due to the shortage of results on N\textsubscript{2}O emissions in agricultural areas in Brazil [18], there are currently no emission factors for N\textsubscript{2}O attributed to the specific soil and climatic conditions in Brazil; therefore, we calculated our estimates using the emission factors for N\textsubscript{2}O suggested by the IPCC [15]. Thus, we apply the emission factor of 1% to the amount of N derived from synthetic N fertilizers applied to the soil, of the N from the organic composts (vinasse and filter cake) and of the N from the crop residues that returns to the soil after harvesting the C. juncea L. and the sugarcane. For indirect emissions, we applied the emission factor of 1% to the fraction of 10% of N volatilized from synthetic fertilizer and 20% of the N volatilized from organic composts (vinasse and filter cake). To

![Fig. 2](image-url) — Harvest conversion rates proposed in this study according with State Law (rate 1 — red line, total conversion until 2021), Protocol (rate 2 — green line, total conversion until 2014) and real observed (rate 3 — blue line, total conversion until 2029) due to the conversion of remaining sugarcane areas harvested with burning (2011 harvest season = 1,670,521 ha) in São Paulo State, Brazil. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

<table>
<thead>
<tr>
<th>Sector</th>
<th>Emission sources and potential of soil carbon accumulation considered for each management scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural</td>
<td>Direct and indirect N\textsubscript{2}O emissions from managed soils</td>
</tr>
<tr>
<td></td>
<td>Synthetic N fertilizer</td>
</tr>
<tr>
<td></td>
<td>N from organic composts (vinasse and filter cake)</td>
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<tr>
<td></td>
<td>N from sugarcane and Crotalaria juncea L. crop residues</td>
</tr>
<tr>
<td></td>
<td>CH\textsubscript{4} and N\textsubscript{2}O emissions from sugarcane residues burning</td>
</tr>
<tr>
<td></td>
<td>CO\textsubscript{2} emissions from limestone</td>
</tr>
<tr>
<td></td>
<td>Emissions related to the pesticides (only production phase)</td>
</tr>
<tr>
<td></td>
<td>Soil carbon accumulation</td>
</tr>
<tr>
<td>Mobile sources (machinery)</td>
<td>Emissions from diesel consumption by machinery</td>
</tr>
<tr>
<td></td>
<td>CO\textsubscript{2}</td>
</tr>
<tr>
<td></td>
<td>CH\textsubscript{4}</td>
</tr>
<tr>
<td></td>
<td>N\textsubscript{2}O</td>
</tr>
</tbody>
</table>

Source: De Figueiredo and La Scala [8].
account for the \( \text{N}_2\text{O} \) emission due to leaching and runoff from these three sources, we adopted the leached fraction of 30% and the emission factor of 0.75% [15].

\( \text{N}_2\text{O} \) emission from N-fixing crop was accounted in the estimates solely as a function of the decomposition of \( \text{C. juncea} \) L. residues as literature has shown that the biological nitrogen fixation process itself is no longer considered as a direct source of \( \text{N}_2\text{O} \) emission [15,19]. As the \( \text{C. juncea} \) L. residues present a low C:N ratio, close to 15 [20], we assumed that the total above-ground and below-ground nitrogen inputs from leguminous would be available for nitrification and denitrification processes in few months, due to the rapid mineralization of the residues in soil by microbial activity.

The synthetic N fertilizers have received increased attention in relation to the life cycle, especially the mineral nitrogen, which, in addition to \( \text{N}_2\text{O} \) emissions during application, also requires large amounts of energy in the production process. Therefore, we assumed that the production and distribution phases of synthetic N fertilizer emit 3.97 kg CO\(_2\)eq kg \( \text{N} \)\(^{-1} \) applied [12].

2.3.1.1. Synthetic N fertilizer and N-fixing crop. The production of sugarcane crop requires high doses of synthetic N fertilizers, in which the expected crop yield is the determining factor in the choice of dose to be applied. In São Paulo State, the expected productivity of 100 t of stalks ha\(^{-1} \) yr\(^{-1} \) requires the application of 30–90 kg N ha\(^{-1} \) in the sugarcane planting, while in the ratoon years the application rate of 100 kg N ha\(^{-1} \) yr\(^{-1} \) is recommended [21].

However, higher doses of synthetic N fertilizer have been recommended for sugarcane areas in the early years of the conversion from burning to green harvest practice [22]. The deposition of crop residues of high C:N ratio on the soil surface can result in the immobilization of N from the soil and fertilizer by microorganisms, making it unavailable for the crop [23]. Thus, Trivelin and Vitti [22] suggest the application of 130 kg N ha\(^{-1} \) yr\(^{-1} \) (30% higher) for the ratoon treatment.

The inclusion of leguminous in the sugarcane crop cycle is widely practiced in the world’s productive systems [14], especially by providing nitrogen through biological nitrogen fixation (BNF) at a dosage that can range from 70 to 250 kg N ha\(^{-1} \) [24]. Traditionally, it is accepted that the amount of synthetic N fertilizer applied in the sugarcane planting can be substantially reduced, or even eliminated, after the cultivation of an N-fixing crop in the renovation period [25]. Based on field experiments, Park et al. [25] demonstrated that the N provision of the leguminous was available for sugarcane until the fourth ratoon year, enabling the reduction of N fertilizer application by almost 100% at planting, and 60%, 25% and 10% in the subsequent ratoon years.

In this study, we considered the introduction of \( \text{C. juncea} \) L. in the sugarcane crop cycle (renovation) with accumulated nitrogen content of approximately 200 kg ha\(^{-1} \), so that the dose of N fertilizer applied was reduced as proposed by Park et al. [25]. Table 3 presents the amounts of N fertilizer applied in the sugarcane agricultural production (planting and ratoon treatment), according to each management scenario.

2.3.1.2. Organic composts. Vinasse and filter cake are used in sugarcane areas for their high fertilizer value. We assumed the content of 0.368 kg N m\(^{-3} \) of vinasse, in which a dose of 120 m\(^3 \) ha\(^{-1} \) corresponds to the application rate of 44.2 kg N ha\(^{-1} \) in each ratoon year (Table 3) [8]. Regarding the N content in the filter cake, Macedo [26] reported a content of 12.5 kg N t\(^{-1} \) of filter cake, while Busato et al. [27] found a content of 29.9 kg N t\(^{-1} \) of filter cake. Usually, the filter cake is applied in sugarcane areas at a dose of 5 t (dry basis) ha\(^{-1} \) at crop planting [12]. Therefore, the N contained in the filter cake was considered to be 21 kg N t\(^{-1} \), which corresponds to application rate of 105 kg N ha\(^{-1} \) in the sugarcane planting (Table 3).

2.3.1.3. Crop residues from green mechanized harvesting. The mechanical harvesting without burning is characterized by the deposition of 10–20 t ha\(^{-1} \) of dry matter on the soil surface [28], and in that material, the amount of nitrogen varies from 40 to 80 kg ha\(^{-1} \) [29,30]. The magnitude of \( \text{N}_2\text{O} \) emissions is related to the decomposition rate of crop residues, in which a high C:N ratio have a negative effect on N availability, and consequently lower \( \text{N}_2\text{O} \) emissions [31]. Studies performed in Brazil [30,32] indicated that sugarcane residues presented a low mineralization and provided from 18% to 30% of total N-residues in one year.

It was considered that the average crop yield of 82 t ha\(^{-1} \) of stalks [11] would result in a deposition of 15 t ha\(^{-1} \) of dry matter on the soil surface, with an N content of 60 kg ha\(^{-1} \) in these residues. As the sugarcane presents a C:N ratio of approximately 100 [30], we assumed that 20% of this nitrogen (60 kg N ha\(^{-1} \)) would be available for nitrification and denitrification within the period of one year, corresponding to 12 kg N ha\(^{-1} \) yr\(^{-1} \) in green harvested areas (scenarios S1 and S2).

2.3.2. \( \text{CH}_4 \) and \( \text{N}_2\text{O} \) emissions from sugarcane residues burning

Despite the substantial release of CO\(_2\) in the sugarcane residues burning, it is assumed that the amount emitted is absorbed into

| Table 3 – Annual quantities of agricultural inputs and diesel consumed for each production scenario, per hectare, during the period of renovation/planting, ratoon treatment and harvest. |
|-----------------|-------|-------|-------|
| **Renovation/planting** |       |       |       |
| Synthetic N fertilizer (kg N) | 60.0  | 60.0  | –     |
| Filter cake (kg N) | 105.0 | 105.0 | 105.0 |
| Limestone (t) | 2.0   | 2.0   | 2.0   |
| Insecticide (kg) | 0.16  | 0.16  | 0.16  |
| Herbicide (kg) | 2.2   | 2.2   | 2.2   |
| Diesel (L)
| 166.7 | 166.7 | 114.5 |
| **Ratoon treatment** |       |       |       |
| Synthetic N fertilizer (kg N) | 100.0 | 130.0 | 100.0 |
| Vinasse (kg N) | 44.2  | 44.2  | 44.2  |
| Insecticide (kg) | –     | 0.16  | 0.16  |
| Herbicide (kg) | 2.2   | 2.2   | 2.2   |
| Diesel (L)
| 16.1  | 20.4  | 17.7  |
| **Harvest** |       |       |       |
| Diesel (L)
| 94.7  | 177.2 | 177.2 |

Adapted from Bordonal et al. [10].

* Total amount obtained from the sum of specific agricultural operations presented in Table 4, according to each management stage.
the next crop cycle through the process of photosynthesis. The same assumption applies to CO₂, which in the atmosphere is rapidly converted to CO₂. Therefore, only CH₄ and N₂O emissions were accounted as net emissions [15]. The emission rates of these gases depend on the relationship between the production of dry matter and crop yield. In a literature review with different varieties of sugarcane, Ronquim [33] found the production of crop residues ranging from 12.5 t ha⁻¹ to 24.9 t ha⁻¹ of dry matter. Hence, we assumed that the crop yield of 82 t ha⁻¹ resulted in 12.5 t ha⁻¹ of crop residues ranging from 12.5 t ha⁻¹ to 24.9 t ha⁻¹ of dry matter. The change factors in the C stocks (Tier 1) are divided into two categories: i) soil management factor (F_MG), and ii) residues input factor (F_I). The determination of these factors is related to the combination of three variables: specific climate, soil, and agricultural management [15]. The climate of São Paulo State was characterized as tropical moist/wet [38].

Changes in C stocks in scenarios S1 and S2 were estimated from the management scenario S0, whose carbon stock was considered as a reference in the calculations. Based on data from the literature, it was found that carbon stocks in sugarcane areas harvested with burning ranged from 28.8 to 59.0 t C ha⁻¹ in sandy soils and from 44.4 to 69.8 t C ha⁻¹ in clay soils, both in the 0–30 cm depth [28]. Therefore, we assumed a reference carbon stock at a depth of 30 cm to be 42 t C ha⁻¹ for the areas cropped in sandy soils and 58 t C ha⁻¹ for the areas cropped in clay soils.

The change factors in the stocks (F_MG and F_I) suggested by the IPCC [15] were originally developed for annual crops whose management practices occur annually. The advent of green mechanized harvest of sugarcane has given rise to the annual deposition of large amounts of harvest residues on the soil surface, ranging from 12.5 t ha⁻¹ to 24.9 t ha⁻¹ of dry matter [33]. On the other hand, soil tillage in the crop management is not performed annually, occurring only in the sugarcane renovation every 6 years. Therefore, the change factors F_MG and F_I used for the calculation of variations in C stocks were 1.225 and 1.11, respectively, in that the adoption of reduced soil tillage (S0 to S2) and the conversion of manual harvesting with burning to the green mechanized harvesting (S0 to S1 or S0 to S2) correspond to an increase of 2.25% and 11% in soil C stocks over a 20-year period.

The estimated values for the changes in soil C stocks were expressed in Mt CO₂ after being converted from carbon (C) to carbon dioxide (CO₂), multiplying them by the ratio of 44/12, in that 1 t of C corresponds to 3.67 t of accumulated CO₂. The potential of soil carbon accumulation was estimated by equation (4):

\[ \Delta C_{\text{soil}} = \gamma \cdot (C_{\text{ref}1} \cdot F_I \cdot F_{\text{MG}}) - C_{\text{ref}1} + \beta \cdot (C_{\text{ref}2} \cdot F_I \cdot F_{\text{MG}}) - C_{\text{ref}2}, \]

where \( \Delta C_{\text{soil}} \) = change in soil C stocks over a 20-year period (t C ha⁻¹); \( \gamma \) = percentage of sugarcane areas harvested with burning in the 2011 harvest season, grown on clay soils; \( C_{\text{ref}1} \) = carbon stock referential for clay soils grown with sugarcane that uses manual harvesting with burning (t C ha⁻¹); \( \beta \) = percentage of sugarcane areas harvested with burning in the 2011 harvest season, grown on sandy soils; \( C_{\text{ref}2} \) = carbon stock referential for sandy soils grown with sugarcane that uses manual harvesting with burning (t C ha⁻¹); \( F_I \) = factor change associated with the deposition of crop residues on the soil (dimensionless); \( F_{\text{MG}} \) = factor related to change of adopted soil management practice (dimensionless).
2.3.6. GHG emissions from diesel consumption by machinery

Farming practices require machinery that consumes considerable amounts of diesel during operations. Estimates of GHG emissions were associated with direct and indirect emissions of CO₂, CH₄ and N₂O according to the emission factors and the methodology proposed by IPCC [15]. The emission factors considered for CO₂, CH₄ and N₂O were 74,100 kg CO₂ TJ⁻¹, 4.15 kg CH₄ TJ⁻¹ and 28.6 kg N₂O TJ⁻¹, respectively [15]. GHG emissions related to the extraction, processing and distribution phases of diesel were considered to be 0.581 kg CO₂eq L⁻¹ [12]. Table 4 presents the description of specific agricultural operations and diesel consumption (L ha⁻¹) during the crop management with respect to production scenarios S0, S1 and S2 [39].

2.4. Calculation of potential GHG mitigation accumulated

To estimate the potential of GHG mitigation in São Paulo State, we considered the sum of the annual avoided GHG emissions due to the conversion of São Paulo’s sugarcane areas harvested with burning (S0; 1.67 Mha) to the management scenarios S1 or S2, according to three conversion rates from the year 2012 up to 2050 (see Section 2.2.1). The results were expressed as megatons of carbon dioxide equivalent (Mt CO₂eq) and the calculation of the annual avoided emissions was based on the difference between GHG emissions of the production scenarios, from S0 to S1 and S0 to S2, integrating all burnt harvested area in accordance with the adopted conversion rates. In addition, the soil carbon accumulation was also accounted with the annual avoided emissions to estimate the potential of GHG mitigation, in that the soil carbon accumulation was assumed for no more than a 20-year time horizon (see Section 2.3.5), for all conversion rates. Based on rate 1 (conversion until 2021), rate 2 (conversion until 2014) and rate 3 (conversion until 2029), the 20-year time period for soil carbon variations will occur in 2041, 2034 and 2049, respectively. For that reason, we assumed a timeframe for this analysis varying from 2012 until 2050.

3. Results and discussion

3.1. GHG emissions and soil carbon accumulation during sugarcane agricultural production

Fig. 3 presents the estimates of GHG emissions (kg CO₂eq ha⁻¹ yr⁻¹) for production scenarios S0, S1, and S2 during the 6-year crop cycle, considering emission sources such as sugarcane residues burning, diesel consumption,
sugarcane and *C. juncea* L. harvest residues, and agricultural inputs (synthetic N fertilizer, organic composts, liming and pesticides) in sugarcane production.

The scenario S0 (pre-harvest burning under conventional soil tillage) resulted in higher GHG emissions during the crop cycle, corresponding to approximately 2651.9 kg CO₂eq ha⁻¹ yr⁻¹, with the pre-harvest burning practice (33.3%), the application of nitrogen fertilizers (29.4%), and diesel consumption (17.6%) as the main emissions sources. Regarding the management scenario S1 (green harvest under conventional soil tillage), the total GHG emissions were 2316.5 kg CO₂eq ha⁻¹ yr⁻¹, with the major emission sources being the application of nitrogen fertilizers (42.5%) and diesel consumed by machinery (32.4%).

It is clear that in the conversion from S0 to S1 (Fig. 3), the emissions from pre-harvest burning of residues were non-existent, but the application of nitrogen fertilizer, the decomposition of sugarcane residues (green harvest), and diesel consumption resulted in additional GHG emissions, as reported by García et al. [40]. Even though, these emissions did not exceed emissions from residues burning. Therefore, it appears that the sugarcane agricultural production according to the scenario S1 could avoid the emission of 353.4 kg CO₂eq ha⁻¹ yr⁻¹, corresponding to a reduction of 14.5% relative to scenario S0.

Considering the total GHG emissions for the management scenario S2 (green harvest under reduced soil tillage and crop rotation with *C. juncea* L.), the estimates pointed to the total emission of 2160.8 kg CO₂eq ha⁻¹ yr⁻¹, where the diesel consumption (32.8%) and the application of nitrogen fertilizer (31.4%) accounted for most of the GHG emissions in the 6-year cycle. The conversion of the harvest practice and the adoption of conservationist agricultural management such as reduced soil tillage and crop rotation (scenario S2) may reduce emissions by 491.1 kg CO₂eq ha⁻¹ yr⁻¹ when compared to scenario S0, avoiding approximately 22.7% of GHG emissions.

Comparing the scenario S2 with S1, we observed that the reduced consumption of nitrogen fertilizer and diesel resulted in lower GHG emissions. Furthermore, the emissions from the *C. juncea* L. residues was lower than the emissions reduction related to lower use of nitrogen fertilizer provided by crop rotation (Fig. 3), showing a possibility to reduce emissions due to this practice [41].

The intersection between the harvest practice and soil maps allowed us to estimate more precisely the changes in soil carbon stocks and classify the sugarcane areas that were harvested in 2011 with the burning practice, according to the texture classes of sandy and clay soils (Fig. 4). Results showed that 57.2% (955,538 ha) were harvested on sandy soils, i.e., mainly around the municipalities of Barretos, São José do Rio Preto, Araçatuba, and Presidente Prudente, while 42.8% (714,983 ha) were harvested on clay soils, i.e., mainly around the municipalities of Ribeirão Preto and Piracicaba.

Our estimates point out that the management conversion of the sugarcane areas grown on clay soils (714,983 ha) to the scenarios S1 or S2 could result in a potential for soil carbon accumulation of 16.7 Mt CO₂ and 20.5 Mt CO₂, respectively, over a 20-year time horizon. On the other hand, the management conversion of the sugarcane areas grown on sandy soils (955,538 ha) to the scenarios S1 or S2 could also result in a similar potential for soil carbon accumulation of 16.2 Mt CO₂ and 19.9 Mt CO₂, respectively, over a 20-year time horizon. Thus, independently of the adopted conversion rate and considering a finite period of 20 years (see Section 2.3.5), the estimated potential for total carbon accumulation could be either 32.9 Mt CO₂ (1.6 Mt CO₂ yr⁻¹) or 40.4 Mt CO₂ (2.0 Mt CO₂ yr⁻¹) if all sugarcane areas harvested with burning in 2011 (1.67 Mha) are converted to the management scenarios S1 or S2, respectively. Those soil carbon accumulations are lower
than the ones measured by Carvalho et al. [42], that studied some conversions based on higher residues input and better management practices which resulted in mitigation potential from 26.4 to 78 Mt of soil C accumulated in a 20-year period in Brazilian sugarcane areas.

3.2. Potential of GHG mitigation accumulated in the period from 2012 to 2050

Fig. 5 presents the estimates for the technical GHG mitigation potential accumulated in the period from 2012 until 2050, due to the conversion of the sugarcane areas harvested with burning (S0) during the 2011 harvest season (1.67 Mha) in São Paulo State, according to the management scenarios S1 and S2, and the conversion rates 1, 2 and 3. Considering the annual conversion rate of 167,062 ha between the years 2012 – 2021 (rate 1-State Law), the estimates present that the change in agricultural management of sugarcane areas harvested with burning (S0) for the scenarios S1 and S2 resulted in a potential mitigation of 52.4 and 68.2 Mt CO2eq, respectively (Table 5).

Adopting the annual conversion rate of 556,840 ha between the years 2012 – 2014 (rate 2 – Protocol), the GHG mitigation potentials estimated were 54.4 Mt CO2eq and 70.9 Mt CO2eq when projecting conversion of sugarcane areas harvested with burning (S0) for the scenarios S1 and S2, respectively (Table 5). Based on the conversion rate of 92,294 ha between the years 2012 – 2029 (rate 3-real data observed), the possibility of converting these areas (S0) for management scenarios S1 and S2 could result in a mitigation potential accumulated until 2050 from 50.5 Mt CO2eq and 65.5 Mt CO2eq, respectively.

Over the studied period, the GHG mitigation potential was variable depending on the adopted conversion rates and management scenarios (Table 5). Scenario S2 presented, on average, an additional mitigation potential of 30% (~15.8 Mt CO2eq) when compared to scenario S1, independently of the adopted conversion rate. Under scenario S1, the management conversion from burning to green harvest at conversion rates 1 and 2 resulted in an additional mitigation potential of 3.7% (1.9 Mt CO2eq) and 7.8% (3.9 Mt CO2eq), respectively, when compared to the rate 3. On the other hand, it appears that in the scenario S2, the management conversion at rates 1 and 2 presented an additional mitigation potential of 4.1% (2.7 Mt CO2eq) and 8.2% (5.4 Mt CO2eq) over the rate 3, respectively.

Assessing the potential for GHG mitigation of croplands and grasslands in Great Britain under different management practices, Fitton et al. [43] found that changes in agricultural management practices have resulted in a technical mitigation potential ranging from 17 Mt CO2eq to 39 Mt CO2eq over 20 years. In a recent study of croplands and soil mitigation measures in the UK, Macleod et al. [44] suggested the greatest potentials for mitigation by 2022 ranging from 1.6 Mt CO2eq to 10.2 Mt CO2eq per year, depending on the policies implemented. These figures are lower when compared to those presented in this study, whose GHG mitigation potential accumulated in the period 2012 to 2050 ranged from 50.5 Mt CO2eq to 70.9 Mt CO2eq, corresponding to a difference of up to
40.4% when different conversion rates and management scenarios are considered (Table 5; Fig. 5).

This study points out the relevance of converting sugarcane areas to different management scenarios that contemplate not only the conversion from burning to green harvest, but also include the adoption of conservationist agricultural practices, such as reduced soil tillage and crop rotation with N-fixing crops during sugarcane field renovation. Another important aspect is related to the conversion rate of sugarcane areas harvested with burning in the 2011 harvest season, in that the anticipation of the burning cessation from 2021 (State Law) to 2014 (Green Ethanol Protocol) evidently resulted in greater mitigation potential for the GHG associated with sugarcane agricultural production.

Brazil was responsible in 2005 for the GHG emissions of 2192.6 Mt CO₂eq \[45\], while the São Paulo State accounted for 139.8 Mt CO₂eq \[46\], which correspond to 6.4% of the total emissions in the country. According to the State Law No. 13,798/2009 \[47\], establishing the State Policy on Climatic Changes, São Paulo State made a commitment facing the challenges of global climate change to reduce its GHG emissions by 20% by the year 2020, concerning to 2005 emissions. Adopting the conversion rate and the management scenario most favorable proposed for GHG mitigation, according to the voluntary protocol signed by most sugarcane mills in São Paulo State (conversion rate 2) and the scenario S2 that uses green mechanized harvesting with reduced soil tillage plus the introduction of \textit{Crotalaria juncea} \textit{L.} during sugarcane renovation (Fig. 5), the estimates presented here can suggest that the changes in management practices in the São Paulo’s sugarcane areas could represent a feasible strategy to reduce GHG from those areas, about 71.4% (20 Mt CO₂eq; Fig. 5) of the target established by state policy on climatic change for the year 2020 (28 Mt CO₂eq).

In estimates of GHG emissions for Danish agriculture in the years 1990–2010, Dalgaard et al. \[48\] analyzed possible measures to mitigate agricultural GHG emissions and indicated that a 50–70% reduction of agricultural emissions relative to 1990 is achievable by 2050, including mitigation measures in relation to the handling of manure and fertilizers, optimization of animal feeding, cropping practices, and land use changes with more organic farming, afforestation and energy

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Table 5 – Potential of greenhouse gases (Mt CO₂eq) mitigation accumulated by 2050 according to the management scenarios S1 and S2, and the conversion rates based on State Law (rate 1), Green Ethanol Protocol (rate 2) and conversion observed on satellite images from 2006 to 2011 harvest seasons (rate 3). The variations of the mitigation potential relative to the scenario S1 and the observed conversion rate during the 2006 – 2011 periods are expressed in percentage (%).

<table>
<thead>
<tr>
<th>Conversion rates</th>
<th>S1(^a)</th>
<th>S2(^b)</th>
<th>Variation S2 – S1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate 1 (2021)</td>
<td>52.4</td>
<td>3.7</td>
<td>4.1</td>
</tr>
<tr>
<td>Rate 2 (2014)</td>
<td>54.4</td>
<td>7.8</td>
<td>8.2</td>
</tr>
<tr>
<td>Rate 3 (2029)</td>
<td>50.5</td>
<td>–</td>
<td>– 29.7</td>
</tr>
</tbody>
</table>

\(^a\) S1: green harvest that uses conventional soil tillage for sugarcane field renovation.

\(^b\) S2: green harvest that uses reduced soil tillage plus crop rotation, during renovation, with \textit{Crotalaria juncea} \textit{L.}
crops. These reduction potentials are comparable to those presented in this study, where the conversion of the remaining sugarcane areas harvested with burning could achieve by 2050 a technical mitigation potential ranging from 36.1% (50.5 Mt CO₂eq) to 50.7% (70.9 Mt CO₂eq) of the total GHG emissions by the São Paulo State in 2005 (139.8 Mt CO₂eq), in that this variation depends on the conversion rate and the management scenario adopted.

Awareness of environmental issues in the medium and long term is essential for sustainable development. It is necessary to develop a set of strategies that include adaptation, mitigation, and new researches to combat climate change. Prospects for mitigating greenhouse gases in agriculture present great potential to reach reductions targets assumed by governments or even companies. However, current initiatives have suggested that identifying the synergy between climate change policies and improvement in environmental quality will likely lead the way to achieve the mitigation potential in agriculture and in other countries [49].

3.3 Sources of uncertainty

The use of IPCC [15] default methodologies (recommended when country-specific data are unavailable) results in a high level of uncertainty associated with the estimates of this study. GHG emissions from plant-soil systems of sugarcane production involve many uncertainties which largely depend on the agricultural practices, such as fertilizer application, residues management, and tillage operations [13]. For example, there is a huge discrepancy in the estimated emission factor (N₂O from N-fertilizer use) due to different soil types (including climate, i.e., moisture and temperature) and measurement techniques [50], which could vary from 1% to 3.87% [13]. In this work we used the mean value of 1% to emission factor associated to N₂O emissions [15].

Since measured data is not often available, life cycle assessment (LCA) practitioners have usually relied on the IPCC tier 1 approach to assess the GHG emissions [50]. Therefore, tier 1 was applied in our work due to the lack of regional emission factor, especially associated to the agricultural practices. The same approach was assumed for soil carbon accumulation, which is a relatively simple carbon accounting that uses default equations, along with default reference carbon stocks and removal factors. This method is frequently applied with limited observations and resources, to account for net changes in soil carbon storage as part of greenhouse gas balance assessment.

Soil carbon inventories are needed to derive regional-to-national-scale estimates of soil carbon stock change, for investigators to attain the basic understanding of current trends, as well as to support policy development and management decisions [51]. The IPCC [15] proposes soil carbon account method to be applied at national-level on greenhouse gas emissions and removals associated with soil carbon dynamics. This method has been used in the U.S. to estimate the potential of agricultural land sequestering atmospheric CO₂ [52].

Certainly, uncertainties remain regarding how long effects of avoided GHG emissions persist once sugarcane burned areas are converted to green harvested scenarios (from conventional to more conservationist practices). In this study, soil carbon accumulation represents approximately 60% of the total potential GHG mitigation. The changes in soil carbon stocks in agricultural areas are a complex issue to address the present understanding of the potential GHG mitigation. For example, the soil stock change factors for land use, tillage and inputs for Brazilian conditions (tropical regions) generally have error levels of 4—14% associated with them but all activities in tropical montane regions have a much higher error of 46—61% [15].

Further research activities should be focused on improving estimates of greenhouse gas emission due to agricultural practices and, especially, the soil carbon sequestration rates in those areas. Improvement in soil accumulation quantification will dramatically reduce the overall uncertainty of estimates derived through an incremental life cycle approach. The estimates presented in our study imply in a mitigation potential derived from better practices adopted in sugarcane areas in southern Brazil, and points that future works have to address the soil carbon stock changes in those areas, which are a source of uncertainty derived from complexity of soil carbon dynamics.

4 Conclusion

This study demonstrates that changes in management practices in the sugarcane agricultural production as the conversion of sugarcane harvest system from burning to green harvest and reduced soil tillage in addition to the introduction of an N-fixing crop during crop renovation, if adopted, could result in GHG mitigation potentials ranging from 50.5 Mt CO₂eq to 70.9 Mt CO₂eq for the period from 2012 to 2050. These potentials of GHG mitigation depends on the conversion rates established for the discontinuation of harvest with burning in São Paulo State (according to State Law, Green Ethanol Protocol and conversion observed on satellite imagery) and each management system applied as harvest type, soil tillage, and introduction of an N-fixing crop, i.e., from conventional to more conservationist scenario. Therefore, the adoption of management practices that lead to the reduction of GHG emissions in sugarcane areas could contribute considerably to achieving the objectives set by state policy on climatic change to curb emissions, in addition to promoting sustainable production of sugar and ethanol in Brazil.

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