Additional Greenhouse Gas Emissions and Offset Potential from Sugarcane Straw Recovery for Bioenergy Production in Southern Brazil

Eduardo Barretto de Figueiredo (✉ eduardobfigueiredo@hotmail.com)

Federal University of Sao Carlos: Universidade Federal de Sao Carlos <https://orcid.org/0000-0003-3232-0933>

Susantha Jayasundara

University of Guelph

Ricardo de Oliveira Bordonal

CTBE: Laboratorio Nacional de Ciencia e Tecnologia do Bioetanol

Alan Rodrigo Panosso

UNESP: Universidade Estadual Paulista Julio de Mesquita Filho

Newton La Scala Jr.

UNESP: Universidade Estadual Paulista Julio de Mesquita Filho

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Abstract

This study was designed to assess the additional greenhouse (GHG) emissions including measurements of soil CO₂-C emissions in sugarcane areas plus emissions associated with the recovery and transport operations of straw bales up to the factory gate for electricity production, contrasting with leaving all straw on the soil surface. The total additional GHG emissions considering the main sources evaluated (i.e., soil CO₂-C, diesel use and N₂O from straw), was estimated at 1,465 kg CO₂ eq ha⁻¹, resulting an emission factor of 212.6 kg CO₂ eq ton⁻¹ of straw recovered. Applying the parameters cited in this study for electricity or 2G ethanol production (GHG balance of emission and offset potential), our results showed that straw-based for electricity production would result in additional GHG emissions of (+) 860 kg CO₂ eq ha⁻¹. In contrast, applying the same study parameters for 2G ethanol production replacing gasoline, an avoided GHG emission of (-) 2,316 kg CO₂ eq ha⁻¹ could be achieved. The route of recovering around 27% of sugarcane straw through bale system for bioelectricity production using technical parameters and industrial efficiency rate of this study could not be a sustainable option because the additional emissions can be higher than its potential to offset generated emissions, based on the emission factor of Brazilian energy matrix. Applying the same experimental parameters, the option of producing ethanol 2G with around 6.89 ton DM ha⁻¹ of sugarcane straw could offset gasoline GHG emissions, contributing with sustainable energy systems.

1. Introduction

Inventorying greenhouse gas (GHG) balance related to sugarcane (*Saccharum officinarum*) based by-products is critical to assess the degree of carbon (C) neutrality of biofuels production [1] and, the advances to better support renewable energy source and the sustainability parameters, including GHG balance of these bioenergy sources should be better investigated to support public policies. The latest effort worldwide comes in the form of Law 13.576/2017 for the fostering of biofuels in Brazil, which creates the National Biofuel Policy, officially known as RenovaBio Program, which will create a controlled market of decarbonization credits (known as CBios). However, the innovation in such mechanisms lies in the fact that the amount of CBios which an entity may emit in the Brazilian stock market will be linked to the reduction in GHG emissions associated with the production of a given biofuel in comparison to its fossil competitor [2], as investigated in this study.

Several acts and standards have been developed in different countries including rigorous requirements for biofuel producers to confirm the environment-friendly characteristics and ability to effectively reduce GHG emissions in comparison to the corresponding fossil fuels [2]. Towards this goal, the National Biofuel Policy, officially known as RenovaBio Program comes in the form of Law 13.576/2017 for the progress of biofuels in Brazil. Bioenergy production could potentially mitigate GHG emissions and climate change by avoiding the combustion of fossil energy, therefore safeguarding energy security. However, there are issues that need to be considered, including the sustainability of practices and the efficiency of bioenergy systems[3]. The increased attention on bioenergy occurs in conjunction with the global interest in transitioning from large scale dependence upon fossil fuels to the use of renewable energy sources to curb

GHG emissions [4]. Research evidence suggests that some already available and well-established options with low lifecycle emissions (*e.g.*, sugarcane, and sustainable use of biomass residues) could reduce GHG emissions, but outcomes are site-specific and rely on efficient integrated 'biomass-to-bioenergy systems'[3].

The impact of sugarcane straw removal on economic, environmental, and agronomic factors are well documented and discussed in terms of sugarcane growth and biomass production, nutrient recycling, soil conservation, soil biological attributes, greenhouse gas emissions, weed control and pest infestation [5–9]. Although the retention of sugarcane straw presents several benefits to the soil, there is potential to withdraw part of the straw from the fields to produce bioelectricity and cellulosic ethanol (second generation–2G). However, further studies are needed to demonstrate the sustainability of this practice and the best options for industrial use of this crop residue.

Regardless of considerable potential for increased energy generation from the use of recovered straw, few studies have investigated the impact of straw removal on soil CO₂-C emissions and additional GHG emissions associated with straw removal and transport operations [6, 10, 11]. In a sugarcane area under 3 years of green mechanized harvesting, [6] showed that around 100% removal of straw from the soil surface led to an additional emission of 927.7 kg of CO₂ ha⁻¹ to the atmosphere over a 25-day measurement period. In terms of the GHG balance, such additional emissions can annul the benefits of banning the pre-harvest burning, which is responsible for an estimated net emission (CH₄ and N₂O) of 941 kg CO₂eq ha⁻¹ [12].

The hypotheses tested in the present study were: (1) The recovery and transport of large amount of sugarcane straw from fields upon mechanized harvesting without burning may result in additional soil CO₂ and other GHG emissions (soil N₂O and emissions from diesel combustion), greater than the potential to offset emissions through the use of straw for bioenergy (bioelectricity or 2G ethanol); (2) Partial removal of sugarcane straw from the soil surface can be a sustainable alternative for its use as bioelectricity source or 2G ethanol production, taking into account their additional GHG emissions and offset potential. This study was designed to assess the additional GHG emissions including measurements of short-term soil CO₂-C emissions as affected by straw removal from the soil in sugarcane areas plus emissions associated with the recovery and transport operations of straw bales up to the factory gate, contrasting with leaving all straw on the soil surface. Specific objective is to contrast the additional emissions of straw recovered-management operations with respective GHG offset potential of straw-based bioenergy production (*i.e.* electricity generation or 2G ethanol), based on Brazilian energy matrix.

2. Materials And Methods

This study was carried out at a commercial sugar, ethanol and energy production plant located in the region of Ribeirão Preto, Sao Paulo, southern Brazil, where the company performs the removal of straw for bioenergy generation. The results of GHG emissions and offset potential for straw recovery were presented in terms of carbon dioxide equivalents (CO₂eq) according to the global warming potentials of 1, 28 and

265 for carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O)[13]. In addition, molar ratio of 1 C=44/12 CO₂eq was used to convert C mass in CO₂eq.

2.1. Short-term measurements of soil CO₂-C emissions, soil water content and soil temperature

The field experiment for measuring soil CO₂-C emissions was in Serrana, Sao Paulo State, Brazil (21°06' S – 47°37' W, 623 m of altitude). According to the data provided by the agricultural and industrial facility, the sugarcane variety in the experimental area was IACSP 95-5000, planted at 1.5 m inter-row spacing, and with a first cutting stalk yield of 143 tons ha⁻¹. The field experiment started on August 03, 2016, immediately after the straw removal, in which all operations were carried out within 20 days of mechanized harvest without burning, following the standard procedure of the company. The regional climate is classified as B₂rB'4a' by Thornthwaite system [14], indicating a mesothermal region with rainy summers and dry winters. The soil is classified as a Eutroferric Red Latosol (Haplustox, USDA Soil Taxonomy).

Short-term soil CO₂-C emissions, soil water content (SWC) and soil temperature (12 cm depth) were monitored starting 24 h after straw removal (August 4th 2016) in different treatment plots where PVC collars were previously inserted into soil (15 replicates per treatment). Measurements were taken 17 days over a 21-day period after straw removal in the morning between 8:00 to 11:00 AM on each sampling day. Soil CO₂-C emissions were measured using a portable LI-COR (LI-8100, NE, USA) system which monitors the changes in CO₂ concentration inside the chamber by an infrared gas analyzer. The floor chamber has an internal volume of 854.2 cm³ with a circular area of 83.7 cm². The soil temperature was monitored with a 20 cm probe (thermistor-based sensor) inserted into the soil near the PVC collars at a depth of 12 cm. This measuring sensor is an integral part of the LI-8100 system. Soil water content (%) was measured (12 cm depth) with a portable time domain reflectometer system (HydroSense System, Campbell Scientific, Utah, USA). During the measurement period, rainfall events occurred on August 10th (02 mm), 15th (10mm), 16th (10 mm), 18th (08 mm), 19th (10 mm), 20th (15 mm) and 23rd (11 mm).

2.1.1. Field treatments for measuring soil CO₂-C emissions

The experiment for measuring soil CO₂-C emissions comprised of three treatments replicated three times. The treatments consisted of a control (T1), which are areas of 12 × 20 m plots (~240 m²) where all straw was left on the soil surface after sugarcane harvest without any straw recovery, and two field conditions (T2 and T3 explained below), according to the soil cover observed after the straw management and recovery operation in a commercial sugarcane plantation (Fig. 1).

In areas where straw is managed for recovery, straw from 6 crop rows (5 inter-row areas) are collected with each passing of a tractor and heaped in between two crop rows (one inter-row area) to be removed later by baling. After straw was baled and removed, there are still more straw left on the soil surface of the inter-row area where straw was heaped prior to baling than in the control area. This inter-row area where straw was

accumulated was defined as T2 (line plots of 1.5×20 m or 30 m^2). The area of 6 crop rows from which straw was collected has less straw on the soil surface than in the control area, and this area was defined as T3. Overall, in a field where straw was managed and recovered, T2 area occupies approximately 17% of the field area and T3 area occupies about 83% of the field area. Therefore, to calculate the $\text{CO}_2\text{-C}$ emissions from 1 ha field in response to straw management and recovery, a weighted average emissions per ha was calculated using measured emissions from T2 and T3 area according to the Equation 1:

$$WAF\text{CO}_2 = 0.83FC\text{CO}_2T3 + 0.17FC\text{CO}_2T2 \quad (1)$$

Where, $WAF\text{CO}_2$: weighted average CO_2 flux; $FC\text{CO}_2T3$: CO_2 flux from T3 area; and $FC\text{CO}_2T2$: CO_2 flux from T2 area. In each treatment (3 replicates), 15 PVC collars were used for measurements of soil $\text{CO}_2\text{-C}$ emissions. In general, straw management and recovery operation resulted in a removal of 27% of sugarcane straw for bioenergy generation (explained below).

2.1.2. Statistical analysis

Data related to $\text{CO}_2\text{-C}$ emissions, soil temperature and soil water content (SWC) were analyzed using a completely randomized experimental design with three treatments and three replicates per treatment (defined in section 2.1.1) and repeated measurements in time. For the analyzes, the mixed-model procedure of SAS statistical software was used [SAS Institute Inc., Cary, North Caroline]. When statistically significant ($P < 0.05$), the means were compared by the Tukey's test at a significance level of 5%. The variables ($\text{CO}_2\text{-C}$, soil temperature and soil water content) were also analyzed by linear correlation, testing if correlation coefficient is statistically different from zero ($P < 0.05$).

2.2. Soil analysis, quantification of post-harvest straw and estimated N_2O emissions

Soil samples were collected to a 0.20-m depth after measurements of soil $\text{CO}_2\text{-C}$ emissions. To obtain 1 kg of soil, 12 single samples were collected from the experimental area, and soil physical-chemical characteristics such as pH, soil organic matter (SOM) and soil texture were analyzed (Table 1). The samples were dried and sieved through a 2 mm mesh prior to analysis. These analyzes include determination of SOM content by oxidation with sulphuric acid [15].

Table 1
Soil chemical and physical characterization of the experimental area (0-20 cm depth).

pH	SOM	P	Ca	Mg	K	CEC	BS	Clay	Silt	Sand
	g dm ⁻³	mg dm ⁻³	mmol _c dm ⁻³				%	g kg ⁻¹		
7	31	10	31	10	6.4	83	58	52	18	30
N = 10; 0–20 cm depth. Clay, Silt and Sand.										
pH, hydrogenic potential (CaCl ₂); SOM, Soil organic matter; P, available phosphorus; Ca, calcium; Mg, magnesium; K, potassium; CEC, Cation exchange capacity; BS, Base saturation.										

The amount of straw deposited on the soil surface after sugarcane green mechanized harvesting, as well as straw management and recovery operation were determined by collecting samples using a metallic frame of 0.64 m² (0.8 × 0.8 m) in each of the three treatments (n=5). The samples were oven dried for 24 hs at 105°C until reaching constant weight and then weighed [16] which resulted in: 25,819 kg DM ha⁻¹ for T1; 44,303 kg DM ha⁻¹ for T2 and 18,927 kg DM ha⁻¹ for T3. The average amount of straw removed from fields after straw management and recovery operation was calculated as the difference of straw mulch dry matter left on soil surface between T1 and T3 (T3-T1) which resulted in 6,89 kg DM ha⁻¹ (or 27% of the total straw in the control area).

Crop residues such as sugarcane straw when returned to the soil after harvest are considered as a direct source of N₂O from agricultural soils, and an average N₂O-N emission factor of 1% for N returned to soil from crop residues is recommended for estimating the direct N₂O emissions from crop residue decomposition [17].

Amount of total N returned to soil from sugarcane crop residues was estimated applying green tops and dry leaves content of 65% and 35%, respectively of the total N present in sugarcane crop residues [18, 19], which translate to an average rate of 7.5 and 3.4 g N kg⁻¹ of dry matter, respectively. Applying a rate of 20% of straw N content available for N₂O emission each year, we estimate an average amount of 31.3 kg N year⁻¹ in T1 when leaving all straw in the field without management (25,819 kg DM ha⁻¹), and an average amount of 23.0 kg N year⁻¹ in T3 (18,927 kg DM ha⁻¹), after recovering 6,89 kg DM ha⁻¹. To evaluate the impact of N₂O emissions from removing 6,89 kg DM of straw we need to compare the potential N₂O emissions from T1 with T3.

In order to derive an N₂O-N emission factor for crop residue removal, carried out field experiments were carried out in commercial sugarcane areas in clay soils (64% clay content) [20][27], similar to the experimental site of this study (52% clay; Table 1) and, reported cumulative N₂O-N emissions of 1.45 kg N₂O-N ha⁻¹ associated with the maintenance of 15 ton DM of straw ha⁻¹ and without N fertilizer application over a 270-days period. Furthermore, the authors showed that N₂O-N emissions decreased to 0.91 kg N₂O-N ha⁻¹ for the management and recovery of total amount of straw from the soil surface without N fertilizer. Considering the similarity with soils and climate conditions of this study, we applied the

same accumulated N₂O-N emissions [20] to be compared with the results derived using the IPCC methodology [17]. Evaluating GHG emissions in response to sugarcane straw removal, authors observed no net CH₄ emissions [21], and thus, CH₄ emissions were not considered in our study.

2.3. Estimation of greenhouse gas emissions from fossil fuel used in the recovery and transport of straw

In addition to industrial plant, further investments on tractors, trucks and other heavy machines are required in the management and recovery of sugarcane straw after green mechanized harvest. For this experiment, the data collected and analysed were: Truck carry capacity of approximately 70 bales per trip; bales weighing on average of 350 kg bale⁻¹ and 24,500 kg of straw transported per trip, with a straw moisture content of around 6 to 10%.

The technical parameters for mechanized operations considered in the straw management and recovery operation and the transport of straw until the biorefinery gate are presented in Table 2. The fossil fuel typically used for sugarcane production systems is diesel oil, consumed mostly during the agricultural operations by machinery, tractors, and trucks [12]. In our study, the diesel consumption related to the final use of sugarcane straw was measured according to all field operations performed (Table 2.).

Table 2

Technical parameters of diesel consumption in mechanized operations for the amount of sugarcane straw recovered of 6.89 tons ha⁻¹ (dry matter-basis).

Operation	Equipment	Horse Power (HP)	Consumption (L diesel ha ⁻¹)	Operation income (ha h ⁻¹)	L diesel ton ⁻¹ of straw
(1) Straw heaping	Tractor	110	7.00	8.2	0.9
(2) Baling	Tractor	210	20.00	5.5	3.0
(3) Bales picking	Tractor	210	13.7	5.4	3.0
(4) Bales loading	Tractor	130	4.5	8.0	2.1
* (5) Bales transport	Truck	-	1.4 km L ⁻¹	-	0.466 (0.233 x 2)
(6) Bales unloading	Loader	130	4.3 (L h ⁻¹)	-	0.122
(7) Crusher feeding	Loader	130	3.1 (L h ⁻¹)	-	0.257
Total (L diesel ton ⁻¹ straw)					9.895
Total (L diesel ha ⁻¹)					68.2
*Truck carry capacity is approximately 70 bales per trip. Bales weight = average 350 kg = 24,500 kg per trip.					
** Distance of the experimental area until the industrial straw processing = 8 km = 16 km round trip.					
Diesel consumption of each operation was informed by the company industrial sector.					

Estimates of GHG emissions related to the use of fossil fuel for straw recovery in this study assumed CO₂, CH₄ and N₂O gases [22]. The emission factors applied were those suggested by Air Pollution Control Program for Auto Engines)/CETESB-Brazil [23], in association with IBAMA (Brazilian Institute of the Environment), considering the types of fuel and vehicles. To calculate these emission factors, vehicles were considered as off-road and machinery, with 74,100 kg CO₂ TJ⁻¹ (TJ = Terajoule), 4.15 kg CH₄ TJ⁻¹ and 28.6 kg N₂O TJ⁻¹, respectively [24]. The GHG emissions related to diesel extraction and distribution were considered as 3.87g C MJ⁻¹ per liter of fuel [25].

2.4. Quantification of energy and cellulosic ethanol (2G) production from straw recovered

The use of sugarcane bagasse as a fuel for combined heat and power (CHP) systems to meet energy needs of the mills for bioenergy generation is a common practice in Brazilian sugarcane industry [26]. In

this study, we present an additional energy generation potential of sugarcane straw recovered after green mechanized harvesting as per the technology used by the company. According to the information from the company's industrial sector, the straw used for energy generation is added to the sugarcane bagasse at a proportion of 5 to 7% of the volume, presenting a potential value for electricity generation of approximately 0.6 MWh ton⁻¹ DM, with humidity between 6 and 10% and the technology being used is high pressure boiler/condensation and steam extraction turbine.

Analysing the use of sugarcane straw for power generation, some authors reported a higher heating value of cane straw of 17.1 MJ kg⁻¹ (DM) and lower heating value of 12.15 MJ kg⁻¹, without considering of the losses through the process [27]. With respect to industrial productivity, the premise to produce 240 L ethanol ton⁻¹ LM (lignocellulosic material on dry basis) in the short-term was reasonably conservative by companies[28]. For some companies, it is already feasible to reach 300 L ethanol ton⁻¹ LM, or even 350 L ethanol ton⁻¹ LM in the long-term. On the other hand, electric power demand for 2G process is depicted as 48 kWh ton⁻¹ LM over a short, medium, and long-term basis. However, the energy demand for 2G ethanol production from the straw can be supplied by the residual material (residual cellulignin) from the 2G process, and thus there is no need to burn additional straw to supply this energy demand [28].

Based on data from parameters for vehicle emissions in Brazil, an emission factor (EF) of 1.750 kg CO₂eq L⁻¹ of hydrated ethanol should be applied for a vehicle year 2010, flex (ethanol or gasoline), using ethanol, with efficiency of 8.2 km L⁻¹, considering emissions of CO₂ (207 g km⁻¹), CH₄ (0.053 g km⁻¹) and N₂O (0.017 g km⁻¹) [23]. The CO₂ emitted through the combustion of ethanol in the vehicle motor is reabsorbed by the sugarcane plants, rendering the balance practically zero [29] and, consequently should not be accounted for in the CO₂ balance. To estimate the avoided GHG emissions when using renewable 2G ethanol from straw replacing gasoline, we considered the use of light vehicle, with efficiency of 10.8 km L⁻¹ of gasoline [23] with EF of 2.312 kg CO₂eq L⁻¹ (207 g CO₂ km⁻¹, 0.009 g CH₄ km⁻¹ and 0.023 g N₂O km⁻¹). Therefore, when replacing 1 liter of fossil gasoline per 1 liter of hydrated ethanol, an avoided emission of 2.26 kg CO₂eq considering only CH₄ and N₂O emission from ethanol was assumed in this study when considering 2G ethanol production from sugarcane straw.

2.5. CO₂ emission factors for electric energy production in Brazil

The CO₂ emission factors of electric energy production used in life-cycle inventories in Brazil estimate the amount of CO₂ associated with the generation of a particular type or source of electric energy. These emission factors are calculated by the average of emissions sources, considering of all the plants that are generating energy, and not only those that are working at the moment [30], presenting emission factors in terms of ton CO₂eq MWh⁻¹.

The CO₂ emission factors calculated according to the methodological approach “Tool to calculate the emission factor for an electricity system, version 04.0 and earlier” approved by the Clean Development

Mechanism (CDM), Executive Board are intended to estimate the contribution, in terms of CO₂ emission reductions, from a project that generates electricity for the grid [30]. Briefly, the interconnected system CDM emission factor is a combination of the operating margin emission factor, which reflects the intensity of CO₂ emissions of the energy dispatched at the margin, with the build margin emission factor that reflects the intensity of CO₂ emissions from the last plants built [30].

The emission factors (ton CO₂ MWh⁻¹) for electricity generation in Brazil presented annual average values of 0.0740; 0.0927; 0.0817; 0.1244; 0.1355; 0.0960; 0.0653 and 0.0292 for the years 2018, 2017, 2016, 2015, 2014, 2013, 2012 and 2011, respectively [30]. However, in this study, the offset potential for straw recovered displacing energy produced by Brazilian energy matrix was calculated based on the EF of 0.1370 ton CO₂ MWh⁻¹, accounting emissions from plants built and energy generation at the margin [30].

3. Results And Discussion

3.1. Short-term soil CO₂-C emissions, soil water content and soil temperature

Figure 2a presents the temporal soil CO₂-C emissions comparing the management of recovering part of straw (T3; leaving 18.9 ton DM ha⁻¹), with the management of keeping all straw on the soil surface without removal (T1; leaving 25.8 ton DM ha⁻¹), resulting in a straw removal rate of 6.89 ton DM ha⁻¹. Significant difference ($P < 0.05$) among the treatments was observed only on day 20, showing that agricultural operations to recover around 27% of straw may not significantly impact the temporal soil CO₂-C emissions during the experiment measurements.

Highest temporal emissions were observed in T2, except for day 20 ($P < 0.05$). This could be explained by the straw management and accumulation of large amount of straw between two crop lines (inter-row), which could promote higher soil aeration, higher O₂ availability for microorganism's activity and higher C accessibility (straw carbon) to be decomposed through mineralization process. In contrast, keeping sugarcane straw on the soil surface without management led to a lower soil CO₂-C emission [6], probably due to higher soil bulk density and lower soil aeration [31], showing that in a condition where soil and straw were managed, the mineralization of SOM (soil organic matter) increased significantly with higher aeration, thus supporting the findings observed in T2.

The impacts of straw management on soil temperature can be observed in Figure 2b, when comparing T1 (straw maintained), with T3 (27% of straw recovery). There was significant difference between these two treatments only on days 07 and 09 ($P < 0.05$), in which soil temperature was higher in T3, showing that recovering 27% of straw had a slight impact on soil temperature.

The higher amount of straw accumulated in T2 (44.3 tons DM ha⁻¹) could explain this higher soil water content (SWC), with straw mulching contributing to soil protection against evaporation. Moreover, when

comparing the management of removing 27% of straw (T3) with the management of keeping all straw on the soil surface (T1), during the dry period, there was no significant difference for soil water content ($P > 0.05$), showing that higher amount of straw could keep higher available soil water content.

In terms of accumulated short-term soil $\text{CO}_2\text{-C}$ emissions (Fig. 2d), lower emissions were observed in T1 with 788 kg $\text{CO}_2\text{-C}$ or 2,889 kg $\text{CO}_2\text{ ha}^{-1}$. However, comparison of the accumulated soil $\text{CO}_2\text{-C}$ emissions in the management of recovering 27% of straw (WAF CO_2 , 963 kg $\text{CO}_2\text{-C}$ or 3,531 kg $\text{CO}_2\text{ ha}^{-1}$) with the management of keeping all straw on the soil surface (T1), did not indicate significant difference between the two managements, showing that recovering 27% of straw in the experiment conditions did not impact the accumulated short-term soil $\text{CO}_2\text{-C}$ emissions. Therefore, the impact of straw removal (27% or 6.89 ton DM ha^{-1}) on accumulated soil $\text{CO}_2\text{-C}$ emission over 21 days (WAF CO_2) was 175.5 kg $\text{CO}_2\text{-C ha}^{-1}$ or 643.5 kg $\text{CO}_2\text{ ha}^{-1}$, which is equivalent to 25.5 kg $\text{CO}_2\text{-C ton}^{-1}$ or 93.4 kg $\text{CO}_2\text{ ton}^{-1}$ of straw (Fig. 3). It is important to note that the additional short-term soil $\text{CO}_2\text{-C}$ emissions in sugarcane areas may be higher soon after straw management, and then these emissions tend to stabilize to similar levels compared with emissions from areas with no straw management, as observed for T1 and T3 at the end of the experimental period. Exploring the GHG responses to sugarcane straw removal, a rate of 6 ton DM of straw ha^{-1} resulted in a total $\text{CO}_2\text{-C}$ emissions of 82.2 g m^{-2} or 3,014 kg $\text{CO}_2\text{ ha}^{-1}$ in a period of 180 days [21]. In a scenario with straw removal and possible SOC losses, we need to consider no-tillage operations during sugarcane crop renovation, mainly if it is combined with other best management practices, such as reduced tillage accompanied with vinasse and filter cake application, which could replace the SOC losses after residue removal [6, 32, 33].

3.2. Emissions from fossil fuel used to recover and transport of straw

Specific management options practiced by sugarcane mills for straw recovery systems certainly have distinct impact on the economic and technical parameters. Taking into account of all additional mechanized field operations for straw recovery and their respective machinery use and diesel consumption (Table 2), the total amount of diesel consumed to recover 1 ton of straw under the experimental parameters was 9.9 L ton^{-1} of straw or 68.2 L of diesel ha^{-1} (6.89 ton ha^{-1} , dry matter-basis), resulting in an emissions of 31.6 kg $\text{CO}_2\text{eq ton}^{-1}$ of straw or 217.1 kg $\text{CO}_2\text{eq ha}^{-1}$ (Fig. 3). These emissions from mechanized operations to recover straw is considered as additional emissions compared with the management of leaving all straw in the field and should be included in assessing the GHG mitigation potential of straw for bioenergy generation.

3.3. Estimation of N_2O emissions derived from post-harvest sugarcane straw

Applying default methodology for N_2O emissions [17] and straw amount measured in the experiment, leaving all straw on the soil surface without management (T1) led to an estimated N_2O emissions of 159.7

kg CO₂eq ha⁻¹. On the other hand, recovering 6.89 tons DM of straw ha⁻¹, resulted in an estimated N₂O emissions of 117.3 kg CO₂eq ha⁻¹. Thus, comparing the practice of leaving all straw on the soil surface against the practice of recovering 27% of straw (6.89 ton DM ha⁻¹), the estimations showed an avoided emission of 42.4 kg CO₂eq ha⁻¹ (N₂O-N, Fig. 3).

Contrasting the results estimated here by other methodology [17], some authors reported higher accumulated N₂O emissions from sugarcane straw left on soil (15 ton DM ha⁻¹), with 2.28 kg N₂O ha⁻¹ or 604.2 kg CO₂eq ha⁻¹ over 270 days-period [20], which was used in our GHG balance for the potential of straw for bioelectricity or 2G ethanol production (Fig. 3). Besides that, the same authors showed that N₂O emissions were reduced to 1.43 kg N₂O ha⁻¹ or 379 kg CO₂eq ha⁻¹ (-37%) upon removal of all straw from the soil surface. Lower N₂O emissions induced by straw removal were also reported by several other studies conducted in Brazil [21, 34, 35].

Compared with the management to recover sugarcane straw from the soil surface for multiple uses, leaving sugarcane straw on the soil surface can lead to higher N₂O emissions, which would strongly influence the extent to which biofuels derived from straw decrease their GHG emissions relative to fossil fuels [36, 37]. Additionally, irrespective of N fertilizer application, the retention of sugarcane crop residue increases N₂O emissions [20], being a catalyst for increased soil microbial activity soil N₂O flux [38].

3.4. Potential for straw-based bioenergy and GHG balance of energy or cellulosic ethanol production

With 6.89 ton of straw DM ha⁻¹ recovered, it is possible to generate 4.1 MWh ha⁻¹ electricity, which means that for each ton of recovered sugarcane straw, considering the emission factor from new projects and energy generation intensity [23] from Brazilian energy matrix (Base year 2018, 0.1370 ton CO₂ MWh⁻¹), it is likely to have an avoided GHG emissions of 81.5 kg CO₂eq ton⁻¹ DM or 562 kg CO₂eq ha⁻¹ (Fig. 3). By using the lower heating value (12.15 MJ kg⁻¹ DM) for sugarcane straw [27], the surplus energy associated with 6,89 ton DM ha⁻¹ of straw could encompass a technical potential of 83,737.8 MJ ha⁻¹ or 23.26 MWh ha⁻¹ (1 MJ = 0.000277778 KWh), equivalent to an avoided GHG emissions (based on Brazilian matrix) of 3,186.6 kg CO₂ ha⁻¹. Therefore, the efficiency rate of energy transformation (*i.e.*, industrial process) of sugarcane straw under our experimental conditions is still lower (~18%) and, should be improved for a better sustainability of the process.

The RenovaBio Program presents itself as a promising and innovative policy in many aspects (biofuels demand planning and boosting energy security in Brazil), which every single biorefinery in the country will pursue the production of biofuels with an ever-higher environmental responsibility [2]. The characteristics of each country's energy matrix, based on fossil fuels or in renewable sources, as found in Brazil [30] will determine the potential for each country to develop and use straw-based bioenergy sources to reach a low-carbon energy matrix.

The 2G ethanol produced from lignocellulosic biomass (LM) has been considered as the biofuel with the greatest potential to replace fossil fuels [39, 40]. Based on our experimental results, with the production potential of 240 L 2G ethanol ton^{-1} LM [26], it would be possible to produce an additional of 1,654 L of ethanol ha^{-1} (6.89 ton DM straw ha^{-1}), which could promote an avoided GHG emissions of 2.26 kg CO_2eq L^{-1} of 2G ethanol by replacing 1 liter of gasoline or 3,738 kg CO_2eq ha^{-1} considering only CH_4 and N_2O emissions from 2G ethanol combustion (Fig. 3).

Taking into account of all mechanized operations to recover around 27% of sugarcane straw, the total additional GHG emissions, considering the main emission sources (*i.e.*, additional soil $\text{CO}_2\text{-C}$, diesel use and N_2O from straw), contrasting with leaving all straw on the soil surface was estimated at 1,465 kg CO_2eq ha^{-1} (6.89 ton DM ha^{-1}), resulting an emission factor of 212. 6 kg CO_2eq ton^{-1} of straw recovered. With an avoided N_2O emissions of 42 kg CO_2eq ha^{-1} , compared with higher N_2O emissions with leaving all straw on soil, 27% of sugarcane straw removal would therefore result in a total additional emissions of 1,422 kg CO_2eq ha^{-1} (Fig. 3).

Applying the parameters cited in this study for electricity or 2G ethanol production, our results for their respective GHG balance (emissions and offset potential) showed that, straw-based electricity would result in an additional GHG emissions of (+) 860 kg CO_2eq ha^{-1} (Fig. 3), which could not be a sustainable route for bioenergy production. In contrast, applying the same parameters for 2G ethanol production replacing gasoline, an avoided GHG emission of (-) 2,316 kg CO_2eq ha^{-1} could be achieved, showing that the route of 2G ethanol production could be the best strategy to use sugarcane straw as a by-product to reduce GHG emissions from the agricultural sector, offsetting emissions from fossil fuel and contributing to mitigate global climate change using a renewable bioenergy source.

The results from this research can support deriving environmental indicators to assess the sustainability of 2G ethanol by regulatory and certifying bodies, such as the CARB (California Air Resources Board) and the most recent State Program “RenovaBio”, whose objective is to stimulate the efficiency of the biofuels industry, in the agricultural and industrial sectors, with an emphasis on total energy demand and the mitigation of GHG emissions (lower C intensity) associated with each stage of the life cycle of bioenergy production.

4. Conclusions

Bioelectricity and cellulosic ethanol production using sugarcane straw recovered may not be a sustainable management strategy to mitigate GHG emissions when considering the associated impacts on sugarcane-cultivated soils and related additional emissions from soil and straw recovering operations. The main additional GHG sources from straw management and agricultural processes include soil $\text{CO}_2\text{-C}$ emissions, soil N_2O emissions and emissions from mechanized field operations (diesel use), which should be accounted for deployment of new sugarcane bioenergy projects using straw as a raw material.

The route of recovering around 27% of sugarcane straw from the soil surface through bale system for bioelectricity production using technical parameters and industrial efficiency rate of this study, could not be a sustainable option because the additional GHG emissions from these processes can be higher than its potential to offset generated emissions, based on the emission factor of Brazilian energy matrix. On the other hand, using the same parameters for straw recovery at the first cutting cycle in a clay soil, the option of producing ethanol 2G with around 27% of the total sugarcane straw recovered (6.89 ton dry matter ha⁻¹), could offset greenhouse gas emissions once replacing fossil gasoline, which can be an option to contribute for a better sustainability of sugarcane straw recovery, supporting renewable and sustainable bioenergy systems, and for reducing the impact of Global Climate Change.

Declarations

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Authors 'contributions

We attest that all authors contributed significantly to the creation of this manuscript, each having fulfilled criteria as established by the journal.

Ethics approval and consent to participate

Written consent to publish potentially identifying information, such as details or the case and photographs, was obtained from the patient(s) or their legal guardian(s).

Consent for publication

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

Competing interests

All authors declare there is no conflict of interest exists.

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Figures

Figure 1

Schematic figure showing T1 area, with 100% of straw maintained on the soil surface; T2, line plots where straw was heaped for subsequent baling (i.e., 17% of 01 hectare) and T3 area where straw was recovered from six lines per each passing of a tractor (i.e., 83% of 01 hectare).

Figure 2

(a, b, c and d). a) Soil CO₂-C emissions ($\mu\text{mol m}^{-2} \text{h}^{-1}$); b) soil temperature ($^{\circ}\text{C}$); c) soil water content (%) plus standard errors (vertical bars) and d) Accumulated soil CO₂-C emission (plus standard error, $\text{kg CO}_2\text{-C ha}^{-1}$) for T1: Control area, with straw maintained on the soil surface; T2: Line plots where straw was recovered and accumulated in one line and later collected for baling (17% of harvest area); T3: Areas where the normal mechanized straw harvesting operations were performed (83% of harvested area); WAFCO₂: Weighted average of soil FCO₂ (weighted average of emission in T2 and the T3). Means followed by the same letters comparing straw management types did not differ by the Tukey test ($P < 0.05$).

Figure 3

Additional GHG emissions (red bars), offset potential (green bars) and GHG balance (Blue bar), from sugarcane straw management and recovery operations that would be used for bioelectricity or ethanol 2G production (All values in kg CO₂eq ha⁻¹ for a straw recovering rate of 6.89 ton DM ha⁻¹).