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Greenhouse gas emissions and offset potential from sugarcane straw for bioenergy production in Brazil

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Abstract

This study aims to assess the additional Greenhouse gas (GHG) emissions affected by straw removal from the soil surface in sugarcane areas, including measurement of short-term soil CO_2-C emissions plus emissions associated with the recovery and transport operations of straw bales until to the industry gate (diesel emissions) and estimated soil N_2O emission, comparing with leaving all straw on the soil surface. Taking into account the main sources evaluated (soil CO_2, diesel and N_2O from straw), the total additional GHG emissions from the recovery of 6.9 Mg Dry Matter ha^{-1} (27%) was estimated at 1423 kg CO_2eq ha^{-1}, resulting in a carbon footprint of 206.2 kg CO_2eq per megagram (Mg) of straw recovered. Applying the parameters cited in this study for electricity generation (GHG emission and offset potential), our results showed an additional GHG emission of (+) 860 kg CO_2eq ha^{-1}. Applying the same parameters for second generation (2G) ethanol production replacing gasoline, an avoided GHG emission of (-) 2316 kg CO_2eq ha^{-1} could be achieved. The route of recovering 27% of sugarcane straw from the soil surface through bale system for bioelectricity production using the technical parameters and industrial efficiency rate of this case study resulted in a C footprint of 347 kg CO_2eq MWh^{-1}. Improving the efficiency rate for straw conversion in bioelectricity based on its lower heating value could reduce its C footprint to 62.26 kg CO_2eq MWh^{-1} produced. For sugarcane straw recovery at the first cutting cycle in clay soil, the option of producing ethanol 2G could offset GHG emissions once replacing fossil gasoline, resulting in a C footprint of 0.86 kg CO_2eq L^{-1} of 2G ethanol in the agricultural phase, an option to contribute to better sustainability of sugarcane straw recovery, supporting renewable and sustainable bioenergy systems, and reducing the impacts of Global Climate Change.

Keywords: Biomass, renewable energy, soil management, harvest systems, climate change

INTRODUCTION

Sugarcane (*Saccharum* spp.) is considered one of the main alternatives for replacing fossil fuels in the biofuel sector due to its great potential in the production of ethanol and its by-products. The sugarcane production in the 2021/22 harvest season in Brazil reached 585.2 million tons with a harvested area of 8317 thousand hectares, a reduction of 299 thousand hectares compared to the 2020/21 due to adverse climatic effects of the drought during the productive cycle[1]. In the global ethanol industry, sugarcane is one of the main crops with an abundant production of crop residue commonly denominated as "sugarcane straw"[2], which can be an option to be recovered to produce additional renewable energy or second-generation ethanol, depending on the management system adopted.

Bioenergy production could potentially mitigate greenhouse gas (GHG) emissions and climate change by avoiding the combustion of fossil energy, therefore safeguarding energy security. However, there are issues to be considered, such as the identification of crop and straw management systems with lower GHG emissions, including the sustainability of practices and the efficiency of bioenergy systems[3-6]. 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[7]. Evidence suggests that bioenergy options with low lifecycle emissions can reduce GHG emissions; however, outcomes are site-specific and rely on efficient integrated "biomass-to-bioenergy systems", and sustainable land use management and governance[3-5,7].

Several acts and standards have been developed in different countries to impose stringent requirements on biofuel producers to confirm the environment-friendly characteristics of their products and their ability to effectively reduce GHG emissions in comparison with corresponding fossil fuels[8]. Towards this goal, the National Biofuel Policy, officially known as RenovaBio Program, was established under Law 13.576/2017 in Brazil. This program provides a framework to certify biofuel production and allows biofuel producers to earn decarbonization certificates (CBIOs) for proven and independently verified reductions in GHG emissions from the production and use of biofuels (1 CBIO = 1 tonne of avoided CO_2eq emissions)[9]. The decarbonization certificates are an important mechanism to price and stimulate management practices that reduce GHG emissions[9] and should be supported by research results. However, the effectiveness of such mechanisms rests on the fact that the amount of CBios will be linked to the reduction in GHG emissions associated with the production of a given biofuel in comparison to its fossil competitor[8], as investigated in this study.

Inventorying GHG balance of sugarcane-based by-products is critical to assess the degree of carbon (C) neutrality of biofuels production[9,10], and the advances to better support renewable energy sources and sustainability parameters, including the GHG balance of the bioenergy sources, should be better investigated to support public policies in Brazil and worldwide.

The impact of sugarcane straw removal on economic[11], environmental and agronomic factors[4,12] are well documented and discussed in terms of sugarcane growth and biomass production[4], nutrient recycling, soil conservation, soil biological attributes, greenhouse gas emissions[5,10,13], weed control and pest infestation[4,11,14,15]. Nevertheless, 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 different practices and the best options for industrial use of this crop residue and their GHG balance.

Regardless of the considerable potential for increased energy generation from the use of recovered straw, few studies worldwide have investigated the impact of sugarcane straw removal on soil CO_2-C emissions and additional GHG emissions associated with straw removal and transport operations[13,16,17]. In a sugarcane area after 3 years of green mechanized harvesting adoption, de Figueiredo *et al.* demonstrated that 100% of straw removal from the soil surface compared with no removal management led to an additional emission of 927.7 kg of CO_2 ha^{-1} to the atmosphere over a 25-day measurement period[13]. In terms of the GHG balance, emissions from straw management or recovery in sugarcane areas can lead to additional soil CO_2 emission and annul the benefits of banning the pre-harvest burning, which is responsible for an estimated net emission (CH_4 and N_2O) of 941 kg CO_2eq ha^{-1}[18]. It is important to highlight that results for measurements of additional short-term soil CO_2-C emission from different managements can support better cause-effect comprehension related to further impact on soil C accumulation.

This study aims to assess the additional GHG emissions affected by straw removal from the soil surface in sugarcane areas, including measurement of short-term soil CO_2-C emissions plus emissions associated with the recovery and transport operations of straw bales to the factory gate (diesel emissions) and estimated soil N_2O emission, in contrast to leaving all the straw on the soil surface.

The specific objective is to quantify the additional GHG emissions associated with straw recovery, assess the potential of straw for bioenergy production (electricity generation or 2G ethanol), and compare these total emissions with the possible avoided emissions if a producer uses electricity from the National energy grid (in the absence of all practice to recover and produce bioenergy-leaving all straw on the soil surface), based on GHG emission factors (Mg CO_2eq MWh year^{-1}) for the Brazilian energy matrix.

The hypotheses tested in the present study were: (1) The recovery and transport of large amounts of sugarcane straw from the field after mechanized harvesting without burning may result in enhanced soil CO_2 and other GHG emissions (soil N_2O and emissions from diesel combustion), greater than the potential to offset emissions through the use of straw for bioenergy (bioelectricity or 2G ethanol); and (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.

MATERIALS AND METHODS

This study was conducted 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 field experiment for measuring soil CO_2-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 Mg ha^{-1}. The field experiment started on 3 August 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 $B_2rB'4a'$ by Thornthwaite system[19], indicating a mesothermal region with rainy summers (B_2, wet climate), with or without hydric deficiency (r), mesothermic (B′4, potential evapotranspiration < 1140 and ≥ 997) and thermal climate subtypes (a′). The soil is classified as a Eutroferric Red Latosol (Haplustox, USDA Soil Taxonomy).

Field treatments for measuring soil CO_2-C emissions, soil water content and soil temperature

The experiment for measuring soil CO_2-C emissions comprised of three treatments replicated three times (03 treatments × 03 times) in a commercial sugarcane plantation. The treatments consisted of a control (T1), which are areas of 12 m × 20 m plots (~240 m^2) where all straw was left on the soil surface after sugarcane harvest without any straw management, and two field conditions (T2 and T3 explained below), according to the soil cover observed after the straw management (straw heaping and bailing) and recovery operation (bale picking and transport) [Figure 1].

In areas where straw is managed for recovery, straw from 6 crop rows (5 inter-row areas) was collected with each pass of a tractor and heaped between two crop rows (one inter-row area) to be removed later by baling [Figure 1]. After straw was baled and removed, there is 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 m × 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 [Figure 1]. 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 [Figure 1].

Short-term soil CO_2-C emissions, soil water content (SWC) and soil temperature (12 cm depth) were monitored, starting 24 h after straw removal (4 August 2016) in different treatment plots where PVC collars were previously inserted into soil (15 replicates per treatment). Measurements were taken for 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 CO_2-C emissions were measured using a portable LI-COR (LI-8100, NE, USA) system, which monitors the changes in CO_2 concentration inside the chamber by an infrared gas analyzer. The floor chamber has an internal volume of 854.2 cm^3 with a circular area of 83.7 cm^2. 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 10 (02 mm), 15 (10 mm), 16 (10 mm), 18 (08 mm), 19 (10 mm), 20 (15 mm) and 23 (11 mm). Therefore, to calculate the additional soil CO_2-C emissions from 1 ha field in response to straw management and recovery, a weighed average emissions per ha was calculated using measured emissions from T2 and T3 area according to Equation 1:

$$\mathrm{WAFCO_2} = 0.83\mathrm{FCO_2T3} + 0.17\mathrm{FCO_2T2} \quad (1)$$

where, $WAFCO_2$: weighted average CO_2 flux; FCO_2T3: CO_2 flux from T3 area; and FCO_2T2: CO_2 flux from T2 area. In each treatment (3 replicates), the same 15 PVC collars were used for measurements of soil CO_2-C emissions.

The results of GHG emissions and offset potential for straw recovery were presented in terms of carbon dioxide equivalents (CO_2eq) according to the global warming potentials of 1, 28 and 265 for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), respectively[20]. In addition, molar ratio of 1 C = 44/12 CO_2eq was used to convert C mass to CO_2eq. According to the company's information, the

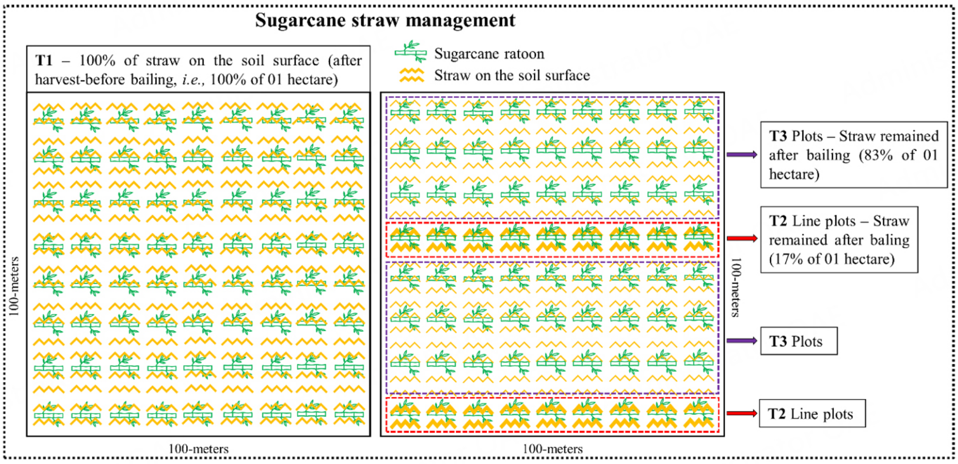

Figure 1. Schematic figure showing T1 area, with 100% of straw maintained on the soil surface; T2, line plots where straw was heaped for subsequent baling (i.e., 17% of 01 hectare) and T3 area where straw was recovered from six lines per each pass of a tractor (i.e., 83% of 01 hectare)

average rate of fertilization per hectare at planting was 32 kg nitrogen (N), 180 kg phosphorus (P_2O_5) and 52 kg potassium (K_2O). After planting, the complementary fertilization rate was 22 kg N ha^{-1} and 60 kg K_2O ha^{-1} with vinasse application at a rate of 300 m^3 ha^{-1}.

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 CO_2-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 after sieving and adjusting the pH to 10-11 with 1 M NaOH; the particle size distribution (sand, silt, and clay) was determined by the pipette method and pH was determined by the pH SMP method measured in water and in the solution of 0.01 mol l^{-1} $CaCl_2$. The samples were oven dried and sieved through a 2 mm mesh prior to analysis. These analyses include the determination of SOM content by oxidation with sulphuric acid[21], presented in Table 1.

The amount of straw deposited on the soil surface after sugarcane green mechanized harvesting, as well as straw management, was determined by collecting samples using a metallic frame of 0.64 m^2 (0.8 m × 0.8 m) in each of the three treatments (5 replications). The samples were oven dried for 24 h at 105 °C until reaching constant weight and then weighed[22], which resulted in: 25.8 Mg Dry Matter (DM) ha^{-1} after oven dried for T1; 44.3 Mg DM ha^{-1} for T2 and 18.9 Mg DM ha^{-1} for T3. The average amount of straw removed from the field after straw management and recovery operation was calculated as the difference of straw mulch dry matter left on the soil surface between T1 and T3 (T3-T1), which resulted in 6.9 Mg 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 N_2O from agricultural soils[23], and an average N_2O-N emission factor of 1% is recommended for N content in any crop residues returned to soil for estimating the direct N_2O emissions attributable to crop residue decomposition, which means that 1% of N from crop residues will be emitted as N_2O[24].

The amount of total N returned to soil from sugarcane crop residues was estimated by applying green tops and dry leaves content of 65% and 35%, respectively of the total N present in sugarcane crop residues[6,25],

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

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; Clay, Silt and Sand: *n* = -number of observations.

which translate to an average rate of 7.5 and 3.4 g N kg^{-1} of dry matter, respectively. We considered that only 20% of sugarcane straw mass was reduced or mineralized during a period of 1 year[26], and applying a rate of 20% of straw N content available for N_2O 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 (25.8 Mg DM ha^{-1}), and an average amount of 23.0 kg N $year^{-1}$ in T3 (18.9 Mg DM ha^{-1}), after recovering 6.9 Mg DM ha^{-1}. The impact of removing 6.9 Mg DM of straw on soil N_2O emissions attributable to crop residue decomposition was derived as the difference in estimated N_2O emissions from T1 and T3.

In order to derive an N_2O-N emission factor for crop residue removal, Gonzaga *et al.* carried out field experiments in commercial sugarcane fields in clay soils (64% clay content) similar to the experimental site of this study (52% clay; Table 1), reporting cumulative N_2O-N emission of 1.45 kg N_2O-N ha^{-1} associated with the maintenance of 15 Mg DM of straw ha^{-1} without N fertilizer applications over a 270-days period[27]. Furthermore, the same authors demonstrated that N_2O-N emissions decreased to 0.91 kg N_2O-N ha^{-1} with the total recovery of straw from the soil surface without N fertilizer. Considering the similarity with soils and climate conditions of this study, we applied the same cumulative N_2O-N emissions[27] to be compared with the results calculated using the IPCC methodology, which consider emission factors of 0.01 kg N_2O-N kg^{-1} N for direct N_2O emissions and 0.00264 kg N_2O-N kg^{-1} N for leaching and runoff of N content in crop residue[24]. There were no net changes in CH_4 emissions in response to sugarcane straw removal[28], and thus, CH_4 emissions were not considered in our study.

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

In addition to industrial plants, further investments in tractors, trucks and other heavy machinery are required for the management and recovery of sugarcane straw after green mechanized harvest. For this experiment, the data collected and analyzed included truckload capacity of approximately 70 bales per trip, bales weighing on average about 350 kg $bale^{-1}$ and 24.5 Mg of straw transported per trip (16 km round trip, Table 2), 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 to the biorefinery gate are presented in Table 2. The fossil fuel typically used for sugarcane production systems is diesel oil, consumed mostly during agricultural operations by machinery, tractors and trucks[18]. In our study, the diesel consumption related to the final use of sugarcane straw was measured according to all field operations performed [Table 2].

Estimates of GHG emissions due to the use of fossil fuel for straw recovery in this study assumed CO_2, CH_4 and N_2O gases[24]. The emission factors applied were those suggested by Air Pollution Control Program for Auto Engines)/CETESB-Brazil[29], 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 CO_2 TJ^{-1} (TJ = Terajoule), 4.15 kg CH_4 TJ^{-1} and 28.6 kg N_2O TJ^{-1}, respectively[24]. The GHG emissions related to diesel extraction and distribution were considered as 3.87g C MJ^{-1} per liter of diesel[30].

Table 2. Technical parameters of diesel consumption in mechanized operations for the amount of sugarcane straw recovered of 6.9 Mg 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 × 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 = 24.5 Mg per trip. Diesel consumption of each operation was informed by the company's industrial sector.

Quantification of energy, cellulosic ethanol (2G) production from straw recovered and metrics for their carbon footprints

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 the Brazilian sugarcane industry[31]. 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 Mg^{-1} DM, with humidity between 6 and 10% and the technology being used is high pressure boiler/condensation and steam extraction turbine. In a literature review for straw availability, quality, recovery and energy use, Leal *et al.* showed that straw can be used after preparation as a complementary fuel to bagasse with an estimated electricity surplus reaching 1048 MJ Mg^{-1} (291 KWh Mg^{-1}) of cane when used in addition to bagasse in an integrated gasification/gas turbine combined cycle (BIG/GT-CC)[32].

Analyzing the use of sugarcane straw for power generation, a higher heating value of cane straw of 17.1 MJ kg^{-1} (DM) and a lower heating value of 12.15 MJ kg^{-1}, without considering the losses through the process, were presented[33]. With respect to industrial productivity, the premise to produce 240 L ethanol Mg^{-1} LM (lignocellulosic material on dry basis) in the short term was reasonably conservative by companies[34] (Milanez, 2015). For some companies, it is already feasible to reach 300 L ethanol Mg^{-1} LM or even 350 L ethanol Mg^{-1} LM in the long term[33]. On the other hand, electric power demand for 2G process is depicted as 48 KWh Mg^{-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[34].

Based on data from parameters for vehicle emissions in Brazil, an emission factor (EF) of 1.750 kg CO_2eq L^{-1} of hydrated ethanol should be applied for a vehicle year 2010, flex (ethanol or gasoline), using ethanol, with an efficiency of 8.2 km L^{-1}, considering emissions of CO_2 (207 g km^{-1}), CH_4 (0.053 g km^{-1}) and N_2O (0.017 g km^{-1})[29]. The CO_2 emitted through the combustion of ethanol in the vehicle motor is reabsorbed by the sugarcane plants, rendering the balance to practically zero[35] and therefore should not be accounted for in the CO_2 balance. To estimate the avoided GHG emissions when using renewable 2G ethanol from straw replacing gasoline, we considered the use of a light vehicle, with an efficiency of 10.8 km L^{-1} of gasoline[29] with EF of 2.312 kg CO_2eq L^{-1} (207 g CO_2 km^{-1}, 0.009 g CH_4 km^{-1} and 0.023 g N_2O km^{-1}). Therefore, when replacing 1 liter of fossil gasoline per 1 liter of hydrated ethanol, considering only CH_4 and N_2O emission from ethanol, an avoided emission of 2.26 kg CO_2eq was assumed in this study when considering 2G ethanol production from sugarcane straw [Table 3].

Carbon footprint is widely defined as the amount of carbon that is emitted during a process or by an organization or entity. It is a popular metric that appeared in media, conferences, and government and environmental institute's reports as pressure from the public concerning pollution and its impact on human health, and it is generally used as a measure of atmospheric pollution due to anthropogenic activities[36]. The parameters used in our study to present the C footprints were based on the total additional amount of GHG emitted related to all practices applied to recover sugarcane straw from the field to produce bioenergy or 2G ethanol. Our metrics were based on these total additional GHG emissions (soil CO_2-C emission, diesel from mechanized operations and N_2O from straw management), divided by four main parameters assessed: (i) bioelectricity production; (ii) 2G ethanol production; (iii) GHG emission by hectare basis; and (iv) GHG emission per megagram of straw recovered and are presented in terms of kg of CO_2eq by the rate of electricity production (kg CO_2eq MWh^{-1}), 2G ethanol production (kg CO_2eq L^{-1} of ethanol), kg CO_2eq ha^{-1} and kg CO_2eq Mg^{-1} of straw.

CO_2 emission factors for electric energy production in Brazil

The CO_2 emission factors of electric energy production used in life-cycle inventories in Brazil predict the amount of CO_2 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 all the plants that are generating energy, and not only those that are working at the moment[37], presenting emission factors in terms of Mg CO_2eq MWh^{-1}.

The CO_2 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 CO_2 emission reductions, from a project that generates electricity for the grid[37]. Briefly, the interconnected system CDM emission factor is a combination of the operating margin emission factor, which reflects the intensity of CO_2 emission of the energy dispatched at the margin, and the build margin emission factor, which reflects the intensity of CO_2 emissions from the last plants built[37].

The emission factors (Mg CO_2 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[37]. However, in this study, the offset potential for straw recovered displacing energy produced by the Brazilian energy matrix was calculated based on the EF of 0.1370 Mg CO_2 MWh^{-1}, considering emissions from plants built and energy generation at the margin[37].

Statistical analysis

Data related to CO_2-C emissions (μmol m^{-2} h^{-1}), soil temperature (°C) and soil water content (SWC, %) were analyzed using a completely randomized experimental design with three treatments and three replicates per treatment (3 × 3) with 5 sub-samples within each experimental unit to compose 01 sample per treatment, totaling 45 sampling points and repeated measurements in time. For the analyses, the mixed-model procedure of SAS statistical software was used [SAS Institute Inc., Cary, North Carolina]. When statistically significant ($P < 0.05$), the means were compared by Tukey's test at a significance level of 5%. In this case, we used SAS PROC MIXED procedure for repeated measurements to test for treatment effects and Tukey's procedure was used to adjust for multiple mean comparisons using LSMEANS options. The variables

Table 3. Parameters of emission factors (EF) for ethanol and gasoline in Brazil and total EF for each fuel and respective efficiency (g CO_2eq L^{-1}).

Ethanol*			EF (g CO_2eq L^{-1})
Gas	EF (g km^{-1})	EF (g L^{-1})	
CH_4	0.053	0.4346	10.87
CO_2		0.0	0.00
N_2O	0.017	0.1394	36.94
Total EF			47.81
Gasoline**		EF (g L^{-1})	EF (g CO_2eq L^{-1})
CH_4	0.009	0.0972	2.43
CO_2	207	0.0	2235.60
N_2O	0.023	0.2484	65.83
Total EF			2303.86

*Ethanol efficiency = 8.2 km L^{-1}; **Gasoline efficiency = 10.8 km L^{-1}; CO_2eq: Carbon dioxide equivalent; g: gram; L: liter.

(CO_2-C, soil temperature and soil water content) were also analyzed by linear correlation, testing if the correlation coefficient is statistically different from zero ($P < 0.05$) using PROC CORR procedure in SAS [Table 4].

RESULTS

Short-term soil CO_2-C emissions, soil water content and soil temperature

Results of Pearson's linear correlation coefficients are presented in Table 4, together with the R^2 values of the adjustment of a linear model to the soil CO_2 emission data, individually adjusted for the studied treatments. In addition, the *P*-value associated with the linear regression analysis was presented, H and zero confirms that the estimated regression coefficient is equal to zero. Thus, for the treatments studied, a linear relationship was observed between soil CO_2 emission and only soil water content ($P < 0.05$). The same was not observed for soil temperature, which shows no relationship between soil CO_2 emission and soil temperature for all treatments studied.

Figure 2A presents the temporal soil CO_2-C emissions comparing the management of recovering part of straw (T3; leaving 18.9 Mg DM ha^{-1}) with the management of keeping all straw on the soil surface without removal (T1; keeping 25.8 Mg DM ha^{-1}), which result in a straw removal rate of 6.9 Mg DM ha^{-1}. A significant difference ($P < 0.05$) among treatments was observed only on day 20, showing that agricultural operations to recover around 27% of straw may not significantly impact the temporal soil CO_2-C emissions during the measurements. The highest temporal emissions were observed in T2, except for day 17 ($P < 0.05$).

The impacts of straw management on soil temperature can be observed in Figure 2B when comparing T1 (100% straw maintained) with T3 (27% of straw recovered). For the 21-day period analyzed, there was a 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.

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 in soil water content ($P > 0.05$), showing that higher amount of straw could keep higher available soil water content. The higher

Table 4. Linear coefficient of correlation between soil CO_2-C emission and soil properties (soil temperature and soil water content)

Treatment	Soil temperature			Soil water content		
	r	*P*-value	R^2	r	*P*-value	R^2
1	0.18	0.48	0.034	0.57	0.01581	0.33
2	0.062	0.81	0.004	0.61	0.01010	0.37
3	0.17	0.51	0.029	0.75	< 0.001	0.56

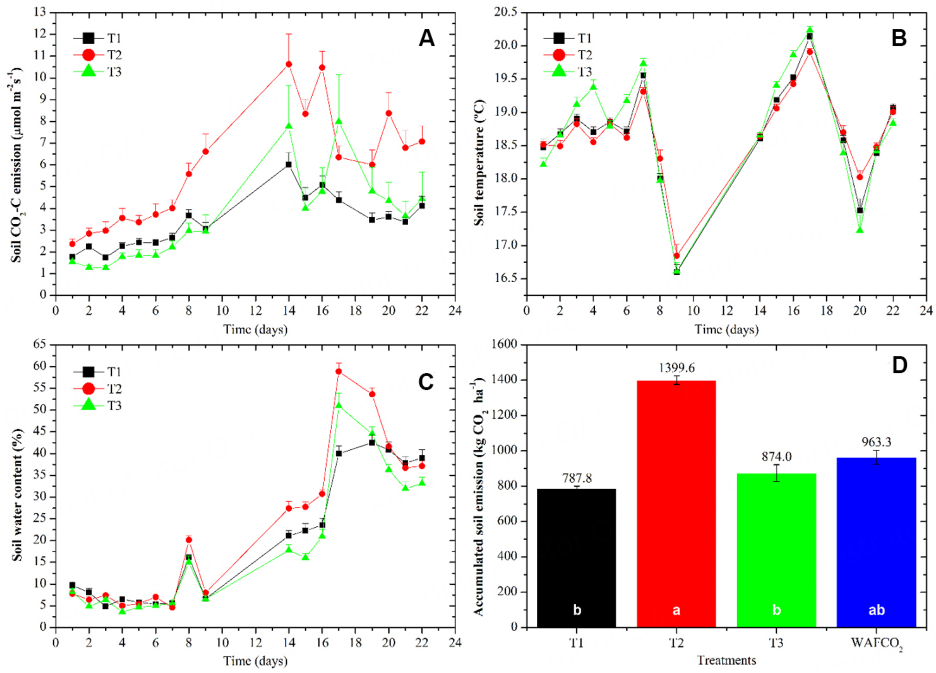

Figure 2. (A) Soil CO_2-C emissions (μmol m^{-2} h^{-1}); (B) soil temperature (°C); (C) soil water content (%) plus standard errors (vertical bars) and (D) Accumulated soil CO_2-C emission (plus standard error, kg CO_2-C ha^{-1}) for T1: Control area, with straw maintained on the soil surface; T2: Line 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 the harvested area); WAFCO$_2$: Weighted average of soil FCO$_2$(weighted average of emission in T2 and T3). Means followed by the same letters comparing straw management types did not differ by Tukey's test (P < 0.05).

amount of straw accumulated in T2 (44.3 Mg DM ha^{-1}) could explain this higher soil water content (SWC) after day 8 [Figure 2C], with straw mulching contributing to soil protection against evaporation.

In terms of the cumulative short-term soil CO_2-C emissions [Figure 2D], the emissions were lowest in T1 (100% straw) with 788 kg CO_2-C or 2889 kg CO_2 ha^{-1}. However, the comparison of cumulative soil CO_2-C emissions in the management of recovering 27% of straw (WAFCO$_2^-$ weighed average T2 and T3 - 963 kg CO_2-C), with those in the management of keeping all straw on the soil surface (T1) did not indicate significant difference, showing that recovering 27% of straw in the experimental conditions did not impact the cumulative short-term soil CO_2-C emissions [Figure 2D]. Therefore, the impact of straw removal (27% or 6.9 Mg DM ha^{-1}) on additional soil CO_2-C emissions over 21 days (WAFCO$_2$) was 175.5 kg CO_2-C ha^{-1} or 643.5 kg CO_2 ha^{-1}, which is equivalent to a C footprint of 25.5 kg CO_2-C Mg^{-1} or 93.2 kg CO_2 Mg^{-1} of straw [Figure 3].

Emissions from fossil fuel used to recover and transport straw

Specific management options practiced by sugarcane mills for straw recovery systems certainly have distinct

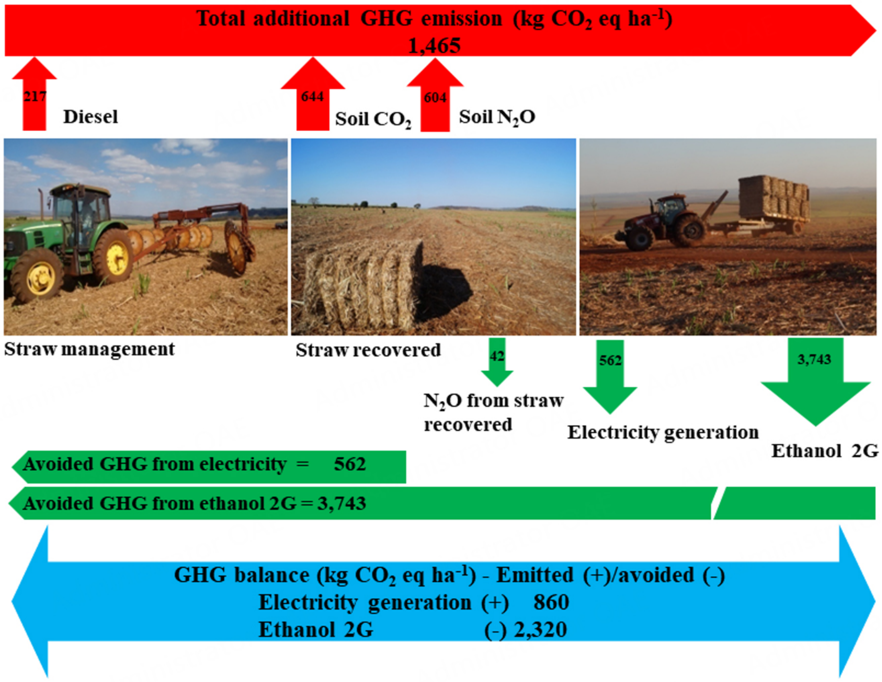

Figure 3. Additional GHG emissions (red bars), offset potential (green bars) and GHG balance (Blue bar) from sugarcane straw management and recovery operations that would be used for bioelectricity or ethanol 2G production (All values in kg CO_2eq ha^{-1} for a straw recovering rate of 6.9 Mg DM ha^{-1}).

impacts on the economic and technical parameters. Taking into account 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 Mg of straw under the experimental parameters was 9.9 L Mg^{-1} of straw or 68.2 L of diesel ha^{-1} (6.9 Mg ha^{-1}, dry matter-basis), resulting in a carbon footprint for diesel of 31.6 kg CO_2eq Mg^{-1} of straw or 217 kg CO_2eq ha^{-1} [Figure 3].

Estimation of N_2O emissions derived from post-harvest sugarcane straw

Applying the default methodology for N_2O emissions[24] and measured straw dry mass in the present experiment, leaving all straw on the soil surface without management (T1 - 100% straw) led to an estimated N_2O emission of 159 kg CO_2eq ha^{-1}. In contrast, recovering 6.9 Mg DM of straw ha^{-1} (27% straw removed-T3) resulted in an estimated N_2O emission of 117 kg CO_2eq ha^{-1}. Thus, comparing the practice of leaving all straw on the soil surface against the practice of recovering 27% of straw (T3), there was an estimated avoided N_2O emission of 42 kg CO_2eq ha^{-1} [Figure 3].

Comparing the estimated N_2O emissions with the IPCC methodology[24], previous research had reported higher cumulative N_2O emission of 2.28 kg N_2O ha^{-1} or 604.2 kg CO_2eq ha^{-1} over a 270-day period[27] when sugarcane straw was left on soil at a rate of 15 Mg DM ha^{-1}, which was used in calculating the GHG balance for the potential of straw for bioelectricity or 2G ethanol production in our study [Figure 3].

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

With 6.9 Mg of straw DM ha^{-1} recovered, it is possible to generate 4.1 MWh ha^{-1} of electricity (Company parameter), which means that for each Mg of recovered sugarcane straw, considering the emission factor from new projects and energy generation intensity[37] from Brazilian energy matrix (the base year 2018, 0.1370 Mg CO_2 MWh^{-1}), GHG emission of 81.5 kg CO_2eq Mg^{-1} of straw or 0.5617 Mg CO_2eq ha^{-1}

(562 kg CO_2eq ha^{-1}, Figure 3) is likely to be avoided.

The 2G ethanol produced from lignocellulosic biomass (LM) has been considered the biofuel with the greatest potential to replace fossil fuels[38,39]. Based on our experimental results, with the production potential of 240 L 2G ethanol Mg^{-1} LM (Dantas*et al.*[31], 2013), it would be possible to produce an additional 1656 L of ethanol ha^{-1} (6.9 Mg DM straw ha^{-1}), which could promote an avoided GHG emission of 2.26 kg CO_2eq L^{-1} of 2G ethanol by replacing 1 liter of gasoline or 3743 kg CO_2eq ha^{-1} considering only CH_4 and N_2O emissions from 2G ethanol combustion [Figure 3].

Taking into account all mechanized operations to recover around 27% of sugarcane straw, the total additional GHG emissions were estimated at 1465 kg CO_2eq ha^{-1} (for 6.9 Mg DM ha^{-1}) minus 42 kg CO_2eq ha^{-1} (from straw removed-avoided), resulting in a carbon footprint of 206.2 kg CO_2eq Mg^{-1} of straw recovered. We considered the main emission sources (i.e., additional soil CO_2-C, diesel use and N_2O from straw), in contrast to leaving all straw on the soil surface. Compared to the 42 kg CO_2eq ha^{-1} of N_2O emissions avoided when all straw is left on soil (T1), 27% of sugarcane straw removal would therefore result in a total additional emission of 1423 kg CO_2eq ha^{-1} [Figure 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 additional GHG emission of (+) 860 kg CO_2eq ha^{-1} [Figure 3]. In contrast, avoided GHG emission of (-) 2320 kg CO_2eq ha^{-1} could be achieved [Figure 3] when applying the same parameters for 2G ethanol production replacing gasoline.

DISCUSSION

Short-term soil CO_2-C emissions, soil water content and soil temperature

The highest temporal CO_2-C emissions observed in T2 (straw accumulated after harvest) could be explained by the straw management and accumulation of large amounts of straw between two crop lines (inter-row), which could promote higher soil aeration, higher O_2 availability for microorganisms activity and higher C accessibility (straw carbon) to be decomposed through mineralization process. In another sugarcane field experiment, keeping all sugarcane straw on the soil surface without management led to a 253 kg CO_2-C ha^{-1} reduction in emissions compared with recovering all straw[13], probably due to higher soil bulk density and lower soil aeration[40], 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.

It is important to note that short-term soil CO_2-C emissions in sugarcane areas may be higher soon after the straw management; however, these emissions tend to stabilize to similar levels compared with the emissions from areas with no straw management, as observed in T1 and T3 at the end of the experimental period [Figure 2A], supporting the importance of short-term measurements instead of longer measurement periods. Previous research on GHG responses to sugarcane straw removal at a rate of 6.9 Mg DM of straw ha^{-1} has resulted in a total CO_2-C emission of 82.2 g m^{-2} or 3,014 kg CO_2 ha^{-1} in a period of 180 days[28], while in this study, for a similar removal rate of 6.9 Mg straw ha^{-1}, an additional emission of 643.5kg CO_2 ha^{-1} was measured in only 21 days after management and stabilized to similar value to T1 without straw management, supporting the need for short-term measurements.

Measurements of short-term soil CO_2 emissions can contribute to a better knowledge of the impact of straw removal on long-term soil organic C storage as a result of short-term higher or lower emissions from different soil and straw management. Our study assessed the variance by comparing the practice of maintaining all straw on the soil surface with the practice of removing part of this straw, and the impact of those practices only on the additional soil CO_2 emission caused by straw management, as straw decays over time and reduces its presence on the soil surface in the long term. Hence, before determining CO_2 sequestration rates, presenting short-term emissions and their correlation with soil properties can help understand the possible impact on soil CO_2 losses. Our results (Figure 2D, T1 x $WAFCO_2$) show that soil CO_2 emission increases with this removal rate (27% of straw), but there is no significant difference from keeping all straw on the surface, which could be an important effect that can explain the long-term changes and straw amount that could be recovered without impacting CO_2 sequestration rate in the long term. This effect of straw management is observed in the short term, simply because after about 30 or 40 days after soil or straw management, those additional emissions tend to stabilize to the same condition as no straw removal as observed in T1, compared to $WAFCO_2$ [Figure 2A]. Other long-term experiments to assess the correlations of the rate of straw removal with the soil organic carbon storage shall be evaluated, but due to the complexity of such evaluations in terms of time and spatial variance, modeling studies may be applied to detect SOC changes.

In a scenario with straw removal and possible additional SOC losses from this management, no-tillage or reduced tillage practices combined with other best management practices, such as vinasse and filter cake application, could reverse the potential SOC losses associated with residue removal[13,26,41], contributing to a long-term soil C increase.

Estimation of N_2O emissions derived from post-harvest sugarcane straw

Gonzaga *et al.* have shown that N_2O emissions were reduced to 1.43 kg N_2O ha^{-1} or 379 kg CO_2eq ha^{-1} (-37%) upon removal of all straw from the soil surface[27]. Lower N_2O emissions induced by straw removal were also reported by several other studies conducted in Brazil[28,42,43].

Compared to the management to recover sugarcane straw from the soil surface for multiple uses, leaving sugarcane straw on the soil surface can lead to higher N_2O emissions, which would strongly influence the extent to which biofuels derived from straw decrease their GHG emissions relative to fossil fuels[44,45]. Additionally, regardless of N fertilizer application, the retention of sugarcane crop residue increases N_2O emissions[27], acting as a catalyst for increased soil microbial activity and soil N_2O flux[46]. Thus, we should find an equilibrium for straw recovering rate and related N_2O emissions once leaving all straw on the soil surface result in higher N_2O emissions and lower CO_2 emissions.

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

The difference of straw energy generation parameter informed by the company (0.6 MWh Mg^{-1} of straw, 6%-10% humidity) resulted in a production of 4.1 MWh ha^{-1} (6.9 Mg DM ha^{-1}), and contrasting with the potential 23.28 MWh ha^{-1}, applying a lower heating value of 12.15 MJ kg^{-1} DM[33], can result in 83,835 MJ ha^{-1} (1 MJ = 0.000277778 MWh), a difference of avoided GHG emission from 562 kg CO_2eq ha^{-1} (Company parameter) to 3186 CO_2eq ha^{-1}. The efficiency of energy transformation can strongly influence the potential for avoiding GHG emissions for a new project using sugarcane straw as a by-product. With the surplus energy associated with 6.9 Mg DM ha^{-1} of straw recovered and a technical energy production of 4.1 MWh ha^{-1}, 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 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), in which every single biorefinery in the country will pursue the production of biofuels with an ever-higher environmental responsibility[8]. The characteristics of each country's energy matrix, based on fossil fuels or renewable sources as found in Brazil[37], with average carbon emission intensity of 0.08735 Mg CO_2 MWh^{-1} from years 2011 to 2018 as reference[37], will determine the potential for each country to develop and use straw-based bioenergy sources to reach a low-carbon energy matrix.

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.

Finally, summarizing results of two large-scale projects aiming to provide quantitative data to support decision-making for straw management and establish rational plans for sustainable straw removal[5], and analyzing scientific findings addressing soil conservation, soil compaction, soil carbon (C) stocks, and biology; nutrient cycling and fertilizer management; GHG emissions; pest management; crop yield; engineering solutions; and industrial performance, this study showed that sustainable straw removal is feasible in Brazil, but the recommendations of optimum removal must not be designed using isolated factors. They must be developed using integrated knowledge to ensure the sugarcane straw will not only provide bioenergy but also sustain multiple soil ecosystem services and crop yield[5]. Therefore, other sustainability parameters related to sugarcane straw recovery should be considered, such as soil type (sand or clay soils), harvest crop cycle and respective crop productivity, impact on soil erosion and crop nutrition, the balance of soil CO_2-C (emission and sequestration rate), as well as N_2O balance.

Conclusions

Bioelectricity and cellulosic ethanol production using different sugarcane straw recovering rates may not be a sustainable management strategy to mitigate GHG emissions, depending not only on the average amount of straw recovered but also on the remaining amount and associated impacts on sugarcane-cultivated soils, related additional GHG emissions and the efficiency rate for straw conversion in bioenergy products.

The main additional GHG emission sources from straw management and agricultural processes include soil CO_2-C emissions, soil N_2O emissions and emissions from mechanized field operations (diesel use), which should be accounted for in the deployment of new sugarcane bioenergy projects that uses straw as a raw material to contribute to a low carbon intensity matrix.

The route of recovering around 27% of sugarcane straw from the soil surface through bale system for bioelectricity production using the technical parameters and industrial efficiency rate of this case 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 compared to the emission factor from the national energy matrix, resulting in a C footprint of 347 kg CO_2eq MWh^{-1}. Improving the efficiency rate for sugarcane straw conversion in bioelectricity based on its lower heating value could reduce its C footprint to 61.2 kg CO_2eq MWh^{-1}.

Employing the same parameters for straw recovery at the first sugarcane cutting cycle in clay soil, the option of producing 2G ethanol with around 27% of the total sugarcane straw recovered could offset greenhouse gas emissions replacing fossil gasoline, resulting in a C footprint of 0.86 kg CO_2eq L^{-1} of 2G ethanol in the agricultural phase, which can be an option to contribute to better sustainability of sugarcane straw recovery, supporting renewable and sustainable bioenergy systems, and reducing the impacts of Global Climate Change.

DECLARATIONS

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Methodology, review & editing, validation: de Oliveira Bordonal R
Software, data analyse, review: Rodrigo Panosso A
Funding acquisition; investigation; project administration, review: La Scala Jr N

Availability of data and materials

All base data and statistical analysis used for this research are available.

Financial support and sponsorship

None.

Conflicts of interest

All authors declared that there are no conflicts of interest.

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.

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