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RESEARCH ARTICLE

Avoiding burning practice and its consequences on the greenhouse gas emission in sugarcane areas southern Brazil

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Abstract

There is a growing need of sustainable solutions for balancing agricultural production with the reduction of its environmental impacts. The rapid increase in sugarcane cultivation and the progressive conversion of pre-harvest burning (BH) to green harvest (GH) have brought into debate the contribution of agricultural sector to the greenhouse gas (GHG) mitigation. This study focused on the estimated GHG emission from sugarcane cultivation during years in which sugarcane areas in southern Brazil expanded and passed throughout an important transition, from 2006 to 2012, when harvest adopted was changed from burned to not-burned based. Sugarcane management and harvest were mapped through visual interpretation of Landsat-type satellite images, and the areas under sugarcane cultivation were distinguished according to each agricultural phase and harvest regime (i.e., manual harvest with burning vs. green mechanized harvest). Based on a broad data review and applying the IPCC (2006) methodologies, the results were expressed in terms of kilograms of carbon dioxide equivalent (kg CO_2eq ha^{-1}). Avoiding burn prior to harvest, even during expansion of sugarcane areas, promoted a mean reduction of GHG emission from 901 to 686 kg CO_2eq ha^{-1} relative to harvest phase (24% lower) and an increase from 1418.3 to 1507.9 kg CO_2eq ha^{-1} related to the ratoon maintenance phase (6% higher). Analyzing the total GHG emission per unit of cultivated sugarcane area (hectare), it was observed a decrease from 2275 to 2034 kg CO_2eq ha^{-1} (11% reduction). The gradual transition of pre-harvest burning on that period has contributed to the reduction of GHG emission associated with sugarcane production being an important step towards GHG mitigation while still providing more sustainable sugar and ethanol production in southern Brazil.

Keywords Inventory · IPCC methodology, Mitigation · Ethanol production · Sugarcane harvest · Burning of residues · Sustainability

Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), the world agricultural production can be seriously impacted by climate change, which is caused mostly by an enhancement of the greenhouse effect, and the agriculture is also an important sector with regard to the emissions of greenhouse gases (GHG). In 2005, the agricultural sector was responsible for the emission of 5.1 to 6.1 Gt CO_2 eq $year^{-1}$ (Gt = 10^9 ton), corresponding to 10–12% of the global anthropogenic GHG emissions (IPCC 2014). Even so, a global technical mitigation potential from agriculture is estimated to be ~ 5500–6000 Mt CO_2eq $year^{-1}$ by 2030, excluding fossil fuels offsets from biomass (Smith et al. 2008).

Although the contribution of sugarcane sector for reducing net GHG emissions, new aspects of mitigation options are still under discussion (Lapola et al. 2010). The use of sugarcane-

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based ethanol in substitution of fossil fuels has been suggested as an alternative option for mitigating GHG emissions by 85–90% (Smeets et al. 2006). Likewise, energy balance ratio of sugarcane-based ethanol is 7.9 (von Blottnitz and Curran 2007), which is by far the most effective option to mitigate GHG emissions compared to other bioenergy crops such as sugar beet (2.0), corn (1.4), or sorghum (2.8) (Renouf et al. 2008; Bordonal et al. 2018).

This sustainability could be at risk if management practices in sugarcane areas, like the one based on burning prior to harvest, would be predominant (Tsao et al. 2011).

In addition to the GHG emissions derived from burning, the lack of crop residues on soil surface during fallow after harvest results in reduction of soil carbon stocks, which is another important aspect related to the GHG balance in agricultural areas (Cerri et al. 2011).

Another opportunity, which has been sustained, is using crop residues left after harvest, in a non-burning scenario, aiming to produce the so-called second-generation ethanol which would increase the biofuel yield and reduce the carbon footprint of sugarcane-based ethanol (Buckeridge et al. 2012; Do Lago et al. 2012).

Brazil is the world's largest producer of sugarcane (*Saccharum* spp.), with a cultivated crop area in the 2019/20 cropping season of approximately 8.4 million hectares. In this scenario, São Paulo State is the largest sugarcane producer, accounting for 51.7% or approximately 4.7 million hectares of this planted area (CONAB 2020). Therefore, changes in the sugarcane management system may have a significant impact in the sustainability of sugarcane-based ethanol.

In Brazil, there are two main harvest systems of sugarcane, including green harvesting (GH) and manual burned (BH). In the practice of manual burned, the cane field is burned a few days before the manual harvesting operation with the objective of reducing the amount of straw and, in this way, facilitating the cutting operations and mechanical loading.

The GH system provides the deposition of up to 15 t ha^{-1} year^{-1} of dry mass of crop residues on the soil surface, thus increasing the store of carbon in the superficial layers (Cerri et al. 2011; Carvalho et al. 2019). Thus, the carbon that would be emitted immediately into the atmosphere during the burning of sugarcane field remains incorporated in the soil, contributing to the mitigation of atmospheric CO_2 concentrations and reducing the contribution of agriculture to the additional greenhouse effect (Galdos et al. 2009).

A great effort to banish the negative environmental and health impacts associated with the pre-harvesting burning has been established in the past years, particularly in São Paulo State, where the GH has become the most common harvest procedure (Aguiar et al. 2011). França et al. (2014) have already reported that an avoidance of pollutants emissions is observed since government actions are becoming effective for reducing sugarcane straw burning.

A significant increase in the mechanization of sugarcane harvest has been driven by the Green Ethanol Protocol agreement, which was signed by the Environmental State Secretariat of São Paulo and the sugarcane sector in order to anticipate the banishment of BH system in the most dense cultivated sugarcane region. Most of GHG emissions associated with ethanol production comes from agricultural sector (~ 90%) instead of industrial processes (Pereira and Ortega 2010; Seabra et al. 2011), and pre-harvesting burning is among the main sources of GHG emissions during sugarcane production (Capaz et al. 2013). However, the conversion from BH to GH also results in additional GHG emissions through higher use of synthetic N fertilizers and diesel consumption (De Figueiredo and La Scala Jr 2011), and the potential impact of these agricultural practices on GHG emissions reduction has so far been neglected.

The National Policy on Climate Change (Federal Law No. 12,187/2009; Brasil 2009) mandates that Brazil, as a voluntary national commitment, will reduce the projected emissions of GHGs between 36.1 and 38.9% by 2020, with an absolute reduction from 1168 to 1259 Gt CO_2eq in relation to nationwide emissions in 2005, respectively, and sugarcane sector may contribute considerably to achieving part of such goals set by federal law.

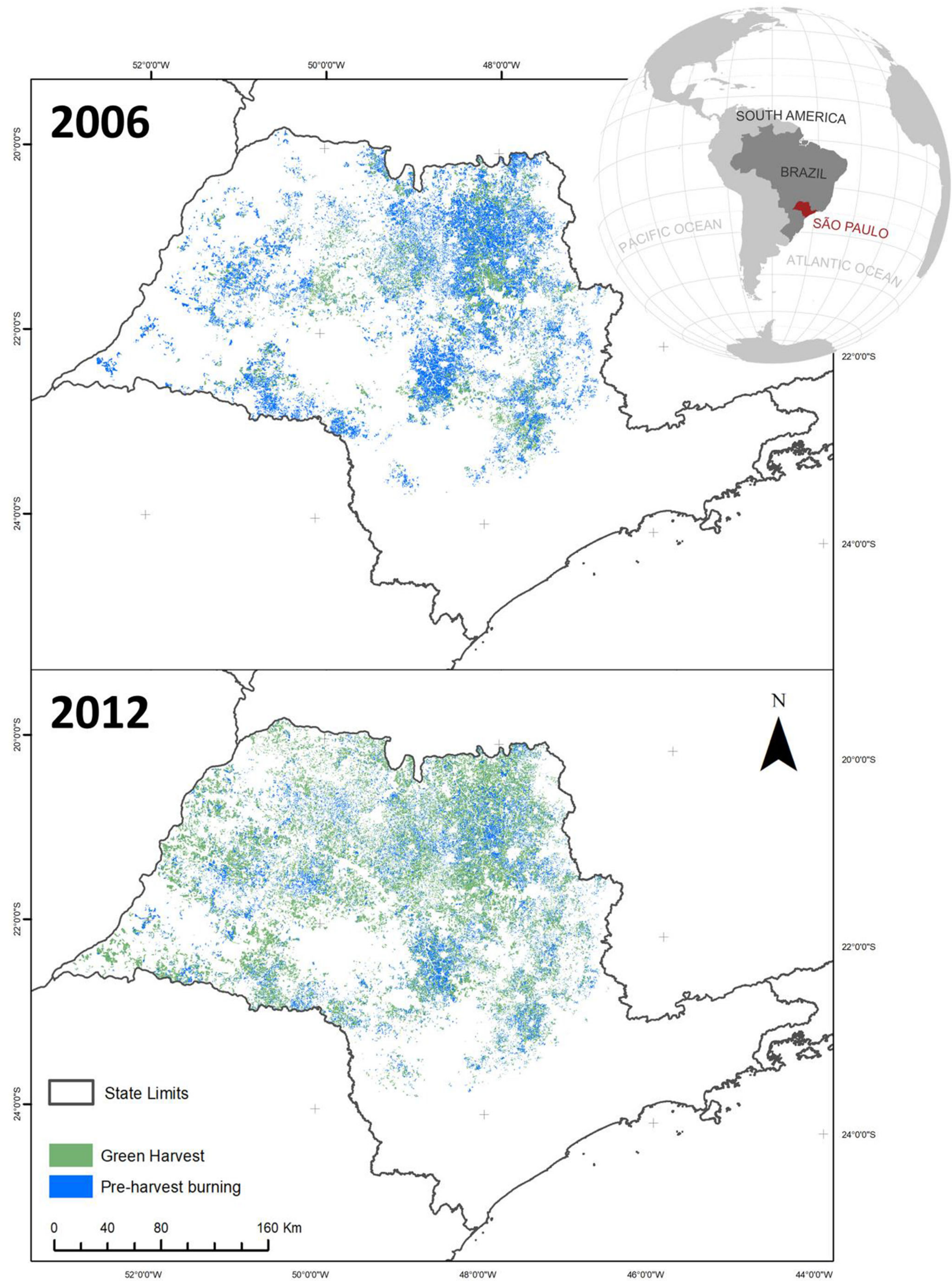
In addition, in 2017, the National Energy Policy Council (CNPE) approved the strategic guidelines that will guide the National Biofuel Policy, named RenovaBio programme. RenovaBio is a state policy that, for the first time, aims to outline a joint strategy to recognize the strategic role of all types of biofuels (ethanol, biodiesel, biomethane, biokerosene, second generation, etc.) in the Brazilian energy matrix, both with regard to its contribution to energy security, with predictability, as well as to mitigate the GHG emissions in the fuel sector (Addington 2020). This study aimed at estimating the changes of GHG emissions associated with sugarcane cultivation over the 2006–2012 period in São Paulo State, in which sugarcane areas expanded and passed throughout an important transition such as the conversion from manual burned to mechanized harvest without burning. Our focus is to provide new insights about the effective contribution of the Green Ethanol Protocol in mitigating GHG emissions associated with sugarcane agricultural sector in southern Brazil.

Material and methods

Description of the sugarcane thematic maps

The thematic maps classified according to the sugarcane management and to the harvest practices (Fig. 1) were obtained

Fig. 1 Sugarcane areas harvested as green harvest and pre-harvest burning practice in São Paulo State–2006 and 2011 harvest season (Source: www.dsr.inpe.br/laf/canasat/)


2006
2012
SOUTH AMERICA
BRAZIL
SÃO PAULO
PACIFIC OCEAN
ATLANTIC OCEAN
N
State Limits
Green Harvest
Pre-harvest burning
0 40 80 160 Km
52°0'0"W
50°0'0"W
48°0'0"W
46°0'0"W
44°0'0"W
20°0'0"S
22°0'0"S
24°0'0"S

from Rudorff et al. (2010) and Aguiar et al. (2011). Sugarcane management is defined according to the following agricultural phases: (a) expansion—sugarcane grown in a new area to be harvested for the first time; (b) renewed—sugarcane fields that were renewed by crop rotation and are available for harvest; (c) ratoon maintenance—refers to the sugarcane fields that are sprouting from a sugarcane base (ratoons) after having been cut in the previous crop season, since sugarcane is a semi-perennial crop which will be harvested every year for 5 or 6 times before to be renewed; and (d) harvest—represented either by manual harvest with burning (BH) or green mechanized harvest (GH) (Table 1).

Methodology and emissions sources

The sources of GHG emission considered in this study were (a) pre-harvest burning of residues (CH_4 and N_2O emissions); (b) limestone application; (c) direct and indirect N_2O emissions derived from synthetic N application, organic composts (vinasse and filter cake), and crop residues deposited on the soil surface due to green harvest; (d) pesticide application; (e) diesel consumption by machinery during the agricultural operations (Fig. 2). In addition, hidden emissions associated with the production and distribution process of the agricultural inputs were also taken into account (Fig. 3).

The GHG emission was expressed in terms of CO_2 equivalent, according to the individual global warming potential (GWP) for each gas over 100-year period, using 1 for CO_2, 25 for CH_4, and 298 for N_2O (IPCC 2007). Emission factors were compiled from scientific literature and an average factor was arbitrarily applied for each emission source to attenuate the uncertainties (Table 2).

Pre-harvest burning of sugarcane

Sugarcane burning-related emissions were evaluated according to the (IPCC 2006) methodology. Only CH_4 and N_2O emission associated with residue burning were taken into account, since the CO (quickly converted into CO_2 in the atmosphere) and CO_2 emissions are assumed to be compensated during the crop growth in the next cycle. GHG emissions were based on the amount of residues produced by sugarcane plantation. In this study, we considered the average yield of 82.4 t ha^{-1} and 140 kg (dry matter) per ton of sugarcane (Macedo et al. 2004). The combustion factor adopted was 0.8 (IPCC 2006), and the emission factors were 2.7 and 0.07 g kg^{-1} of dry matter burned for CH_4 and N_2O, respectively (Andreae and Merlet 2001). Thus, the emissions derived from burning of sugarcane residues were estimated as 815.5 kg CO_2eq ha^{-1} (Table 2).

Limestone application

Average consumption of dolomite limestone in São Paulo State is 2.0 t ha^{-1} during the sugarcane field reform and 1.0 t ha^{-1} during the ratoon maintenance every 2 years (Macedo et al. 2004). Emission factor was considered as 0.5 kg CO_2eq kg^{-1} dolomite applied (Macedo et al. 2008), which also includes the upstream emissions related to the limestone production (Table 2).

Direct and indirect N_2O emissions

Nitrous oxide (N_2O) emissions are related to the amount of synthetic N fertilizers, organic composts (vinasse and filter cake), and crop residues left on soil surface after the harvest under green cane regime. IPCC (2006) methodology was applied to estimate N_2O emission, which assumes that 1% of the N content in the synthetic fertilizer, vinasse, filter cake, and crop residues is emitted directly to the atmosphere. For indirect emission, a 1% emission factor was applied to 10% of synthetic N fertilizer and to 20% fraction of volatilized N from the organic composts (vinasse and filter cake). Regarding the indirect N_2O emissions derived from leaching and runoff, a

Table 1 Sugarcane cultivated area in São Paulo State during 2006–2012, according to each phase of agricultural production: expansion, renovated, ratoon maintenance (manual burned-BH vs. green mechanized-GH) and harvest (manual burned-BH vs. green mechanized-GH)

Year	Expansion	Renovated	Ratoon		Harvest	
			GH	BH	GH	BH
2006	305,603	306,684	966,166	1,877,347	1,110,120	2,131,990
2007	636,814	287,993	1,317,001	1,554,197	1,764,992	2,025,448
2008	661,874	428,663	1,738,155	1,835,465	1,924,075	1,997,630
2009	321,801	344,710	2,074,805	1,660,890	2,266,403	1,810,531
2010	137,445	306,883	2,320,867	1,859,199	2,627,025	2,101,110
2011	156,437	531,759	2,703,795	1,421,403	3,125,619	1,670,521
2012	216,415	667,838	2,936,528	1,103,364	3,381,313	1,277,003

Source: CANASAT Project - INPE (http://www.dsr.inpe.br/laf/canasat/)

30% leached fraction and a 0.75% emission factor were considered for synthetic N fertilizer, organic composts, and crop residues (IPCC 2006).

Synthetic fertilizers (N-P_2O_5-K_2O)

Fertilizer application is a practice to maintain soil fertility and increase crop yields. Likewise, industrial by-products such as vinasse and filter cake can be applied in sugarcane fields and reduce the nutrient requirements through synthetic fertilizers (e.g., N, P_2O_5, and K_2O). In the case of vinasse, its potassium content can eliminate the need for potassium fertilization. In addition, filter cake can be used to supply half of the annual phosphorus demand of sugarcane (Spironello et al. 1997). In this work, the recommendations of the adopted agricultural inputs are presented in Table 3. We assumed that the filter cake was mainly applied in the renewed sugarcane fields followed by the sugarcane expansion areas.

Emission factor of 3.97 kg CO_2eq kg N^{-1} was assumed for the emissions associated with the feedstock production and transport of synthetic N fertilizer (Macedo et al. 2008), corresponding to an emission factor of 10.2 kg CO_2eq kg^{-1} of N fertilizer applied. In addition, emission factors related to the production, processing, and distribution of phosphorous and potassium were considered as 0.7 and 0.5 kg CO_2eq kg^{-1}, respectively (Table 2).

Organic composts

Vinasse application may vary according to the soil characteristics, potassium concentration, and crop nutritional needs. In Brazil, there is a standard establishing criteria and procedures for vinasse application. On average, the vinasse nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) levels are 0.433, 0.034, and 2.206 kg m^{-3}, respectively (Fiesp 2009). The rate of vinasse adopted herein was 120 m^3 ha^{-1} (De Figueiredo and La Scala Jr 2011). Emissions regarding the filter cake were based on dose fertilization of 30 t ha^{-1}, and we considered that filter cake supply half of phosphorus needs by the synthetic fertilizer. Filter cake has 77% moisture content with a mean composition of 3 g kg^{-1} N, 2 g kg^{-1} P_2O_5, and 0.6 g kg^{-1} K_2O (Spironello et al. 1997).

We assumed that all the vinasse and filter cake produced in São Paulo State were applied to the sugarcane fields, considering the relation of 12 L L^{-1} of ethanol and 30 kg t^{-1} of sugarcane for vinasse and filter cake, respectively (Fiesp 2009) (Table 3). We arbitrarily adopted that the vinasse application was performed first on sugarcane ratoons that were harvested mechanically without burning followed by those that were harvested with pre-harvest burning of residues. For the filter cake application, we considered only the renewed sugarcane fields.

Green harvest residues

The amount of crop residue left on the soil surface after the green harvest is variable. Sugarcane/residue ratio might range from 11 to 17% (Leal et al. 2013). This leads to an N input into the soil surface varying from 39 to 60 kg N ha^{-1} (Franco et al. 2010; Fortes et al. 2012). However, the N present in sugarcane crop residues follows a decay rate of 3 to 30% during one agricultural year and the crop could absorb from 5 to 18.4% of the N available (Vitti et al. 2011; Fortes et al. 2012). In this study, we adopted an average crop yield of 82.4 t ha^{-1} (Macedo et al. 2004), a 19% yield/residue rate, a 0.5% N content, and a 12% available nitrogen for emissions, which results in a rate of 9.4 kg N ha^{-1} $year^{-1}$ in green harvested areas.

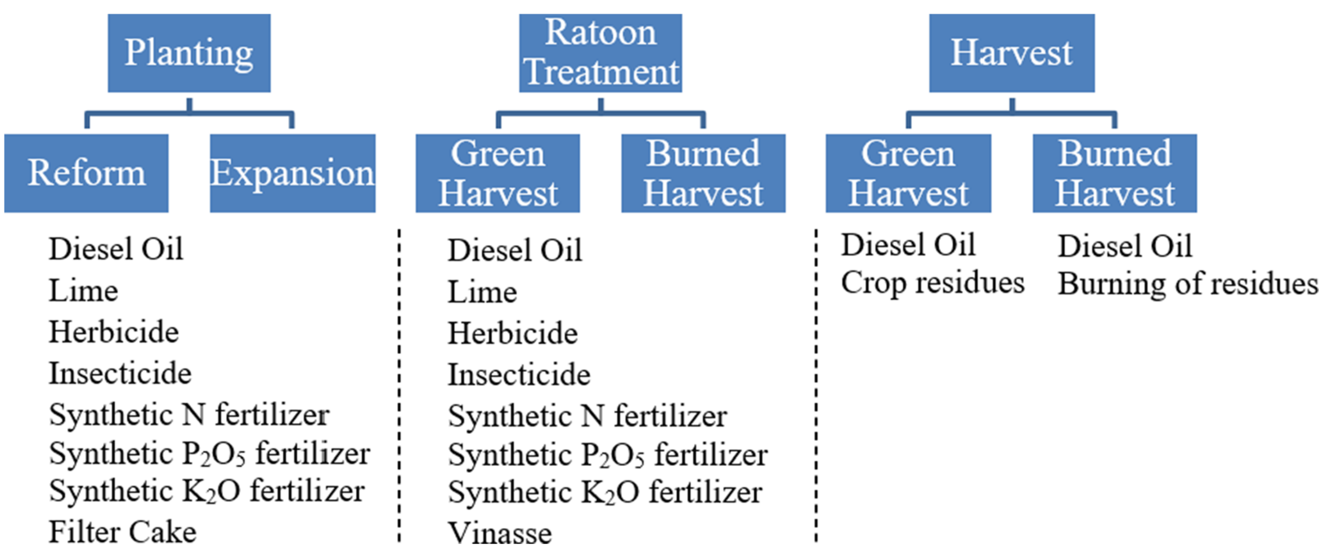


Fig. 2 GEE sources considered in each phase in this study

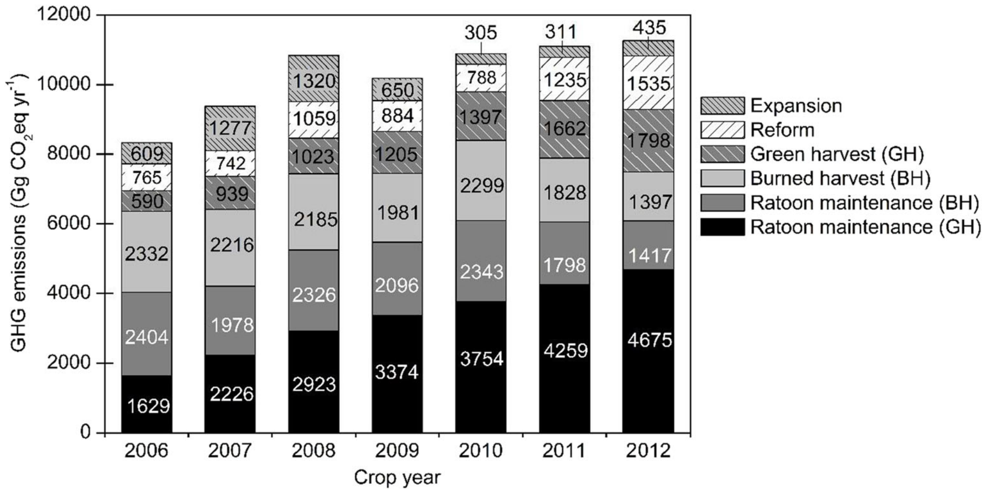


Fig. 3 Estimate GHG emissions (in Gg CO_2 eq year^{-1}) from each agricultural phase of sugarcane crop in São Paulo State, 2006 to 2012

Pesticides application

The amount of pesticides applied per area was estimated based on the amount of herbicide and insecticide commercialized in Brazil for sugarcane plantation. To estimate the pesticide amount per area, we considered the total pesticide amount divided by the total cultivated sugarcane area in Brazil (MAPA 2015) (Table 4). The amount of applied fungicide is negligible and was not considered in this study.

We adopted the same herbicide amount for either green harvest (GH) or burned harvest (BH) systems. A half dose was applied during sugarcane planting and the remaining during the first sugarcane ratoon. The insecticides in the GH system are applied in planting and ratoon maintenance, whereas in the BH system is applied during planting season only. Emission factors associated with the pesticides application were based on the average values found in literature, which are 29.0 and 25.0 kg CO_2eq kg^{-1} of insecticides and herbicides applied, respectively (Table 2).

Diesel consumption

Sugarcane management demands large amount of diesel by the agricultural machinery such as tractors and trucks. In Brazil, diesel consumption during sugarcane operations varies from 164 to 600 L ha^{-1} (De Oliveira et al. 2005; Macedo et al. 2008), depending on the adopted scope or the portion accounted for as essential operation (Macedo et al. 2008). In this work, the emissions related to the diesel were estimated according to each agricultural phase and the specific diesel

Table 2 Average emission factors used for each source considered in our approach

Sources	Emission factor *	Unit
Diesel [a]	3.2	(kgCO_2eq L^{-1})
Insecticide [b]	29.0	(kg CO_2eq kg i.e^{-1})
Herbicide [b]	25.0	(kg CO_2eq kg i.e^{-1})
Synthetic N fertilizer [c]	10.2	(kg CO_2eq kg N^{-1})
Synthetic P_2O_5 fertilizer [d]	0.7	(kg CO_2eq kg $P_2O_5$$^{-1}$)
Synthetic K_2O fertilizer [d]	0.5	(kg CO_2eq kg $K_2O$$^{-1}$)
Limestone [b]	0.5	(kg CO_2eq kg dolomite^{-1})
Residues burning [e]	815.5	(kg CO_2eq ha^{-1})

*EFs were based on the following references: [a] IPCC (2006), [b] Lal (2004), and [c] Macedo et al. (2008)

[a] Emission factor includes direct emissions (Brasil 2011) and indirect emissions (Macedo et al. 2008)

[b] Values adopted from Macedo et al. (2008)

[c] It was assumed that 1.325% of the synthetic N fertilizer applied in the sugarcane fields would be emitted into atmosphere as N_2O (IPCC 2006); the emissions related to the production and transport of the feedstock adopted from Macedo et al. (2008)

[d] Values adopted from Lal (2004)

[e] EF for residues burning was based on the CH_4 and N_2O emissions of 2.7 and 0.07 (all values in g kg^{-1} of dry matter burned), respectively (Andreae and Merlet 2001). A combustion factor of 0.80 (IPCC 2006) and a straw yield (db; dry basis) of 140 kg db t^{-1} of sugarcane (t_{SC}) have been applied (Macedo et al. 2004)

Table 3 Quantities of sugarcane, ethanol, vinasse, and filter cake produced in São Paulo State during 2006–2012

Crop year	Sugarcane (ton)	Ethanol (m^3)	Vinasse* (m^3)	Filter cake** (ton)
2006	265,379,217	11,060,113	132,721,356	7,961,377
2007	297,135,707	13,351,305	160,215,660	8,914,071
2008	352,277,735	16,904,039	202,848,468	10,568,332
2009	362,644,755	14,918,631	179,023,572	10,879,343
2010	361,723,269	15,465,605	185,587,260	10,851,698
2011	305,636,316	11,639,325	139,671,900	9,169,089
2012	331,173,721	12,018,061	144,216,732	9,935,211

Source: Ministério da agricultura, pecuária e abastecimento (MAPA 2017)–SAPCANA

*Estimated by author-vinasse: 12 L L^{-1} of ethanol

**Filter cake: 30 kg t^{-1} of sugarcane (FIESP 2009)

consumption was based on Bordonal et al. (2013). Emission factor adopted herein was 3.2 kg CO_2eq L^{-1} (Table 2), of which 2.6 kg CO_2eq L^{-1} are related to direct emissions (Brasil 2011) and 0.6 kg CO_2eq L^{-1} are associated with the indirect emissions for extraction, processing, and distribution (Macedo et al. 2008).

Results and discussion

Greenhouse gas emissions associated with sugarcane crop production

The contribution of ratoon maintenance on GHG emissions increased from 1629 Gg CO_2eq ha^{-1} $year^{-1}$ in 2006 to 4675 Gg CO_2eq ha^{-1} $year^{-1}$ in 2012 (Fig. 3), mainly due to the increase of ratoon GH areas. Otherwise, emissions from ratoon maintenance in BH areas decreased from 2404 Gg CO_2eq ha^{-1} $year^{-1}$ in 2006 to 1417 Gg CO_2eq ha^{-1} $year^{-1}$ in 2012, also due to a reduction of BH areas probably as a result of Green Protocol Agreement adoption. Taking into account only the contribution of emission from harvest practices phase and, comparing the impacts of changes in BH to GH areas, our results show that the increment of sugarcane areas under GH practice resulted in higher total GHG emission from this crop phase (Fig. 3), despite BH areas emit more GHG per area than GH (De Figueiredo and La Scala Jr 2011).

Table 4 Amounts of pesticides consumed (ton of active ingredient) during sugarcane cultivation in São Paulo State in the crop years 2006–2012.

Class	Crop years						
	2006	2007	2008	2009	2010	2011	2012
Herbicide (kg ha^{-1})*	3.40	3.76	3.52	3.08	2.97	3.33	4.85
Insecticide (kg ha^{-1})*	0.28	0.27	0.26	0.19	0.28	0.21	0.27

Source: SINDAG (2012)-Sindicato Nacional da Indústria de Produtos para Defesa Agrícola

Information of cultivated area was based on Ministério da Agricultura, Pecuária e Abastecimento (MAPA 2012)

*Estimated by author

Relative contribution of the renovation phase of sugarcane areas (reform) increased from 765 Gg CO_2eq ha^{-1} $year^{-1}$ in 2006 to 1535 Gg CO_2eq ha^{-1} $year^{-1}$ in 2012 (Fig. 3). Sugarcane producers usually replant around 20% of their areas each year, but this renovation is highly dependent on the financial sources and raw material prices and can vary each year. As a result of that, during the years of 2008 and 2009, an expansion of sugarcane areas of 636,814 and 661,874 ha respectively (Table 1) was occurred mainly over annual crops and pasture areas. However, due to the world economic crises in 2008–2009, after this period, sugarcane expansion areas decreased to a rate of 137,445 ha in 2011 and 156,437 ha in 2012 (Canasat 2014).

Taking into account the mean values of the total GHG emission from sugarcane crop encompassing the period of 2006 to 2012, the highest contribution phase came from ratoon maintenance (GH + BH areas), with 51.7% of the total, when high agricultural inputs to cultivate the crop are applied, followed by the harvest practice phase with 31.8% (GH + BH) (Fig. 4). The crop renovation phase (reform) to establish a new planting area contributed to 9.7% of the total emission and the expansion areas contributed to 6.8% about total (Fig. 3), showing that higher effort to reduce sugarcane emissions should be focused mainly in ratoon phase, especially in N fertilizer application and diesel consumption from harvest and agricultural operations which were the higher emission sources contributing to the total, corroborating results of De Figueiredo and La Scala Jr (2011) and Bordonal et al. (2013). Different methods for fertilizers application in sugarcane areas are being discussed and tested, especially in GH areas when high amounts of straw are deposited on the soil surface after harvest (Gonzaga et al. 2018; Borges et al. 2019), leading to the need of using agricultural machinery to cut this crop residue and place the fertilizer around 5 cm below soil surface (Capaz et al. 2013). This results in better nutrient use and efficiency (Cherubin et al. 2019), better plants absorption, lower fertilizer loss due erosion (Martins Filho et al. 2009) and thus lower associated N_2O emission as a result of reduction in volatilization, leaching, and run-off process (Borges et al. 2019).

Despite total sugarcane cultivated area increased from 3.66 to 5.53 Mha in 2006 and 2012 respectively (Table 1 and Fig. 5), as well as total GHG emissions from sugarcane areas increased from 8329.5 Gg CO_2eq to 11,256.8 Gg CO_2eq (Fig. 3) in the same period (2006–2012), it is pertinent to show that average GHG emission per hectare base decreased during the

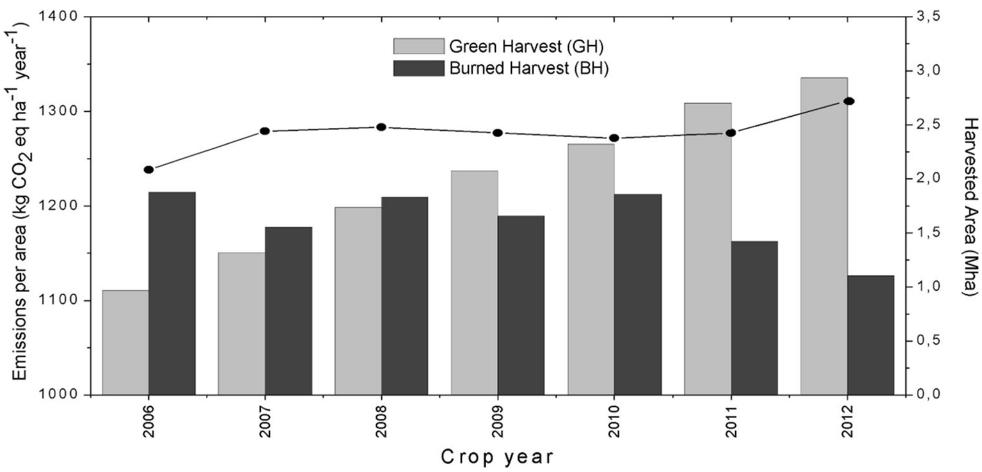


Fig. 4 GHG emissions per area for ratoon treatment phase in São Paulo State under green and burned harvest scenario

same period (Fig. 5), mainly due to the conversion of harvest system from BH to GH, showing that the adoption of Green Protocol Agreement effectively contributed to the reduction of GHG emission. This corroborates with França et al. (2014), who reported that government actions to reduce sugarcane straw burning emission are becoming effective. Furthermore, ethanol production during the studied period (2006 to 2012) (Table 3) increased from 11,060,113 m^3 to 12,018,061 m^3 respectively (Mapa 2012) and, consequently, once the ethanol use as biofuel is assumed to be strategy to substitute fossil fuel use with emissions reductions (EPA 2020), estimating an increase in the ethanol production of 957.948 m^3 from 2006 to 2012 would correspond to an avoided gasoline use of 670,563 m^3 (with ethanol having 30% less consumption efficiency). Therefore, the volume of ethanol replacing gasoline during the study period corresponds to an emission of 87,173,268 kg CO_2eq, and comparing if gasoline was used, we should have emission of 1,575,823,050 kg CO_2eq, or an avoided emission of 148,864,978.2 kg CO_2eq replacing gasoline for ethanol in this period. According to IPCC (2014), replacement of fossil fuel by biofuels is considered as an effective option for mitigation strategies.

A study conducted by Brazilian Agricultural Research Corporation (Embrapa) showed that during the period of 1986 to 2008, sugarcane cultivated area and crop yield increased 170% and 23% respectively, which resulted in a sugarcane production 180% higher in São Paulo State. However, the GHG emissions related to the harvest operations increased only 20.6% (Lima et al. 2010). Indeed, several studies have reported lower GHG emissions for GH compared to BH (Bordonal et al. 2012; Capaz et al. 2013; De Figueiredo and La Scala Jr 2011; García et al. 2011). On the other hand, estimated reductions of GHG emission per hectare base due to the conversion of sugarcane harvest system from BH to GH may vary from 310.8 (De Figueiredo and La Scala Jr 2011) to 644 kg CO_2eq ha^{-1} (Capaz et al. 2013). According to our results, taking into account the period from 2006 to 2012, the contribution of pre-harvest burning on the total GHG emission was reduced from 28 to 12%, while emissions associated with GH operations increased from 7 to 16% of the total (Fig. 3), probably for the reason that GH consumes more diesel in harvest operations and thus other options to reduce related emissions as the use of biodiesel currently available in Brazil should be highly incentivized (Bordonal et al. 2018).

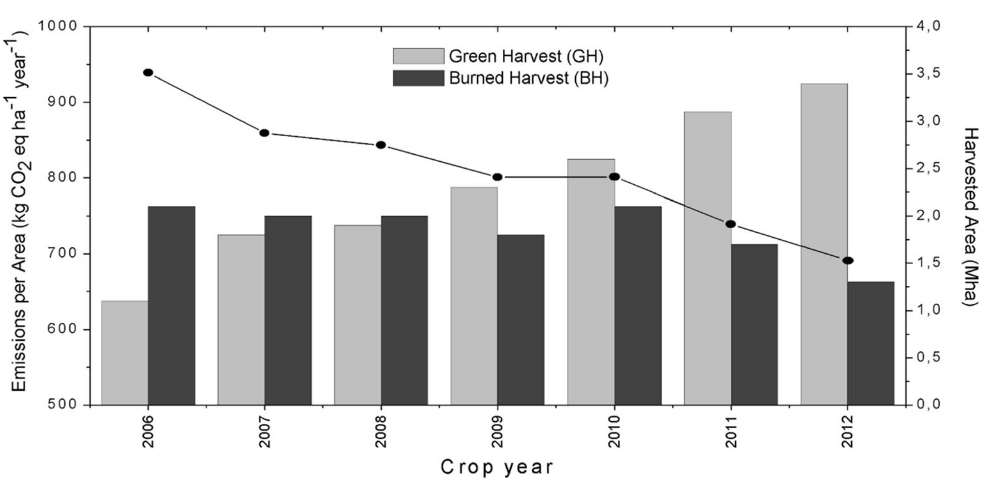


Fig. 5 GHG emissions per area for harvest phase in São Paulo State under green and burned harvest scenario

Ratoon maintenance area under GH system increased 204% during the study-period (Table 1), which implies in a higher amount of synthetic N fertilizers, pesticides, and diesel consumption, leading to higher emissions (De Figueiredo and La Scala Jr 2011; Gentile et al. 2008; Macedo et al. 2008). Improvement in fertilizer application is a key issue which should be addressed in order to reduce excessive use of fertilizer as well as its N_2O emissions, so that less fertilizer is used without jeopardizing the sugarcane yield (Yuttitham et al. 2011). In addition, it is expected a reduction in N synthetic fertilizers use around 4 to 5 years after GH adoption because high amounts of straw decomposition can further provide N available to sugarcane plants, leading to a reduction of fertilizers use and related emissions (Trivellin and Vitti 2020).

GHG emissions associated with agricultural inputs

When analyzing the contribution of each GHG emission source during the period between 2006 and 2012 (Table 5), the contribution of synthetic N fertilizers use increased from 32% in 2006 to 37% of the total emission in 2012, probably because during the first years of harvest systems conversion, GH areas demanded around 30% more N compared to BH system, due to the immobilization of N by the microbial biomass. Likewise, emission related to diesel consumption increased from 21% in 2006 to 26% of the total in 2012 due to the higher diesel consumption in the GH system, in which mechanized operation for harvesting also demands more fossil fuel (De Figueiredo and La Scala Jr 2011; Bordonal et al. 2013).

In contrast, the contribution of crop residues burning was responsible by approximately 20% of the total sugarcane crop emission in 2006 and decreased drastically to 9% in 2006, showing the benefits of changing harvest practices in São Paulo State during the assessed period, not only related to reduced GHG emissions but also contributing to avoid human respiratory diseases caused by the practice of residues burning (Tsao et al. 2011). According to Canasat (2014), 72.6% of the sugarcane crop area harvested in the state of São Paulo during the 2012/2013 crop season were carried out under green mechanized harvest (3.38 million hectares) and 27.4% of the area were harvested under the pre-harvest burning regime (1.28 million hectares). In addition, the GH practice leaves high amounts of residues available for other uses, as second-generation ethanol or bioelectricity (Carvalho et al. 2019). Sugarcane crop residues left on soil surface after GH are reported to be between 10 and 20 ton of dry matter ha^{-1} $year^{-1}$ (de Figueiredo et al. 2010; Leal et al. 2013). Estimating the

Table 5 Estimate of GHG emissions (Gg CO_2 eq $year^{-1}$) according to each agricultural source related to sugarcane cultivation in São Paulo State during 2006–2012

Emission source	2006 (Gg CO_2 eq $year^{-1}$)	2007	2008	2009	2010	2011	2012
Diesel oil	1784.4 (21.42%)	2231.5 (23.80%)	2471.7 (22.81%)	2392.0 (23.48%)	2589.1 (23.79%)	2827.0 (25.48%)	2930.1 (26.03%)
Lime	1296.7 (15.57%)	1609.8 (17.17%)	1944.3 (17.94%)	1568.4 (15.39%)	1459.6 (13.41%)	1685.1 (15.19%)	1856.3 (16,.49%)
Herbicide	146.9 (1.76%)	178.4 (1.90%)	205.2 (1.89%)	169.5 (1.66%)	171.7 (1.58%)	200.4 (1.81%)	298.5 (2.65%)
Insecticide	12.8 (0.15%)	17.6 (0.19%)	21.3 (0.20%)	15.1 (0.15%)	22.5 (0.21%)	20.7 (0.19%)	29.9 (0.27%)
Synthetic N fertilizer	2696.8 (32.38%)	2886.0 (30.78%)	3593.8 (33.17%)	3664.7 (35.97%)	4008.5 (36.83%)	4116.2 (37.10%)	4153.9 (36.90%)
Synthetic P_2O_5 fertilizer	47.8 (0.57%)	74.7 (0.80%)	87.8 (0.81%)	50.8 (0.50%)	32.2 (0.30%)	53.6 (0.48%)	70.2 (0.62%)
Synthetic K_2O fertilizer	116.9 (1.40%)	128.4 (1.37%)	155.4 (1.43%)	148.7 (1.46%)	152.5 (1.40%)	192.7 (1.74%)	202.3 (1.80%)
Filter cake	159.4 (1.91%)	178.5 (1.90%)	211.6 (1.95%)	217.8 (2.14%)	217.2 (2.00%)	183.6 (1.65%)	198.9 (1.77%)
Vinasse	269.5 (3.24%)	325.3 (3.47%)	411.9 (3.80%)	363.5 (3.57%)	376.8 (3.46%)	283.6 (2,56%)	292.8 (2.60%)
Burning of residues	1738.5 (20.87%)	1651.7 (17.61%)	1629.0 (15.03%)	1476.4 (14.49%)	1713.4 (15.74%)	1362.2 (12,28%)	1041.3 (9.25%)
Residues (straw)	59.8 (0.72%)	95.2 (1.01%)	103.8 (0.96%)	122.2 (1.20%)	141.7 (1.30%)	168.5 (1,52%)	182.3 (1.62%)
Total	8329.5 (100%)	9377.0 (100%)	10,835.7 (100%)	10.189,3 (100%)	10,885.2 (100%)	11,093.5 (100%)	11,256.8 (100%)

available residues left in the field for other uses, we can have around 50.7 Mton of crop residues available for other purposes, which can significantly contribute to further improve the sustainability of sugarcane crop as a sustainable bioenergy crop. Furthermore, studying the sugarcane straw availability, quality, recovery, and energy use, Leal et al. (2013) reported that the rapid increase in the implementation of GH system provides an excellent opportunity to improve the energy performance of sugarcane, the economics, and the sustainability of the ethanol production in Brazil.

However, there is currently a concern in the sugar-energy sector due to this thick straw cover remaining from the crop harvest that increases the density of the soil, reducing the porous space which would harm the production of sugarcane, in order to solve this problem, several studies have emerged addressing practices alternatives associated with straw management, such as the control of machinery traffic in the areas and mainly the partial removal of straw (Cherubin et al. 2019; Carvalho et al. 2019; Menandro et al. 2019).

Emission from lime application kept a similar trend during the evaluated period with around 15% of the total, as well as the contribution of other emissions sources as P_2O_5 and K_2O fertilizers, and pesticides. According to Seabra et al. (2011), emissions derived from the use and production of fertilizers, vinasse, filter cake, and liming represented 42% of the total emissions in sugarcane cultivation, followed by diesel consumption with 27% and burning of residues with 15%, which represents around 84% of the total GHG emissions related to sugarcane production. Our results showed that, the same emissions sources in the 2012 crop season were responsible for 60.2% of the total emission. Despite the emissions from those sources increased in 2012 comparing to data of Seabra et al. (2011), applying organic amendments such as vinasse and filter cake (i.e., by-products from sugar and ethanol industry) in the next crop can avoid considerably amounts of synthetic fertilizers and thus should be accounted for.

Our study indicates a steady growing of GHG emission associated with diesel consumption from 1784.4 to 2930.1 Gg CO_2eq (Table 5). The increase in the adoption of GH system resulted in a greater annual diesel consumption during the harvest season (Bordonal et al. 2013). In São Paulo State, the diesel consumption during the harvest season represented 13.5% of total GHG emissions in 1990 and increased to 38.5% in 2009 (Capaz et al. 2013). In our study, the diesel consumption contemplates diesel use in all agricultural operations besides the harvest operations only, showing an increase from 21.42 to 26.03% in relation to the total emissions in 2006 and 2012, respectively (Table 5).

Emissions regarding the insecticide and herbicide application increased proportionally with the sugarcane expansion. For organic composts (e.g., vinasse and filter cake), we observed a steady GHG emission over time. Regardless of the growing adoption of GH system during 2006–2012 (~ 204%), N_2O emissions from crop residues left on the soil surface increased from 0.72 to 1.62% (Table 5). However, there is a huge potential to use this residue as second generation ethanol and/or renewable energy, which could compensate this additional N_2O emission from residues mineralization on the soil surface.

Despite total sugarcane cultivated area in São Paulo state increased from 3.66 Mha in 2006 to 5.53 Mha in 2012, it is important to highlight that, according to our results, emission per area base decreased from 2275 to 2034 kg CO_2eq ha^{-1} year^{-1} (Fig. 6), showing that the management conversion of BH to GH system significantly contributed to the GHG mitigation in the São Paulo State. Therefore, changes related to harvest practices and crop management, taking into account 2006 to 2012 crop seasons, contributed to a reduction of 1.33 Mton of CO_2eq in this period, without considering the technical potential for soil C accumulation due to the conversion of BH to GH, as presented by Cerri et al. (2011) and Bordonal et al. (2013), which estimated additional GHG emission reduction due to the adoption of conservationist management practices.

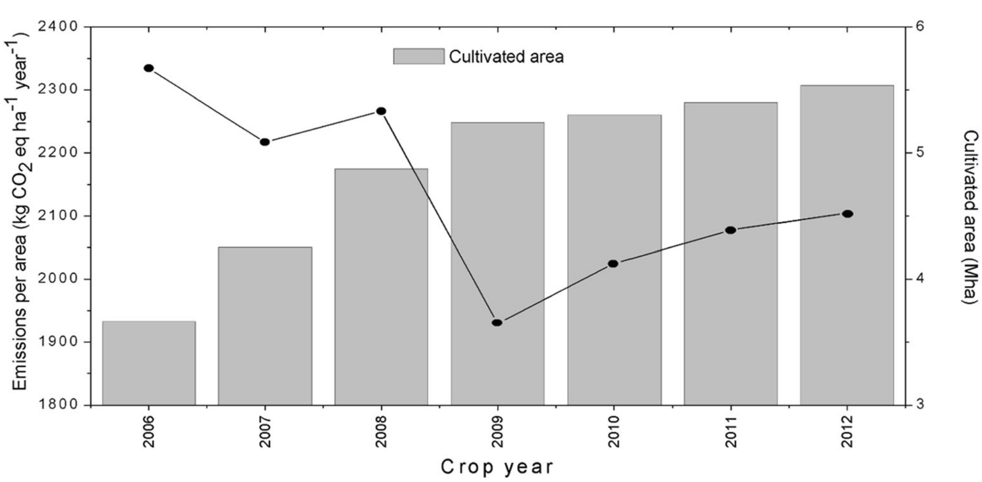


Fig. 6 GHG emissions per area for ratoon treatment phase in São Paulo State under green and burned harvest scenario

Conclusion

The increase in sugarcane production area under GH system, replacing BH system, has contributed to a steady reduction in GHG emissions per area over the years, even with the recent expansion of the total sugarcane area in southern Brazil. The estimated data of this work showed that the adoption of Green Ethanol Protocol has effectively contributed to the reduction of GHG emissions from sugarcane areas, and showed to be a useful governmental initiative for monitoring public policies and improvements for a more sustainable management of the sugarcane production chain.

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Availability of data and materials The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Authors' contributions L.I.P, R.O.B, E.B.F, M.R.M, and N.L.S.J wrote the main manuscript text and D.A.A, B.F.T.R and A.R.P. helped with data analysis. All authors reviewed, read, and approved the final manuscript.

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Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare that they have no competing interests.

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