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Short-term CO_2-C emissions from soil prior to sugarcane (*Saccharum* spp.) replanting in southern Brazil

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Abstract

New management strategies should be identified to increase the potential of bioenergy crops to minimize climate change. This study quantified the impact of sugarcane (*Saccharum* spp.) harvest systems, straw and soil management on carbon dioxide (CO_2) fluxes prior to crop replanting carried out on February 2010 in southern Brazil. The soil studied was classified as Haplustult (USDA Soil Taxonomy). Three sugarcane harvest systems were considered: burned (BH) and green harvest with straw maintained on (GH SM) or removed from (GH SR) the soil surface. Our hypothesis is that intensive tillage and the management of sugarcane crop straw could lead to higher CO_2 emissions from soil. We measured CO_2 emissions in no-till (NT) conditions and after conventional tillage (CT), and with or without dolomite and agricultural gypsum applications. Soil CO_2 emissions were measured with a Li Cor chamber (Model Li-8100). Water content of soil and soil temperature readings were first taken 24 h after tillage, over the next 25 days after tillage with 18 measurement days. The removal of sugarcane straw from the soil surface resulted in the rapid reduction of water content of soil (6% in volume) followed by a 64% increase in soil CO_2-C emissions, supporting our hypothesis. Additional soil CO_2-C emissions caused by removal of crop straw were 253 kg CO_2-C ha^{-1}, which is as high as CO_2-C losses induced by tillage. Dolomite and agricultural gypsum applications did not always increase CO_2 emissions, especially when applied on soil surface with crop straw and tilled. The conversion from burned to green harvest systems can improve the soil C sequestration rate in sugarcane crops when combined with reduced tillage and straw maintenance on soil surface. The effect of straw removal and related CO_2 emission for electricity generation should be considered in further studies from sugarcane areas.

Keywords: agriculture, crop straw, dolomite, greenhouse gas emissions, harvest systems, mitigation strategies

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Introduction

The United Nations Framework Convention on Climate Change treaty of 1992 (UNFCCC, 1992) recognizes the importance of accounting for net carbon (C) fluxes when it refers to 'emissions by sources and removals by sinks' (West & Marland, 2002). There is a need for the development of greenhouse gases (GHG) mitigation techniques in many agricultural sectors to minimize climate modification and meet agreed GHG target levels. Several agricultural practices have been shown to minimize GHG emissions. The main challenge facing the agricultural sector is to reduce net emissions while increasing production to meet the growing demand for food, fiber, and biofuel (Smith *et al.*, 2010).

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Several studies have shown that tillage induces large soil C losses in the short-term. Similar to deforestation, soil tillage accelerates the oxidation of soil organic matter, thus releasing large amounts of CO_2 in only a few days (Reicosky, 1997; Rochette & Angers, 1999; Prior *et al.*, 2000; La Scala *et al.*, 2001, 2008).

Because data on C inputs and losses are ambiguous due to the large variety of soil types, agricultural systems and management, questions on soil C sequestration and emissions associated with changes in agricultural practices have persisted (Schlesinger, 1999; Izaurralde *et al.*, 2000). Options to mitigate CO_2 emissions from management or land use changes include the reduction of emissions or the establishment of C sinks (Cole *et al.*, 1997).

In Brazil, several of those managements are usually adopted in sugarcane (*Saccharum* spp.) crop in most regions, and they can influence the dynamics of the crop C balance. These practices can be analyzed to establish which management should lead to the largest gains or losses. Two additional facts must also be considered. First, C sequestration rate seen in sugarcane areas that are converted from burned to mechanized green harvest (GH) is lower in sandy soils (1.02 ± 0.22 t C ha^{-1} yr^{-1}) probably due to lower soil aggregation and second, few studies in the literature consider the renovation of sugarcane fields, which occurs every 5 or 6 years after planting and causes the sequestration potential to be almost completely lost (La Scala *et al.*, 2012).

There is a large amount of C as crop straw deposited on the soil over several harvest years on sugarcane green harvested areas. During crop renovation, a substantial portion of this C could be lost in the short-term due to intensive soil tillage (Reicosky & Lindstrom, 1993; La Scala *et al.*, 2006, 2008). Conventional tillage with intensive soil disturbance promotes the rapid decrease of SOM and the subsequent increase of CO_2 emissions (Bayer *et al.*, 2000). Increases in SOM once sugarcane areas are converted from burned to GH systems vary from 0.93 to 1.45 t C ha^{-1} yr^{-1} in sandy soils and 1.59–2.27 t C ha^{-1} yr^{-1} in clay soils (Cerri *et al.*, 2011). However, the results of studies that consider tillage operations during the replanting season have shown lower sequestration rates (0.16 t C ha^{-1} yr^{-1}) and losses of 0.14 t C ha^{-1} yr^{-1} even 12 years after the adoption of GH system (Rezende *et al.*, 2006; Cerri *et al.*, 2011). Studies are needed to quantify CO_2-C fluxes as they relate to the management and soil properties during the period of sugarcane replanting in burned and green harvested areas. The effects of crop straw management, tillage operations, and chemical amendments as dolomite and agricultural gypsum, usually applied in most sugarcane areas to raise soil pH and to annul toxic aluminum in sub surface, should be studied to obtain a better understanding of soil C balance in sugarcane areas in Brazil.

This study aimed to quantify the impact of different harvest systems, management of crop straw, tillage and amendments in sugarcane areas on short-term CO_2-C fluxes prior to crop replanting in Brazil. In particular, electricity production from biomass is a key issue, mainly due to its potential for reducing CO_2 emissions (IEA, 2004). Straw management, either left on soil surface after harvest, incorporated into soil through tillage, or recovered for electricity generation as well as dolomite application could impact directly on the GHG balance of biofuel production and should be better investigated. Our hypothesis was that intensive tillage, the straw management and the application of dolomite and gypsum during renovation of sugarcane areas, could lead to higher short-term CO_2 emissions.

Materials and methods

Area description

The experimental field was in a sugarcane farm near Mococa city (21°25′S; 47°05′W), São Paulo State, southern Brazil. According to Thornthwaite (1948), the climatic classification of the area is B_1rB_4a, which is tropical moist with an average annual temperature of 21 °C. The mean annual precipitation is approximately 2500 mm. The major rainfall period is between October and March with a relatively dry period between April and September. The soil is classified as Haplustult (USDA, Soil Taxonomy). The site has been planted to sugarcane as a monoculture for 20 years, with the burning harvest regime. The conversion from burned (BH) to green harvest (GH) occurred 3 years before experiment started and, in adjacent plots, as shown in Fig. 1, due to higher slope (>12%) one of the plots was kept with pre-burning, where BH treatments was installed in our experiment. Both areas, BH and GH have been harvested for 3 years consecutively without renovation of planting, representing 1 harvest after replanting and 2 ratoons (two harvests of sprouting), and the varieties cropped were SP81-3250 for the burned and SP91-3011 for the GH areas.

On February 2nd, 2010, twelve (12) experimental treatments were established in adjacent treatments in previously BH and GH areas (Fig. 1) separated by an unpaved road (ca. 5 m), all of which had been harvested on September 20th, 2009. Treatments were established in 7 × 10 m plots. All areas remained under fallow following harvest until February 2010 when it was sprayed glyphosate herbicide to kill old plants. Thus, the experimental treatments were defined as three harvest systems: (i) Burned Harvest (BH), straw burned preharvest as common practice to facilitate manual harvest 4 months before experiment started; (ii) GH with straw removed from the soil surface (GH SR) 1 day before experiment started; and (iii) GH with large amount of straw maintained on the soil surface (GH SM). Each harvest type was combined with four management systems: (i) No till (NT), (ii) conventional tillage (CT), (iii) conventional tillage + dolomite (CTDol), and (iv) conventional tillage + dolomite + gypsum application (CTDolG) (Table 1). The plots in GH have been mechanically harvested about 4 months before experiment started, resulting in a large amount of sugarcane straw (9231 kg dry matter ha^{-1}) left on the soil surface. In four of the GH treatments, crop straw was removed manually from the soil surface with minimum soil disturbance. This resulted in four treatments in the burned area without straw, which were burned preharvest (BH) and another eight in the GH area, four with straw and four without straw on soil surface, totalizing 12 treatments.

Conventional tillage and application of amendments were performed in the same day in each treatment of the harvest systems (BH, GH SR, and GH SM, on February 2nd, 2010) with the following operations: (i) heavy offset disk-harrow (discs of 66 cm) to a depth of around 30 cm with a Valtra BH 180 tractor at a speed of 6 km h^{-1}; (ii) medium offset disk-harrow (discs of 60.9 cm) to a depth of around 20 cm with a New Holland TM150 tractor at a speed of 6 km h^{-1}; (iii) subsoil tillage to a depth of 40 cm with four rods; and (iv) equalizer disk-harrow

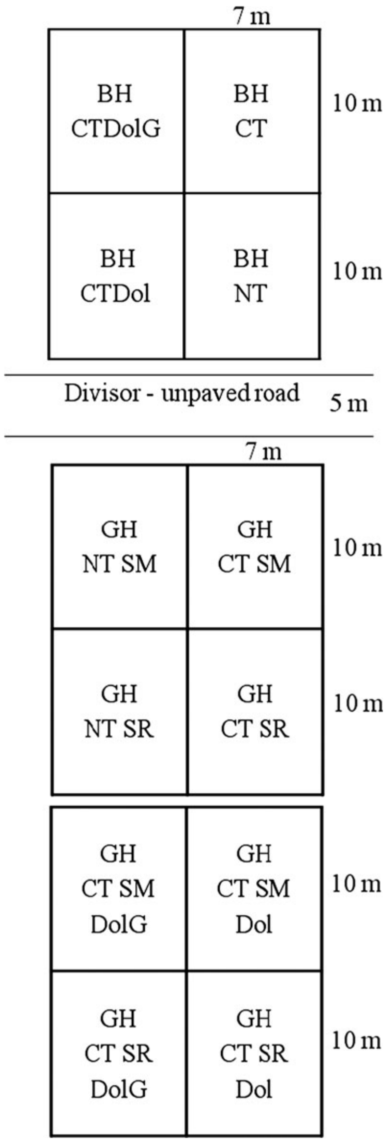

Fig. 1 Schematic figure showing experimental design, BH, Burned harvest; GH SM, Green harvest, straw maintained; GH SR, Green harvest, straw removed; NT, no till; CT, Conventional tillage; Dol, Dolomite application; G, Gypsum application.

(discs of 55.8 cm) to a depth of 10 cm with a New Holland TM150 tractor at a speed of 7 km h^{-1} (twice). This sequence is considered as conventional soil tillage for sugarcane in the region, and NT treatments were left without any tillage operations. Chemical management included dolomite ($CaMg(CO_3)_2$) and gypsum ($CaSO_4.2H_2O$) applied and incorporated into the soil in selected treatments (Table 1) at 2 t ha^{-1} each. Dolomite is usually applied to increase soil pH, whereas gypsum is applied to reduce aluminum toxicity to plant roots in the subsoil and to provide calcium and sulfur for better root growth. In the experimental areas, No-till treatments in BH, GH SR, and GH SM were left as controls without tillage and without dolomite and gypsum only to determine additional emission

Table 1 Description of 12 treatments considering 3 harvest systems, burned harvest (BH) with straw burned preharvest, green harvest with straw removed from soil surface (GH SR), and green harvest with straw on soil surface after harvest (GH SM), and four managements within each harvest system (NT, CT, CTDol, and CTDolG) placed on sugarcane areas

Harvest system	Management	Description
BH	NT	Burned harvest. No tillage and not disturbed.
	CT	Burned harvest. Conventional tillage.
	CTDol	Burned harvest. Conventional tillage plus dolomite.
	CTDolG	Burned harvest. Conventional tillage plus dolomite and gypsum.
GH SR	NT	Green harvest, straw removed. No tillage, not disturbed.
	CT	Green harvest, straw removed. Conventional tillage.
	CTDol	Green harvest, straw removed. Conventional tillage plus dolomite.
	CTDolG	Green harvest, straw removed. Conventional tillage plus dolomite and gypsum.
GH SM	NT	Green harvest with straw. No tillage, not disturbed.
	CT	Green harvest with straw maintained. Conventional tillage.
	CTDol	Green harvest with straw maintained. Conventional tillage plus dolomite.
	CTDolG	Green harvest, with straw maintained. Conventional tillage plus dolomite and gypsum.

effect of each management, where the subtraction of emissions from BH CT to BH NT result in additional emission effect of tillage (CT), as well as subtracting emissions of BH CT to BH CTDol is possible to obtain the additional emission effect of dolomite and, BH CTDolG subtracted of BH CTDol results emission effect of gypsum application. In addition, emission from GH SM CT minus emission from GH SR CT results emission effect of straw mixed on soil. On February 2nd, immediately following soil tillage, nine PVC soil collars (10 cm in diameter) were inserted to a depth of 3 cm in each of the treatments, giving a total of 108 emission measurement points for all treatments.

Sugarcane straw left on soil surface was characterized by collecting samples on 1 m^2 in each of the GH SM treatments (N = 4), using 1 × 1 m mold. Those samples were dried in an oven for 72 h at 70 °C until dry and resulted in an average of 9231 kg dry matter ha^{-1}. Based on an estimated C concentration in sugarcane straw of 420 g kg^{-1} (Trivelin *et al.*, 1995), 3877 kg C ha^{-1} accumulated on soil surface in GH SM NT treatment.

Soil sampling, physical, and chemical analysis

Soil samples were collected to a depth of 20 cm after CO_2-C emission measurement and 30 days after dolomite and gypsum applications. Ten samples per treatment were combined to yield 1 kg (Table 2). Volumetric soil samples of the surface layer were taken with a stainless steel cylinder (100 cm^3) for bulk density determination, with four replicates per treatment with approximately 150 g of soil in each sample. The chemical characteristics of soil analyzed were pH, soil organic matter (SOM),physic characteristics, size of soil particle distribution, and soil bulk density from BH and GH areas. Samples were dried and sieved through a 2-mm mesh prior to further analyses. These analyses included SOM content by oxidation with sulfuric acid (Raij *et al.*, 1987). 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 method pH SMP measured in water and in solution of 0.01 mol l^{-1} $CaCl_2$ (Table 2).

To estimate the contribution of soil, straw, dolomite, and gypsum in each harvest system (BH, GH SR, and GH SM) to CO_2 emissions, we calculated corrected stocks to a 20-cm depth, based on constant depth basis and expressing values as soil organic carbon (SOC) stock (Bayer *et al.*, 2000). We used the formula $\text{CStock} = (\text{OC} \times \text{SD} \times e)/10$, which yields in Mg ha^{-1}, where OC is SOC content (g kg^{-1} = SOM/1.724), *SD* is soil bulk density measured at the surface (Mg m^{-3}), and *e* is the layer thickness (m). With C data from soil, straw and dolomite, it was also possible to estimate the C stock contained in each of those emission sources.

By the total emissions from each treatment in each harvest system and estimations of total amount of SOC stocks (Table 2), crop straw (3877 kg C ha^{-1}) and dolomite (carbonate carbon content, 13%, Intergovernmental Panel on Climate Change, IPCC, 2006), we estimated induced emissions from soil C losses from each source (soil, straw, and dolomite).

CO_2 emission, water content of soil and temperature measurements

Measurements of soil CO_2 emissions, water content of soil and temperature (12 cm depth) were initiated 24 h after tillage (February 3rd, 2010) and continued until February 27th, 2010. Those were measured 18 times over 25 days. Measurements were usually taken in the morning between 8:00 hours and 11:00 hours with two portable LI-COR systems (LI-8100 LI-COR, NE, USA). The LI-8100 system monitors the changes in CO_2 concentration inside the chamber by an infrared gas analyzer. The soil chamber has an internal volume of 854.2 cm^3 with a circular area of 83.7 cm^2. Soil temperature was monitored with a 20-cm-length probe (thermistor-based sensor) inserted into the soil close to the collars to a 12 cm depth. This measurement sensor is an integral part of LI-8100 system. Water content of soil (v v^{-1}) was measured (12 cm depth) with a portable Time Domain Reflectometer system (HydroSense System, Campbell Scientific, Utah, USA). On days 15 and 21 after tillage, measurements were not taken due to precipitation events of 20 and 23 mm respectively. In all measurements, a period of 90 s at each measurement point was used to measure CO_2 emissions on each collar, completing 108 points as quickly as possible to minimize soil temperature variation during the measurement period. The cumulative soil CO_2-C emissions during the study period were estimated by integrating the area under the curves of soil CO_2-C emissions over time with R software (R Development Core Team, 2011).

Statistical analyses

The CO_2-C emissions, temperature and water content of soil data were analyzed as a two-factor experiment (Harvest system and management) in a completely randomized design and repeated measurement over time, using a mixed model procedure (Proc Mixed) performed by statistical software SAS. [SAS

Table 2 Soil properties in treatments from each harvest system and management in burned and green harvested systems

Harvest system	Management	SOC stock* (Mg ha^{-1})	pH ($CaCl_2$)	Soil bulk density (Mg m^{-3})	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})
BH	NT	12 760	4.6	1.45	675	175	150
	CT	12 760	4.6	1.31	675	175	150
	CTDol	12 760	6.1	1.34	675	179	146
	CTDolG	12 760	5.7	1.36	677	175	148
GH SR	NT	13 920	4.7	1.48	672	130	198
	CT	15 080	4.9	1.29	651	170	179
	CTDol	16 240	5.1	1.21	636	130	234
	CTDolG	16 240	5.3	1.24	624	149	227
GH SM	NT	13 920	4.7	1.52	672	130	198
	CT	16 240	4.8	1.30	688	120	192
	CTDol	16 240	5.1	1.24	636	130	234
	CTDolG	16 240	5.3	1.18	627	155	218

*0–20 cm layer.

BH, Burned harvest; GH SR, Green harvest straw removed; GH SM, Green harvest with straw maintained, and managements; NT, no-till; CT, conventional tillage; CTDol, Conventional tillage plus dolomite application; and CTDolG, Conventional tillage plus dolomite and gypsum application.

Institute (2004) SAS/STAT User's Guide (Ver. 9.1.3 Service Pack 4) SAS Institute Inc., Cary, North Carolina]. The linear correlation analyses were also performed with the SAS System. Pairwise comparisons of means were done with Tukey's procedure; a $P < 0.05$ was considered significant.

Results

Influence of harvest systems, tillage, straw, dolomite, gypsum, and interaction among factors on CO_2-C emissions

The analysis of variance of repeated measures indicate a high significance ($P < 0.0001$) among harvest systems (BH, GH SR, and GH SM), managements (NT, CT, Dol, and G), and time (days) for soil CO_2 emission, temperature, and water content of soil.

Twenty-four hours after tillage, lower emissions in all three harvest systems have been observed in NT treatments (Fig. 2), with 0.086, 0.137, and 0.070 g CO_2-C m^{-2} h^{-1} for BH, GH SR, and GH SM respectively ($P < 0.0001$). Emissions from NT treatments in each of those harvest systems considered were lower during the entire studied period ($P < 0.0001$). Changes in CO_2-C emissions in all harvest systems can be clearly seen when tillage, dolomite or gypsum were applied. For instance, in the BH system, initial emissions at day one after tillage were 0.164, 0.227, and 0.278 g CO_2-C m^{-2} h^{-1} for CT, CTDol, and CTDolG, respectively, showing not only an increase on conventional tillage (CT) when compared with no till (NT) ($P < 0.0001$) but also further increases induced by dolomite and gypsum applications.

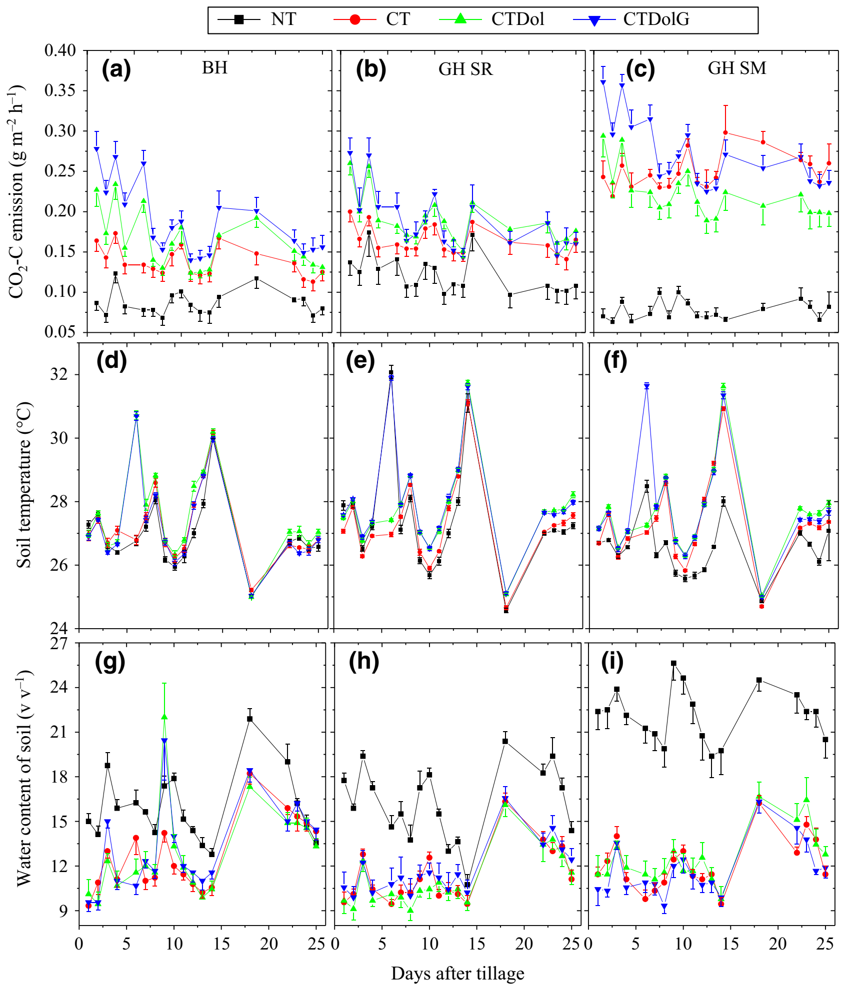

Fig. 2 (a–i) CO_2-C emissions (g m^{-2} h^{-1}), soil temperature (°C), and water content of soil (v v^{-1}), plus half of standard errors (vertical bars), for the BH (Burned harvest, a, d, g), GH SR (Green harvest straw removed, b, e, h) and GH SM (Green harvest straw maintained, c, f, i) and managements, NT: No tillage; CT: Conventional tillage; CTDol: Conventional tillage plus dolomite; CTDolG: Conventional tillage plus dolomite and gypsum.

Emissions from GH SM, considering all managements where conventional soil tillage has been performed were higher than those of GH SR where straw have been removed to access this effect (Fig. 2b–c), especially after the third day after tillage ($P < 0.05$), except in GH SM NT, where lower emissions were observed when compared to GH SR NT ($P < 0.05$). Those higher emissions observed when tillage was applied can be related to water content of soil only in GH SM NT which was higher than in GH SR NT (22.2 and 16.2% respectively) ($P < 0.001$) with time following crop straw removal (Fig. 2h–i). In addition, water content of soil in GH SM NT was significantly higher ($P < 0.05$) when compared with water content of soil in BH NT (Fig. 2g–i) on most days.

Increased CO_2-C flux observed for all harvest systems when tillage or amendments have been applied (Fig. 2a–c) was directly related to lower water content of soil, as shown in Fig. 2g–i. In GH SM and GH SR systems, NT management presented a significant effect on water content of soil compared with all other managements (CT, CTDol, and CTDolG), except in BH treatment, which showed no difference between managements ($P > 0.05$). By comparing graphs in Fig. 2a–c, g–i, it can be seen that the lowest emissions only in NT treatments from all harvest systems were associated with higher water content of soil (v v^{-1}).

Emissions after tillage in GH SR and BH systems converged to values close to NT emissions ($P > 0.05$) at the end of the experiment (0.165, 0.176, and 0.160 for GH SR and 0.125, 0.131, and 0.156 g CO_2-C m^2 h^{-1} for BH, CT, CTDol, and CTDolG respectively). On the other hand, emissions in GH SM tilled treatments, including CT, CTDol, and CTDolG, presented higher values ($P < 0.0001$) throughout the measurement period (0.260, 0.198, and 0.260 g CO_2-C m^2 h^{-1} respectively) and did not converge to values close to NT plot at the end of the experiment.

Results of linear correlation analyses among soil CO_2 flux, temperature, and water content of soil showed no significant linear correlation between soil CO_2 flux and temperature, except for GH SR NT system ($r = 0.46$; $P < 0.05$). There was a positive and significant linear correlation between soil CO_2 flux and water content of soil for BH NT ($r = 0.57$; $P < 0.05$), GH SM NT ($r = 0.48$; $P < 0.05$), and GH SM CT ($r = 0.65$; $P < 0.05$).

Soil temperature was similar for all management and harvest systems during the experiment, with means from 26.4 to 27.9 °C. Our results showed that soil temperatures in GH SM NT treatments presented the lowest values ($P < 0.05$) when compared with GH SR NT and BH NT treatments without straw (straw burned preharvest), indicating that straw, when maintained on soil surface after harvest, could significantly influence soil temperature.

Total short-term CO_2-C emissions

Total CO_2-C emissions for all treatments, accumulated in 25 days after tillage, are presented in Fig. 3 and were calculated as the area below the curves presented in Fig. 1a–c. When comparing the effect of straw removal from GH systems (Fig. 3), the data show an increase in total emissions (446 kg CO_2-C ha^{-1} in GH SM NT to 699 kg CO_2-C ha^{-1} in GH SR NT), representing an additional loss of 253 kg CO_2-C ha^{-1} ($P < 0.05$). Converting the data from CO_2-C to CO_2, this loss represents an avoided emission of 928 kg CO_2 ha^{-1} over 25 days if the crop straw can be maintained on the soil surface in GH SM without tillage and no chemical amendments.

In NT treatments, soil bulk densities were 1.45, 1.48, and 1.52 Mg m^{-3} for BH, GH SR, and GH SM respectively; these values are higher than those where tillage was applied (Table 2) and can be related to lower emissions in NT treatments. The highest total emission induced by tillage was observed in GH SM CTDolG management, resulting in 1550 kg CO_2-C ha^{-1} over 25 days. Subtracting GH SM NT plot emission (446 kg CO_2-C ha^{-1}), to GH SM CTDolG emission (1550 kg CO_2-C ha^{-1}), this amount would represent the CO_2-C loss from conventional soil tillage and amendments normally applied in GH areas during crop renovation, resulting in additional 1104 kg CO_2-C ha^{-1} or 4047 kg

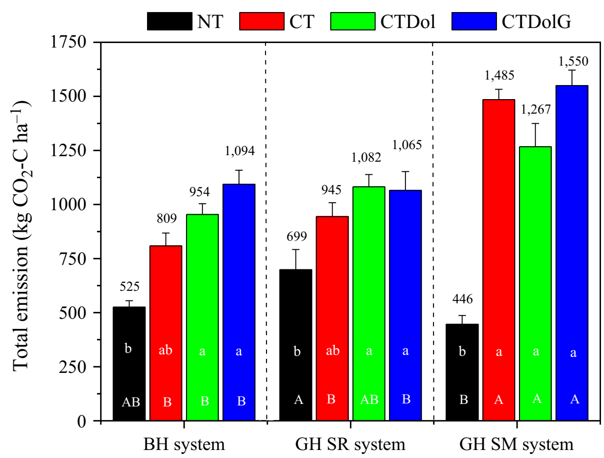

Fig. 3 Total CO_2 emission (plus half of standard error, kg CO_2-C ha^{-1}) from the sugarcane harvest systems, burned harvest (BH), green harvest with straw removed (GH SR) and green harvest with straw maintained (GH SM), and respective managements (NT, CT, CTDol, and CTDolG), 25 days after tillage. NT, No tillage; CT, Conventional tillage; CTDol, Conventional tillage plus dolomite; CTDolG, Conventional tillage plus dolomite and gypsum. Means followed by the same letters comparing management types within each harvest system (small letter) and comparing each system across harvest systems (capital letter) did not differ by the Tukey test ($P < 0.05$).

CO_2 ha^{-1} released into the atmosphere on short-term. The same management as usually performed during renovation of sugarcane areas, when applied to BH (CTDolG) would cause extra emissions of 569 kg CO_2-C ha^{-1} respect to NT (1094 minus 525, Fig. 3), corresponding to 2086 kg CO_2 ha^{-1} released into the atmosphere over 25 days due to crop renovation operations on BH area.

For BH and GH SR systems, additional emissions induced by the conventional tillage (CT), after subtracting NT emissions, were 284 and 246 kg CO_2-C ha^{-1} respectively. These amounts correspond to a loss of 2.22 and 1.63% of SOC stock (0–20 cm layer, Table 2) in those plots in the BH and GH SR systems, respectively, only on 25 days.

A much higher emission induced by tillage and straw incorporation has been observed in GH SM CT which when subtracted from GH SM NT (Fig. 3) results +1039 kg CO_2-C ha^{-1}. In addition, field measurements showed that there were 9231 kg of dry matter ha^{-1} of sugarcane straw on soil surface before tillage in GH SM treatments, which represents 3877 kg C ha^{-1} (Trivelin *et al*., 1995). Our results pointed out to additional emissions induced by straw in GH SM CT treatments when compared with GH SR CT treatments, with an increase of 540 kg CO_2-C ha^{-1} (GH SM CT - GH SR CT) coming primarily from sugarcane straw C losses, as soil conditions and tillage systems were the same in both treatment (Fig. 3). Based on this difference, we can infer that 14% of C incorporated from straw in the soil has been lost as CO_2-C post-tillage emission along 25 days in GH SM CT.

The effect of dolomite on additional emissions is addressed by subtracting the total emissions of the treatment with dolomite from the treatment without dolomite (i.e., CTDol minus CT, in each of the harvest systems). The increase in CO_2-C emissions due to dolomite application was higher in BH and GH SR systems, where 145 and 137 kg CO_2-C ha^{-1} or 532 and 502 kg CO_2 ha^{-1}, respectively, have been induced by dolomite.

Treatments where agricultural gypsum was applied presented increased emissions in BH and GH SM (Fig. 3). Additional emissions due to the application of 2 t ha^{-1} of gypsum (CTDolG - CTDol) were 140 and 283 kg CO_2-C ha^{-1} for BH and GH SM respectively.

Figure 3 also presents the total emissions comparing managements within each harvest system (small letter) and comparing each management system across harvest systems (capital letter). Within each harvest systems, total emissions in NT treatments were lower ($P < 0.05$) when compared with the others, CT, CTDol, and CTDolG (Fig. 3), with the exception of BH NT when compared with BH CT management and GH SR NT, when compared with GH SR CT management ($P > 0.05$).

Discussion

Effects of surface straw on CO_2-C emission

Considering all harvest systems and treatments tested in our study related to the most common sugarcane harvest practices in Brazil, burned harvest and green harvest systems and usual managements, the lowest CO_2-C emission was observed in GH SM NT treatment where crop straw have been maintained on the soil surface after green harvest. The experimental area had been harvested 4 months before the experiment started; showing that decomposition of straw on the soil surface in GH SM NT was not significantly contributing to higher CO_2-C fluxes under the undisturbed condition. As reported by Reicosky *et al.* (1999), effects of surface straw produced lower CO_2 and H_2O fluxes from NT treatments, with surface straw serving as a 'mulch' barrier for CO_2 diffusion from the soil to the atmosphere. Studying net GHG fluxes in Brazilian ethanol production systems, Galdos *et al.* (2010) showed that there is an annual input of 5–10 Mg of C left on the soil surface as dry sugarcane leaves and tops and much of the C in crop straw will be remineralized and eventually incorporated into the soil with potential to increase SOC stock in long-term. However, there are several factors which must be taken into account when assessing the potential for increases in soil C.

Recent studies have indicated that the maintenance of sugarcane straw on soil after harvest has physical, chemical, and biological effects (Galdos *et al*., 2009). Some sugarcane mills in Brazil are considering the potential to power generation using crop straw when they are reaped mechanically after green harvest and later burned on boilers to power generation or to produce second generation ethanol. Harvesting burning practices, which result in intense air pollution, are being phased out, resulting in energy benefits of mechanization due to higher surpluses of electricity that can be produced from sugarcane byproducts corresponding to 30% more in terms of biomass availability (Goldemberg *et al*., 2008). Several aspects should be investigated by the impact of straw removal on soil erosion, nutrients recycling, GHG balance, soil water availability as well as the amount of the straw that could be reaped with less impact for agricultural sustainability. A positive correlation between the maintenance of sugarcane straw and the increase in soil organic matter content has been observed in several studies, influenced by time since adoption of the unburned harvest, soil texture, and soil disturbance in the replanting period (Robertson, 2003; Cerri *et al*., 2004a, b). Nevertheless, a very limited number of studies provide any recommendation on the amount of crop straw that should be maintained in agricultural fields in Brazil (Carmo *et al.*, 2013). In contrast, if straw can be kept on the soil surface after harvest, this practice will lead to N_2O emissions due to the straw mineralization (IPCC, 2006). Further studies should be carried out to compare benefits of straw maintenance on soil surface against straw removed for power generation and production of second generation ethanol, accounting CO_2 emissions as a component of crop GHG balance and related N_2O emissions.

Effects of straw removed from soil surface on CO_2-C emissions

Additional emissions reported here when crop straw have been removed (GH SM NT–GH SR NT) (+253 kg CO_2-C ha^{-1}), even considering short-term data, are equivalent to the annual potential of soil C sequestration in sugarcane areas in Brazil, which vary from 0.14 to 2.38 Mg C ha^{-1} yr^{-1} (Cerri *et al.*, 2011). On the other hand, Walter & Ensinas (2010) studying the production of second-generation biofuels and electricity from sugarcane residues considered that 50% of the sugarcane straw available at the field could be recovered and transported to the mill to be used as fuel and presented emission factor of 38.3 kg CO_2eq per ton of stalks.

Comparing the GHG balance after the conversion of sugarcane areas from burned to green harvest, De Figueiredo & La Scala (2011) estimated net emissions of CH_4 and N_2O due to straw burning preharvest on the field as 941 kg CO_2eq ha^{-1}. Hence, the removal of straw from the soil surface after green harvest in our experiment (928 kg CO_2 ha^{-1}) resulted in additional soil emissions which represent amounts close to the burning of sugarcane field presented by De Figueiredo & La Scala (2011) which could annul the benefit of nonburning practice. According to our results, the sugarcane area of 5.3 million ha in São Paulo State (Rudorff *et al.*, 2010), harvested under the green harvest system, could avoid additional emissions of 4.92 Mt CO_2 yr^{-1} by keeping crop straw on soil surface instead to remove, so that could represent a feasible strategy to reduce emissions from sugarcane GH areas.

Studying the effect of C cycling and sequestration opportunities in Brazil, Cerri *et al.* (2004a, b) concluded that the CO_2 mitigation related to the main management practices and the adoption of good management strategies has the potential to raise soil carbon levels and consequently improve soil structure and this would result in increased infiltration rates, better soil water relations, reduced surface sealing, and erosion which should lead to increased crop yields. The improvement and maintenance of soil carbon and soil structure are necessary for sustainable agricultural systems and conservation of the soil resource.

Agronomic effects should be considered when sugarcane straw can be removed for any purpose. Galdos *et al.* (2009) showed that several studies have indicated that the maintenance of sugarcane straw has physical, chemical, and biological effects on the soil. The effect of straw in nitrogen dynamics has been studied, with focus on aspects such as soil nitrogen immobilization by litter decomposing microbes, and the availability of litter-derived nitrogen to the crop (Meier *et al.*, 2006). The maintenance of sugarcane straw on the field affects soil temperature and water content (Dourado-Neto *et al.*, 1999), soil density (Tominaga *et al.*, 2002), infiltration rates, and aggregate stability (Graham *et al.*, 2002). A positive correlation between the maintenance of sugarcane straw and the increase in soil organic matter content has been observed in several studies, induced by time since adoption of the unburned harvest, soil texture, and soil disturbance in the replanting period (Robertson, 2003; Cerri *et al.*, 2004a, b).

Effect of intensive tillage on CO_2-C emission

Theoretically, the additional CO_2-C emissions in CT treatments (Intensive tillage) compared with NT in BH and GH SR systems should come from soil C losses, as no straw, dolomite, or gypsum have been added to the soil on this plots. Tillage-induced soil C loss has been shown to be an important practice especially in short-term periods when soil tillage accelerates organic C oxidation releasing high amounts of CO_2 to the atmosphere in a few weeks (La Scala *et al.*, 2001, 2006; Prior *et al.*, 2000; Ellert & Janzen, 1999; Rochette & Angers, 1999; Reicosky, 1997; Reicosky & Lindstrom, 1993). Emissions from tilled treatments are addressed in terms of the non-disturbed emission plus tillage induced component as well as performed in our study, assuming labile C in SOM decays following a first order differential equation (La Scala *et al.*, 2008). Cerri *et al.* (2011) emphasized that lower amounts of soil C sequestration has been observed in places with intensive tillage, which primarily occurs in the renovation of sugarcane areas. Paustian *et al.* (2000) also have shown that intensive tillage, particularly moldboard plowing, results in large soil CO_2 losses.

These results reinforce the importance of evaluating short-term emissions after tillage, dolomite, and gypsum amendments in sugarcane areas, especially during replanting operations. Measurements of soil gas fluxes induced by different tillage or management are important to identify which practices would most impact on the soil C balance (Post *et al.*, 1990; Reicosky, 1997).

Our results from field measurements showed that there was 12 760 Mg of SOC ha^{-1} (0–20 cm layer, Table 2) in BH CT plot and 15 080 Mg of SOC ha^{-1} in GH SR CT and therefore, emissions from those treatments (Intensive tillage) can represent a loss of 2.22 and 1.63% of SOC stock from those plots, respectively, only in 25 days. However in our study, BH CT plot where straw has been burned 4 months prior to the experiment beginning, presented lower SOC stock and higher soil CO_2-C flux, unlike GH SR CT which presented higher SOC stock and lower CO_2-C flux.

Effect of straw incorporation on CO_2-C emissions

A much higher total CO_2 emission accumulated in 25 days after tillage has been observed in GH SM CT (+540 kg CO_2-C ha^{-1}) compared with GH SR CT (Fig. 3), which might be associated with sugarcane straw incorporated into the soil through tillage, demonstrating a huge influence of straw incorporation on enhanced emissions in GH SM CT. Considering that 14% of C incorporated from straw (3877 kg C ha^{-1}) in the soil has been lost as CO_2-C post-tillage emission along 25 days, this result is similar as those of La Scala *et al.* (2006, 2008), who suggested that 30% of C from the straw of sugarcane crop could be lost in 30 days after plowing a tropical soil. Bayer *et al.* (2000) showed that under conventional tillage, crop straw incorporated in soil becomes a readily available source of energy to microorganisms. Reicosky & Lindstrom (1993) determined that over a 19-day period following soil tillage, more C was liberated as CO_2 than was added by crop straw at the season end (1.85 Mg C ha^{-1} yr^{-1}), indicating substantial SOM oxidation. It is important to note that our estimates do not account for any priming effect, in which the addition of fresh organic matter would increase the microbial activity and thus cause further decay in older SOM. Many authors have noted these effects after adding other straw with lower C : N ratios than sugarcane straw (Kuzyakov *et al.*, 2000; Dijkstra & Cheng, 2007). Some better management practices during sugarcane crop renovation as reduce tillage could promote reduced emissions and improve the potential for soil C sequestration. The adoption of an annual reduced tillage strategy in place of the conventional tillage would result in a 15% increase in the soil carbon stock in sugarcane areas over a 20-year period at the 0–30-cm layer (Bordonal *et al.*, 2012).

When comparing all tilled treatments on GH SM where crop straw has been incorporated on soil at around 25 cm depth (Fig. 2b and c) to GH SR, we can observe that higher CO_2-C emissions throughout the measurement period in GH SM system should probably come from the effect of continuous straw decomposition on soil and higher microbial activity promoted either by the influence of dolomite and gypsum. Further studies should be conducted to assess the long-term influence of straw incorporated on soil in GH systems during replanting operations for crop renovation.

For all harvest systems tested, mean values of total CO_2-C emissions showed no significant difference when CT management has been compared with CTDol and CTDolG management (Fig. 3). These results also indicate that the additional short-term soil CO_2 losses induced by tillage (mechanical management) are more significant than losses induced by chemical management, such as the additions of dolomite alone or with gypsum. Further emissions induced by liming or gypsum in addition to tillage (Fig. 3), were not as evident in the GH SR and GH SM systems ($P > 0.05$).

Effects of dolomite application on CO_2-C emissions

The emissions reported here from dolomite application correspond to 55.8% and 52.8% of C from dolomite applied which was released into the atmosphere as CO_2 in BH and GH SR treatments, respectively, 25 days after application. In GH SM, dolomite was applied over sugarcane straw and incorporated to a depth of 25 cm and thus, the effect of dolomite application on enhanced emissions in GH SM system did not result in higher CO_2-C emissions, when comparing total emission from GH SM CT to GH SM CTDol treatment. In contrast, a reduction of emissions was observed. West & McBride (2005) estimated a net loss of CO_2 equivalent of 0.059 and 0.064 Mg C Mg^{-1} limestone (calcite) and dolomite, respectively, in the year following application. This is about half of the CO_2 emissions used by the methodology outlined by Houghton *et al.* (1997) which is presented in revised Guidelines for National Greenhouse Gas Inventories (IPCC, 1996). In addition, our results pointed out to a loss of 0.0725 and 0.0685 Mg C Mg^{-1} dolomite applied for BH and GH SR systems, respectively, on short-term of 25 days, similar results presented by West & McBride (2005). Liming is also expected to lead to increases in microbial activity, as indicated by basal respiration (Shah *et al.*, 1990; Badalucco *et al.*, 1992), oxygen consumption (Lang, 1986), or heat output (Zelles *et al.*, 1990). These factors can explain the higher emissions detected in our study when dolomite was applied in the BH and GH SR systems. Coale & Schueneman (1993) demonstrated that the reaction rates of calcite and dolomite amendments reached apparent pH equilibriums approximately 2 months after application, suggesting that dolomite caused additional emissions for more than 25 days in our study.

CO_2-C emissions effect by soil bulk density and soil aeration

In NT treatments, soil bulk densities were higher than those where tillage was applied which corroborates the idea that lower emissions in NT compared with tilled treatments could be also related to lower soil aeration (Vor *et al*., 2003), soil porosity, pore size, and gas exchange. These authors showed that the mineralization of SOM decreased considerably with reduced aeration. Higher soil density and the presence of crop straw on soil surface may contribute to lower O_2 concentration inside the soil, resulting in lower CO_2 emissions. On the contrary, treatments where intensive tillage has been performed presented higher emissions when compared with NT plots for all harvest systems studied. Tillage also reduces bulk density thereby increasing total porosity, promoting gas diffusion, and convection with improved oxygen, temperature, and moisture for decomposition (Molina *et al*., 1983; Sartori *et al*., 2006). In addition, other studies have shown that tillage disrupts the aggregates exposing once protected fresh organic matter (Bronick & Lal, 2005; Jacinthe & Lal, 2005; Wright & Hons, 2005).

Effects of water content of soil and rainfall on CO_2-C emissions

The increase of CO_2-C emissions in GH SR NT associated with lower water content of soil when straw were removed, when compared with GH SM NT (Fig. 2b and c), suggest that oxygen diffusion was limiting emissions, probably due to straw effect on soil surface. The influx of oxygen is necessary for microbial activity as in GH SM NT, lower emission could be related to lower influx of oxygen. Water content of soil is a factor that influences CO_2 production and diffusion as well as the amount of oxygen influx into the soil (Solomon & Cerling, 1987; Xu & Qi, 2001; Reichstein *et al*., 2002; Xu *et al*., 2004; Tang & Baldocchi, 2005). Linn & Doran (1984) found microbial respiration peaks when water content of soil was near 60% of soil water-filled pore space. However, Lou *et al.* (2004) indicated that water content of soil had a small effect on soil CO_2 flux, indicating that this effect depends also upon soil structure (Davidson *et al*., 1998; Knapp *et al*., 1998). Corroborating our idea, Sierra & Renault (1996) determined that respiration rates of soil aggregates decreased CO_2 emission with decreasing O_2 concentration. The highest water content of soil during the entire experimental period occurred when straw has been kept on the soil surface (Fig. 2i). On the other hand, tillage when applied leaded to lower water content of soil in contrast with higher emissions for all harvest systems tested. Tillage stimulated soil C losses by the increase of aeration, changes of temperature, and water content of soil conditions, mixing soil, and straw, and thus favoring microbial decomposition (Reicosky *et al*., 2008).

General trends of emission curves found in our study are similar to trends reported in the literature that show a gradual decline over time after tillage (Reicosky & Lindstrom, 1993; Rochette & Angers, 1999; La Scala *et al*., 2006, 2008).

In our study, the decrease over time persisted up to 13 days after tillage, and this behavior was followed by increases due to rain events on days 15 (20 mm) and 20 (23 mm). In addition, small rainfall events occurred during the study and increased water content of soil and related emissions: 3.5 mm on day 3; 1.5 mm on day 5; 8 mm on day 9; 2.5 mm on day 10; 2.5 mm on day 16; 2 mm on day 17; 1.5 mm on day 23; 4.5 mm on day 26 and 6 mm on day 27. Increases in soil CO_2 emissions related to changes in water content of soil due to precipitation had been observed in other studies (Davidson *et al*., 2000; Lee *et al*., 2002; Xu *et al*., 2004). This feature is less marked in NT treatments, especially in GH SM, due to the presence of sugarcane straw on soil surface. This effect was also observed by Panosso *et al.* (2009) who reported that after the induction by precipitation, CO_2 emissions were much less in treatments with straw when compared with treatments without straw. Postrainfall increases in soil CO_2 flux are primarily caused by the increased microbial activity and/or population (Rochette *et al*., 1991; Franzluebbers *et al*., 2000). Others have suggested that those increases could be due to water infiltration and its effect on air removal/displacement of CO_2 efflux. The influence of water content of soil on soil respiration is more pronounced than the influence on CO_2 efflux (Maier *et al*., 2011).

Fluctuations in soil temperature in our study (Fig. 2d–f) are more clearly observed following precipitation events, similar to the results of Franzluebbers *et al.* (1995) and Kessavalou *et al.* (1998).

Influence of sugarcane crop renovation on CO_2-C emissions

Short-term CO_2-C emission induced by conventional tillage plus dolomite and gypsum applications in the GH SM plots (+4048 kg CO_2 ha^{-1}) which are the most usual practices performed during sugarcane crop renovation in Brazil was 69% higher than the annual GHG emission balance (in CO_2 equivalents) estimated by inventory methodologies (IPCC, 2006) in GH sugarcane areas accounting emissions from diesel consumption and agricultural activities (2793 kg CO_2eq ha^{-1} yr^{-1}) (De Figueiredo & La Scala, 2011), reinforcing the importance of introducing better management practices with less intensive soil tillage, better efficiency for amendments application as dolomite and gypsum, and also promoting better crop straw management which could result in reduced emissions from sugarcane crop renovation.

Our results showed that intensive tillage and the incorporation of sugarcane straw on soil increased short-term CO_2 emissions and suggest that the reduction of tillage frequency as well as the maintenance of straw on soil surface in areas of sugarcane green harvested would probably increase the soil C stock in the long-term as a result of reduced emissions. Studying tillage-induced CO_2 emission from soil, Reicosky (1997) concluded that when keeping crop straw on the soil surface and reducing tillage intensity not only reduces erosion but also reduces physical release of CO_2 and possibly the biological oxidation of soil C which is less obvious but usually the greater cause of organic matter depletion in the soils.

The contribution of CO_2-C emissions due to the sugarcane replanting operations in burned and green harvest systems could promote significant soil C losses, and new aspects should be studied to better understand the benefits of the GH system on reduction of CO_2-C emissions and its potential for soil C sequestration in those areas.

Among the harvest systems and managements studied, NT treatments presented the lowest emissions during entire 25 days of the measurement period, especially due to the presence of the sugarcane straw kept on the soil surface. Greatest CO_2-C emissions were observed in the renovation of the green harvested area, due to the crop straw, dolomite, and agricultural gypsum incorporated into the soil through conventional tillage.

The effect of straw removal on soil CO_2-C emission should be considered in further studies of GHG balance in sugarcane areas for electricity generation and for production of second generation ethanol.

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