

## Soil and crop residue CO<sub>2</sub>-C emission under tillage systems in sugarcane-producing areas of southern Brazil

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**ABSTRACT:** Appropriate management of agricultural crop residues could result in increases on soil organic carbon (SOC) and help to mitigate gas effect. To distinguish the contributions of SOC and sugarcane (*Saccharum* spp.) residues to the short-term CO<sub>2</sub>-C loss, we studied the influence of several tillage systems: heavy offset disk harrow (HO), chisel plow (CP), rotary tiller (RT), and sugarcane mill tiller (SM) in 2008, and CP, RT, SM, moldboard (MP), and subsoiler (SUB) in 2009, with and without sugarcane residues relative to no-till (NT) in the sugarcane producing region of Brazil. Soil CO<sub>2</sub>-C emissions were measured daily for two weeks after tillage using portable soil respiration systems. Daily CO<sub>2</sub>-C emissions declined after tillage regardless of tillage system. In 2008, total CO<sub>2</sub>-C from SOC and/or residue decomposition was greater for RT and lowest for CP. In 2009, emission was greatest for MP and CP with residues, and smallest for NT. SOC and residue contributed 47 % and 41 %, respectively, to total CO<sub>2</sub>-C emissions. Regarding the estimated emissions from sugarcane residue and SOC decomposition within the measurement period, CO<sub>2</sub>-C factor was similar to sugarcane residue and soil organic carbon decomposition, depending on the tillage system applied. Our approach may define new emission factors that are associated to tillage operations on bare or sugarcane-residue-covered soils to estimate the total carbon loss.

**Keywords:** soil respiration, carbon dioxide, emission after tillage, soil organic carbon

### Introduction

Losses of soil organic carbon (SOC) due to soil management in agricultural areas have been identified as a factor that accelerates the greenhouse effect, especially by emitting CO<sub>2</sub> in the atmosphere (Eugster et al., 2010). Losses of SOC can be assessed either by directly measuring changes in SOC content or by monitoring soil CO<sub>2</sub> emissions. The latter has the advantage to detect immediate or near-immediate effects of management practices on C loss via emissions. The impact of tillage on the loss of SOC and associated emission factors under different management systems has been studied (Smith et al., 2010; La Scala et al., 2008; La Scala et al., 2009 a,b), and some researchers have used tillage emission factors as bias for estimating soil conversion from conventional to no-till. However, Smith et al. (2010) noted that this conversion can be affected by the depth of tillage, and multiple factors should be developed to reduce estimation errors.

Agricultural activities contribute with approximately 20 % to the global greenhouse gas emissions (Lokupitiya and Paustian, 2006). No-till farming combined with the maintenance of crop residues on the soil surface has been identified as an important strategy for sequestering carbon (C) from the atmosphere (Lal, 2007). Tillage induces the loss of C as CO<sub>2</sub> by breaking up soil aggregates and exposing the protected organic matter to microbes. Tillage also incorporates and mixes residues, improving

aeration, which can lead to additional C losses by maximizing soil-residue contact compared with no-residue incorporation (Jacinthe and Lal, 2005; Six et al., 1999).

Soil organic matter decay induced by tillage is related to soil temperature, soil moisture, and the amount and quality of soil organic carbon (Zhang et al., 2011; Heal et al., 1997; Schomberg and Steiner, 1997; Beare et al., 1992). But, some researchers have shown higher emissions under NT relative to tilled plots attributed to decomposition of old surface residues (Oorts et al., 2007; Soane et al., 2012). Recently, some researchers have used no-till emission and its exponential decay in time as a reference to estimate CO<sub>2</sub> emission after tillage (La Scala et al., 2008, 2009 a,b); by subtracting the CO<sub>2</sub> emission after tillage from the no-till emission, it is possible to estimate the effect of tillage. Our hypothesis is that accelerated decomposition due to tillage is the major cause of short-term CO<sub>2</sub> emissions. Our objectives were to distinguish the effect of both soil and crop residues on the CO<sub>2</sub> emissions caused by several tillage systems in sugarcane (*Saccharum* spp.) areas of Brazil.

### Materials and Methods

#### Experimental plots and treatment application

This research was conducted in 2008 on a field inside a sugarcane mill area located in Barrinha (location A - 21°11' S and 48°09' W, 542 m above sea level), and in 2009 on a field located in Guatapar (location B - 21°29' S and 48°02' W, 512 m above sea level), So Paulo State, Brazil. The climate is described as Aw, according to Kop-

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pen, i.e., subtropical with an average annual temperature of 21 °C, with mean annual precipitation of 1,380 mm. The soil in these locations is an Oxisol (Psamitic Eutroferic red latosol, FAO, respectively) and is described as a Latossolo Vermelho Eutroférrico according to Brazilian Soil Classification. Both soils presented a pH around 5.0, Location A soil (2008) presented an average organic carbon content of 18.1 g C dm<sup>-3</sup>, base saturation of 44 % from 0–40 cm depth. Particle size distribution of sand, silt, and clay were 190 g kg<sup>-1</sup>, 166 g kg<sup>-1</sup> and 644 g kg<sup>-1</sup> respectively. Location B soil (2009) presented an average organic carbon content of 22.67 g C dm<sup>-3</sup>, base saturation of 63 % from 0–40 cm depth. Particle size distribution of sand, silt, and clay were similar to those values observed in the soil of the first year experimental plots.

The soils of both locations have been used for sugarcane production in the last 15–20 years, by using a green management system which involves mechanized harvesting. This harvesting procedure has provided the return of large amounts of sugarcane crop residues on soil surface and favored soil organic matter accumulation, compared to the burn system where the sugarcane is burned in the field a few days before harvesting. The crop residues (15 Mg ha<sup>-1</sup>, dry mass) had high C:N ratios (close to 125:1 in location A; Gava et al., 2005, and close to 99:1 in location B). Tillage operations were applied every six years with chisel plows and ratoon remover.

On July 12, 2008, four tillage systems were applied to 10 × 2 m plots (Table 1) as follows: 1) heavy offset disk harrow followed by offset disk harrow (HO); 2) chisel plow (CP); 3) rotary tiller (RT); and 4) sugarcane mill tillage system with a ratoon remover followed by subsoiler coupled with a roller for clod breaking (SM). Each of the tillage systems was applied to two plots, one with crop residues (wc) on the soil surface and the other without crop residues (nc). In addition, no-till plots (NT) without crop residues (nc) were left as controls without tillage.

Three optional passes of the rotary tiller were used to achieve higher aggregate breakdown and smaller soil aggregate sizes. Tillage was performed using a tractor with motor power of 77.3 kW, a forward travel velocity of 3.5 km h<sup>-1</sup> and a rotary tiller running at 2.5 km h<sup>-1</sup>. The plots with no crop residues had the residue removed just before tillage. The residues had lain on the soil surface since the harvest two days previously. Residue pieces were approximately 0.20 m long before and 0.05 m after tillage, and most were incorporated into the soil.

In the second experiment, 11 treatments were established in plots of 10 × 2 m in 2009 (Table 1). As in 2008, the sugarcane residues were removed from the soil surface in plots without crop residues. Plots under moldboard plowing (MP) were tilled to a working depth of 30 cm with three shanks. The configurations adopted

Table 1 – Configuration and description of tillage treatments in plots having (with crop = wc) and not having (no crop = nc) sugarcane residues on soil surface in the experiments of 2008 and 2009. Tractor travel velocity was the same in all treatments (3.5 km h<sup>-1</sup>).

Treatment	Description	Tillage depth (cm)
Experiment year 2008		
NTnc	No till, no crop residues on soil surface	-
HOnc	Heavy offset disk harrow followed by offset disk harrow. No crop residues	25/15
HOwc	Heavy offset disk harrow followed by offset disk harrow. With crop residues	25/15
CPnc	Chisel plow conjugated with clod breaker. No crop residues	30
CPwc	Chisel plow conjugated with clod breaker. With crop residues	30
RTnc	Rotary tiller (3×, 153 rpm), rear shield lowered. No crop residues	08
RTwc	Rotary tiller (3×, 153 rpm), rear shield lowered. With crop residues	08
SMnc	Sugarcane mill tiller: ratoon remover followed by subsoiler coupled with a roller for clod breaking plus followed by offset disk harrow. No crop residues	15/35
SMwc	Sugarcane mill tiller: ratoon remover followed by subsoiler coupled with a roller for clod breaking plus followed by offset disk harrow. With crop residues	15/35
Experiment year 2009		
NTnc	No till, no crop residues on soil surface	-
MPnc	Moldboard plow. No crop residues	30
MPwc	Moldboard plow. With crop residues	30
CPnc	Chisel plow conjugated with clod breaker. No crop residues	30
CPwc	Chisel plow conjugated with clod breaker. With crop residues	30
RTnc	Rotary tiller (1×, 153 rpm), rear shield lowered. No crop residues	08
RTwc	Rotary tiller (1×, 153 rpm), rear shield lowered. With crop residues	08
SMnc	Sugarcane mill tiller: ratoon remover followed by subsoiler coupled with a roller for clod breaking plus followed by offset disk harrow. No crop residues	12/35
SMwc	Sugarcane mill tiller: ratoon remover followed by subsoiler coupled with a roller for clod breaking plus followed by offset disk harrow. With crop residues	12/35
SUBnc	Subsoiler no crop residues	35
SUBwc	Subsoiler with crop residues	35

for the tillage with rotary tiller (RT) were a lowered impact plate and a rotor speed of approximately 153 rpm with 32 C-type knives and a medium working depth of 8 cm. The typical tillage used by the sugarcane mill (SM) consists of applying the ratoon remover, followed by disk harrows and subsoiler to a working depth of 12 cm. In treatments with a chisel plow (CP), a pull-type ripper with five shanks, 2.90 m in width, spacing between shanks of 0.45 m, and working depth of 30 cm was combined with a roller. The plots treated with the subsoiler (SUB) were tilled to a working depth of 35 cm, with 45 cm between shanks, using a simple 7 cm tip.

### Soil CO<sub>2</sub> emission, soil temperature and moisture measurement

In each plot and for both experiments, a total of six PVC collars were inserted 3 cm into the soil, resulting in a total to 54 collars in experiment 1 and 66 collars in experiment 2 to support the chamber used for measuring soil respiration. The collars were inserted 24 h before the first measurement, just after the tillage, in order to minimize the disturbances due to placing the chamber into the soil; the placement of the chamber may disrupt, for example, the soil pore structure and artificially increase soil CO<sub>2</sub> emissions, leading to overestimation of the value at that point. Measurements of CO<sub>2</sub> flux, temperature and soil moisture, for experiment 1, were made until July 27, 2008, 15 days after tillage. During the first seven days of study, daily measurements were taken, and thereafter, measurements were performed every other day. For experiment 2, measurements were made until Aug 13, 2009. Until Aug 9, measurements were made daily, at 24 hour intervals, and then another measurement was made on Aug 13, 2009, so that all 13 evaluations were performed within 16 days of study. No rain occurred during the experiments, which were performed during the dry season.

Soil CO<sub>2</sub> emission was measured using a portable LI-8100 system (LI-COR, Lincoln, Nebraska, USA). This system consists of a closed chamber connected to the PVC collars previously installed in the soil, with an internal volume of 991 cm<sup>3</sup> and a soil contact area of 71.6 cm<sup>2</sup>. Every measurement started at 07h30 and each data point was measured within 90 s. In the measurement mode, the CO<sub>2</sub> concentration of the air inside the chamber is continuously measured by optical absorption spectroscopy. The increase in CO<sub>2</sub> concentration inside the chamber was followed every second during approximately two minutes, provide the basis for computing the soil CO<sub>2</sub> emission for each sample point. The CO<sub>2</sub> concentration data on the first moments after the close of the chamber were not considered for the subsequent procedures, and thus around 90 measurements data were used to interpolate and calculate emissions. At the end of logging period, an exponential regression analysis between the CO<sub>2</sub> concentrations inside the chamber and time was computed, and the emission on that point was calculated based on CO<sub>2</sub> concentration increases in time after chamber closure.

Soil temperature was monitored with a LI-8100 system consisting of a 20 cm rod inserted into the soil perpendicular to the surface near the PVC collars used for measuring the CO<sub>2</sub> emissions. Soil temperature readings were taken simultaneously with measurements of soil CO<sub>2</sub> emission. Soil moisture was measured with a TDR (time-domain reflectometry) system, the Hydrosense System (Campbell Scientific, Utah, USA). The TDR also consisted of 12 cm rods inserted vertically into the soil near the PVC collars. Because the experiment was performed in the dry season, there was no precipitation during the experiment.

### Mathematical and statistical analysis

To calculate emission factors we assumed the C in sugarcane residue as 40 % of mass content (Ball-Coelho 1993; De Oliveira et al., 1999), therefore the amount of C in the sugarcane residue on soil surface at tillage was determined by multiplying 15 Mg ha<sup>-1</sup> of residue by a factor of 0.4 which resulted in 6.0 Mg ha<sup>-1</sup> of organic carbon. Soil organic carbon loss induced by tillage was assessed by subtracting the emission from plots tilled without crop residues from that of non-tilled plots without crop residues (NTnc). Likewise, the CO<sub>2</sub>-C loss from crop residues was assessed by subtracting CO<sub>2</sub>-C from plots where the same tillage system was applied, but with or without crop residues on the soil surface. Here, we assume that in a plot without crop residues, the difference between tillage-induced and no-till emission is directly related to soil organic carbon loss, while that between tillage-induced emission in plots with crop residues and tillage-induced emission in plots without crop residues is directly related to the crop residues. Hence, the additional soil CO<sub>2</sub>-C loss due to residues was divided by the total of carbon present in crop residues to derive crop residues emission factors.

The temporal variability of CO<sub>2</sub>-C was characterized by two-way analysis of variance (each one of the six PVC was used as a pseudo-replicate). This was performed in a completely randomized design in repeated measurement over time, using a mixed model: treatments and the interaction treatments × time as fixed effect and time as random effect, using the Proc Mixed procedure of SAS (SAS version 9.1, SAS institute, Cary, NC, USA) (Kepner and Robinson, 1988). Prior to the above analysis, the data were tested for sphericity using the Mauchly's test of sphericity matrix of variance and covariance between times. Only for FCO<sub>2</sub>, in both experiments, the Mauchly's test was significant at 5 % level, therefore, the assumption of sphericity was rejected, however, it was possible to analyze repeated measures data by first modeling the variance and correlation structure of the repeated measures. In this case the structure of covariance that best fitted the data, according to Bayesian information criterion (BIC), were *Factor Analytic* and *Unstructured* for first and second-years experiment, respectively (Littel et al., 1998).

When significant, differences between treatments within each measurement time were compared using the Fisher's least significant difference ( $p < 0.10$ ). The total emission was estimated by the area under emissions curves in time after tillage, and one-way analysis of variance (ANOVA) in a completely randomized design was applied to test the hypotheses of differences in the total emission means. In this case, pairwise comparison of means, for all treatments in each of the experiments was performed using Tukey procedure, with a  $p$  value  $< 0.10$  considered significant.

**Results and Discussion**

**Temporal variability of CO<sub>2</sub>-C emission**

Tilled plots with crop residues had the highest values ( $p < 0.10$ ), with CPwc, RTwc and SMwc treatments

showing emissions of 0.42, 0.38 and 0.35 g m<sup>-2</sup> h<sup>-1</sup> of CO<sub>2</sub>-C respectively, in the first four of the study when compared with NTnc plot (Figure 1). However, higher emissions persisted for SMwc till the end of the studied period. NTnc emissions were different ( $p < 0.10$ ) when compared to the other treatments in all experimental days, except for 4th day of study, when no difference was observed between NTnc and SMwc ( $p > 0.10$ ). When NTnc and treatments with no crop residues were compared, the tillage effect showed a difference in emissions that decreased with time, and this decrease was similar to the exponential decay observed in many studies (Reicosky and Lindstrom, 1993; Fortin et al., 1996; Rochette and Angers, 1999; Al-Kaisi and Yin 2005; La Scala et al., 2001, 2005, 2006). Similarly, emissions were generally greater under tillage without residues relative to NTnc.

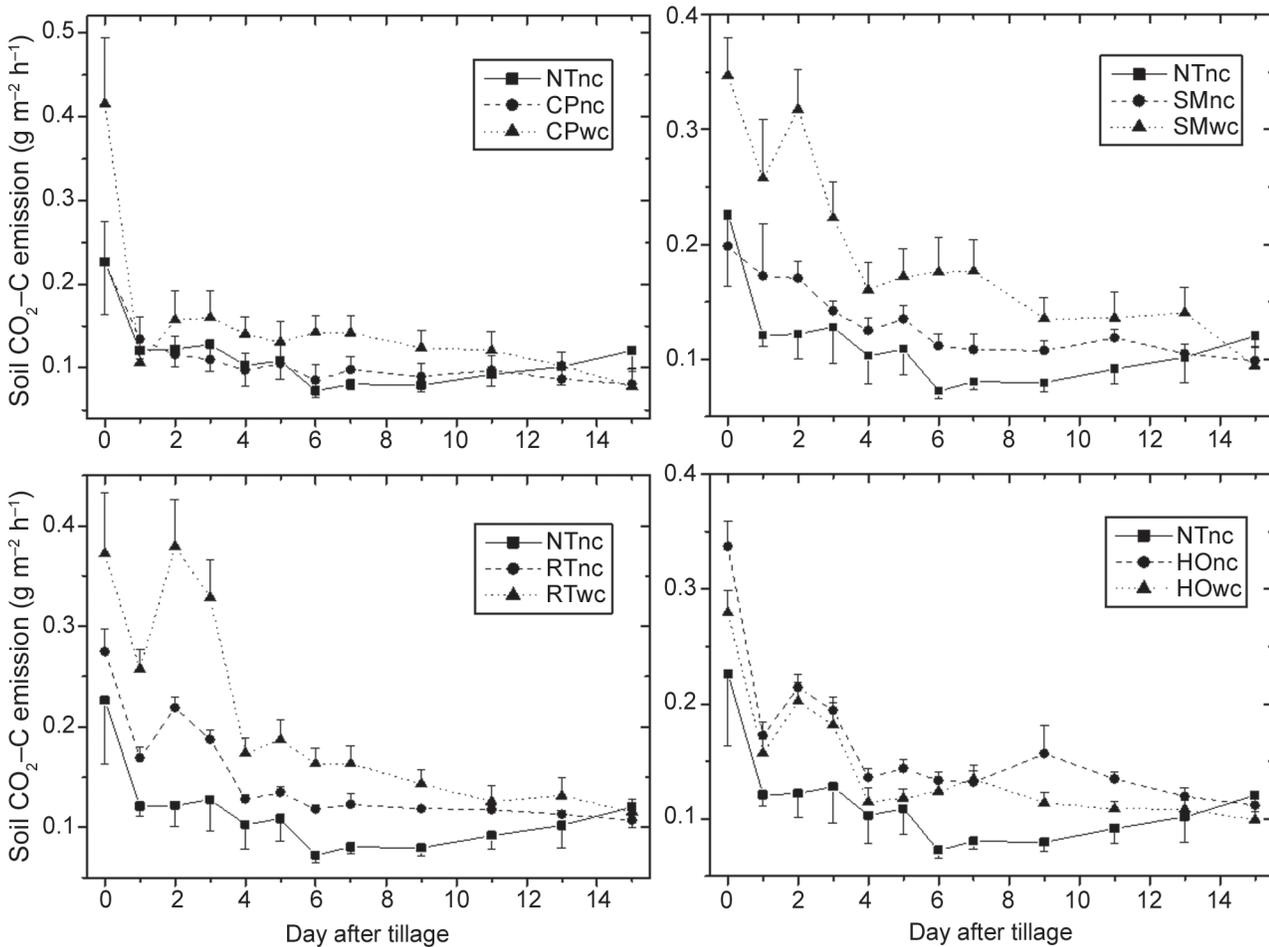


Figure 1 – Soil CO<sub>2</sub>-C emission due to tillage with and without sugarcane residues relative to no-till (NT) at location A in 2008. Vertical bars represents standard errors of means (n = 6). NTnc = no-till without crop residues; CPnc = chisel plow without crop residues; CPwc = chisel plow with crop residues; SMnc = sugarcane mill tillage system without crop residues; SMwc = sugarcane mill tillage system with crop residues; RTnc = rotary tiller without crop residues; RTwc = rotary tiller with crop residues; HOnc = disk harrow + by offset disk harrow without crop residues; HOWc = disk harrow + by offset disk harrow with crop residues.

The differences between NTnc and RTnc or NTnc and SMnc CO<sub>2</sub>-C emission were mostly due to the exposure of additional labile C to microbes. This exposure was caused by the breaking of aggregates by rotary tillage and the consequent changes in the soil organic carbon decay factor. However, when CO<sub>2</sub>-C emissions of RTnc and RTwc or SMwc and SMnc were compared, an additional increase, most likely due only to the contribution of crop residues, was observed. Here, it is assumed that the aggregate breakdown and the contribution of labile C to the emissions were the same in both plots with the same tillage treatment.

Tillage with the chisel and heavy offset disk harrowing did not result in differences in emissions in plots with or without crop residues, during to the experimental period, except for chisel on the first and sixth days of study (Figure 1). The persistence of crop residues in plots under CPwc and HOwc tillage indicated that in these treatments, the crop residues were not incorporated into the soil and/or were not as fragmented as those under other tillage methods. This difference was reflected in the absence of additional emission due to the presence of crop residue on surface on most days. Despite these differences, all the plots reached a similar emission value at the end of the 15<sup>th</sup> day of the study of approximately 0.12 g m<sup>-2</sup> h<sup>-1</sup> of CO<sub>2</sub>-C.

For second-year experiment, higher soil CO<sub>2</sub>-C emissions ( $p < 0.10$ ) were observed after SM and CP tillage systems, with values of 0.26 and 0.24 g m<sup>-2</sup> h<sup>-1</sup>, respectively, one day of study, with lower emissions coming from the NTnc plot as expected. The effects of tillage and the presence of crop residues associated with the tillage are shown in Figure 2. When NTnc and treatments without crop residues are compared, as in the first-year experiment, the effect of soil tillage was reflected in a difference in emissions that decreased with time (Al-Kaisi and Yin 2005; La Scala et al., 2005; 2006). However, emissions in plots with crop residues did not show uniformly high differences when compared with emissions from plots without crop residues, for example, under rotary tillage.

#### Total/cumulative emissions

The total emissions during the 15-day study were as high as 68.11 and 63.88 g CO<sub>2</sub>-C m<sup>-2</sup> for RTwc and SMwc, respectively, and as low as 36.82 and 37.32 g CO<sub>2</sub>-C m<sup>-2</sup> in CPnc and NTnc, respectively (Figure 3). The 18.10 and 18.76 g CO<sub>2</sub>-C m<sup>-2</sup> increases in total emission from RTnc to RTwc and from SMnc to SMwc are equivalent to 181 and 188 kg CO<sub>2</sub>-C ha<sup>-1</sup> emitted in 15 days, mainly from the incorporated crop residues. Given that sugarcane C concentration of 40 % was about 15 Mg ha<sup>-1</sup>, we estimated short term loss to be 3 % of total C associated with sugarcane residues. Our result is consistent with that reported by Resende et al. (2006), who found that part of the C stored and associated with crop residues in soil was lost after tillage during the replanting period, which usually occurs every six years in

sugarcane areas. Changes in SOC emission due to tillage incorporation have previously been reported by Adiku et al. (2008) and Al-Kaisi and Yin (2005).

The treatments RTwc and RTnc resulted in similar total CO<sub>2</sub>-C emissions with values of 49.12 and 49.34 g CO<sub>2</sub>-C m<sup>-2</sup>, respectively, 16 days after soil tillage (Figure 4). The remaining tillage systems, subsoiling and chisel plowing, led to only small differences in additional emissions, when crop residue was or was not present in the soil surface at the time of tillage (Figure 2).

Treatment RT did not cause large differences in emissions over the day following tillage between plots with and without crop residues (Figure 3). The effect of tillage on losses of soil organic carbon and crop residues was more pronounced in the plot with moldboard plowing (MP), as is expected from a tillage system that causes a large breakdown of aggregates. An increase in total emission (Figure 4) of 18.21 g CO<sub>2</sub>-C m<sup>-2</sup> from NTnc to MPnc was presumably loss from soil, while 23.95 g CO<sub>2</sub>-C m<sup>-2</sup> from MPnc to MPwc was loss from crop residues. The chisel plow, subsoiler, sugarcane mill tiller and moldboard plow systems caused increases in emissions owing to the presence of crop residues on the surface at the time of tillage. However, the subsoiler system apparently did not affect carbon loss via soil CO<sub>2</sub> only, as shown by the similar emissions from the NTnc and SUBnc plots (Figure 4).

The differences between NTnc and other treatment emissions in plots without crop residues on soil surface could be due to abiotic factors, just like, changes in soil moisture, soil temperature and oxidation degree could affect the decay factor of soil organic carbon. However, when emissions of CO<sub>2</sub>-C from NTnc and other treatments with crop residues were compared, a further increase, most likely contributed by only the crop residues. This result suggests that the disruption of aggregates and the contribution of labile C emissions are the same in both plots with the same tillage (Six et al., 1999; Jacinthe and Lal 2005; La Scala et al., 2008).

In general, emissions increased with soil tillage and with the presence of crop residue on the surface except under rotary tillage, where large differences in emissions from plots with or without crop residues were not observed. The persistence of crop residues in this plot indicates that they were not incorporated into the soil and/or were not sufficiently fragmented compared to other methods of tillage. These conditions account for the absence, on most days, of additional emissions due to the presence of crop residue on the surface.

Cumulative emission was higher for MPwc (67.97 g CO<sub>2</sub>-C m<sup>-2</sup>) and CPwc (61.40 g CO<sub>2</sub>-C m<sup>-2</sup>) and lower for NTnc (25.80 g CO<sub>2</sub>-C m<sup>-2</sup>) and SUBnc (28.77 g CO<sub>2</sub>-C m<sup>-2</sup>) (Figure 4). Presumably, the differences in emissions were not only due to the differing tillage treatments but also due to different effects. For example, CO<sub>2</sub>-C increase for MPnc relative to NTnc was presumably loss from SOC. In contrast, the increases in MPwc compared to MPnc or CPwc compared to CPnc are mainly due to the

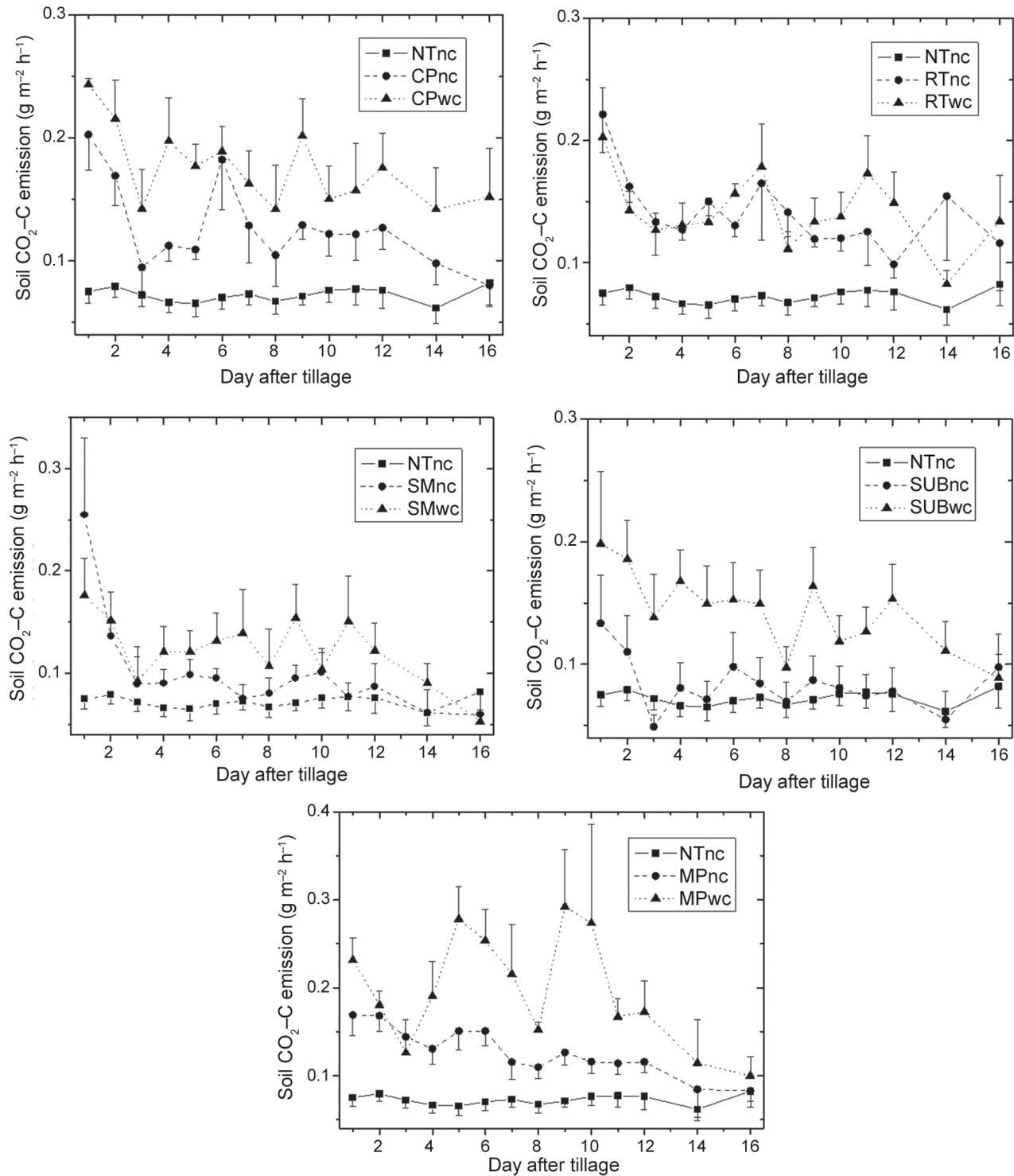


Figure 2 – Soil CO<sub>2</sub>-C emission due to tillage with and without sugarcane residues relative to no-till (NT) at location B in 2009. Vertical bars represents standard errors of means (n = 6). NTnc = no-till without crop residues; CPnc = chisel plow without crop residues; CPwc = chisel plow with crop residues; RTnc = rotary tiller without crop residues; RTwc = rotary tiller with crop residues; SMnc = sugarcane mill tillage system without crop residues; SMwc = sugarcane mill tillage system with crop residues; SUBnc = subsoiler without crop residues; SUBwc = subsoiler with crop residues; MPnc = moldboard plowing without crop residues; MPwc = moldboard plowing with plot residues.

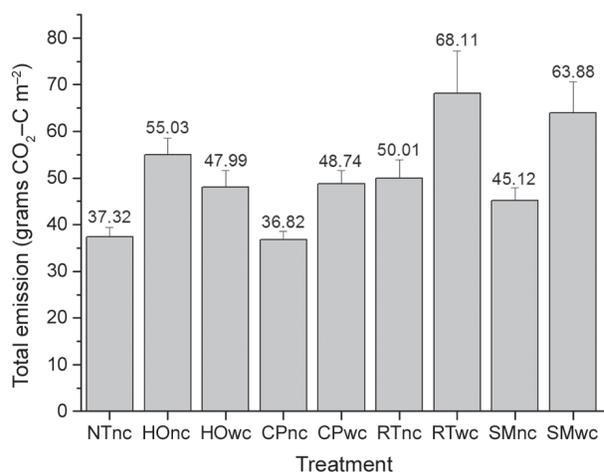


Figure 3 – Total soil CO<sub>2</sub>-C emission due to tillage with and without sugarcane residues at location A in 2008. Vertical bars represents standard errors of means (n = 6). NTnc = no-till without crop residues; HOnc = disk harrow + by offset disk harrow without crop residues; HOwc = disk harrow + by offset disk harrow with crop residues; CPnc = chisel plow without crop residues; CPwc = chisel plow with crop residues; RTnc = rotary tiller without crop residues; RTwc = rotary tiller with crop residues; SMnc = sugarcane mill tillage system without crop residues; SMwc = sugarcane mill tillage system with crop residues.

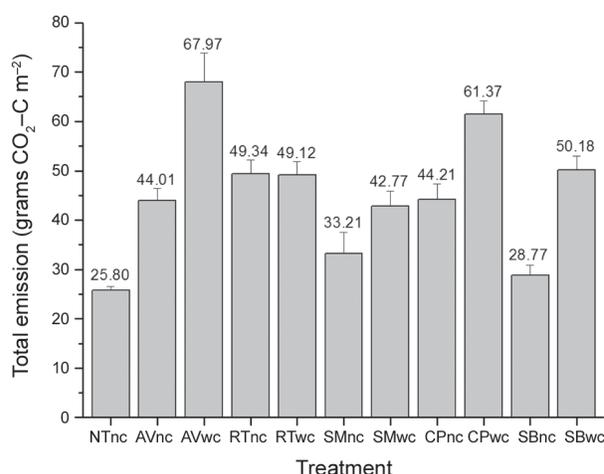


Figure 4 – Total soil CO<sub>2</sub>-C emission due to tillage with and without sugarcane residues relative to no-till (NT) at location B in 2009. Vertical bars represents standard errors of means (n = 6). NTnc = no-till without crop residues; CPnc = chisel plow without crop residues; MPnc = moldboard plowing without crop residues; MPwc = moldboard plowing with plot residues; RTnc = rotary tiller without crop residues; RTwc = rotary tiller with crop residues; SMnc = sugarcane mill tillage system without crop residues; SMwc = sugarcane mill tillage system with crop residues; CPwc = chisel plow with crop residues; SUBnc = subsoiler without crop residues; SUBwc = subsoiler with crop residues.

incorporation of crop residues and the mixing because the labile C from the breakdown of aggregates should be the same when MPnc and MPwc or CPnc and CPwc are compared. The increase of 23.95 and 17.16 g CO<sub>2</sub>-C m<sup>-2</sup> in the total emission from MPnc to MPwc and CPnc to CPwc are equivalent to 240 and 172 kg CO<sub>2</sub>-C ha<sup>-1</sup>, respectively, emitted within 16 days, mainly from crop residues.

#### Calculated emission factors

The percentage of C loss due to emission factors associated with tillage, either from the crop residues, could be easily calculated under the same assumptions described above. Table 2 presents all the tillage emission factors after these calculations were performed. Despite the similarities in the induced emissions apparent in Figure 3, the sugarcane residues on the surface resulted in a higher percentage of CO<sub>2</sub> loss than that induced by tillage alone. Moreover, when crop residue is incorporated to soil, not all labile C is immediately available for microbial activity because the decay of residue depends strongly on its contact with soil (Thorburn et al., 2001). This fact may explain the variation found in our results. Although the emission factors of sugarcane residues varied from 1.17 to 3.13 %, the same tillage system resulted in soil organic carbon loss from near zero (the chisel plow loss was actually negative) to 0.88 %. Thus, average emission factors of 0.345 and 2.326 % induced by tillage were associated with soil and sugarcane residues, respectively.

Table 2 presents the emission factors associated with loss of C from crop residues in the second-year experiment. The tillage system that caused the greatest relative loss in terms of additional CO<sub>2</sub>-C from residues was MP which led to an equivalent loss of around 3.99 % of C from residues in short-term emissions. Accounting all tillage systems studied, despite all the similarities induced by tillage (Figure 2), emission factors of sugarcane residues in the second-year experiment varied from -0.04 (almost zero) to 3.99 %.

Table 2 – Experiment years 2008 and 2009. Soil and crop residues emission factors for each of the studied tillage systems.

Treatment	Sugarcane Residues (%)
Experiment year 2008	
HO: Disk harrow + by offset disk harrow	1.17
CP: Chisel plow	1.99
RT: Rotary tiller	3.02
SM: Sugarcane mill tiller	3.13
Mean emission factor	2.33
Experiment year 2009	
MP: Moldboard Plow	3.99
CP: Chisel plow	2.86
RT: Rotary tiller	-0.04
SM: Sugarcane mill tiller	1.59
SUB: Subsoiler	3.57
Mean emission factor	2.40

### Relationship between emission and soil temperature and moisture

Soil temperature varied widely in our experiment (Table 3). The lowest and highest mean temperatures registered in the NTnc and HOwc plots were 20.6 and 34.3 °C, respectively on the first-year experiment. Soil temperature varied lesser during the second-year than during the first-year experiment. For example, in the NTnc plot, the mean soil temperature varied only approximately 1 °C during the two week study. Lower mean soil temperatures of 19.7 °C were observed in the SUBwc plot and higher ones in the RTnc (20.4 °C); thus, soil temperature in the second-year study was lower than that in the first-year study (Table 3). For the first-year experiment the lowest and highest mean soil moisture were from 7.2 and 13.1 % (m<sup>3</sup> m<sup>-3</sup>), in the CPwc and NTnc, respectively. In contrast, during the second-year experiment the soil moisture differences were much greater, with lower soil moisture (13.4 %) observed in the RTnc plot and higher (33.4 %) in the NTnc plot.

In the first-year experiment, the linear correlations of soil CO<sub>2</sub>-C emission with soil temperature and soil

moisture were not significant in the NTnc, even considering that most of the emission occurred of the plots ( $p < 0.05$ ). However, emissions from RTnc and SMwc plots were positively correlated with soil moisture ( $r = 0.84$ ;  $p < 0.05$ ), while emissions from HOwc and CPwc were negatively correlated with soil temperature ( $r = -0.78$ ;  $p < 0.05$ ). These observations are consistent with a significant ( $p < 0.10$ ) linear correlation observed between soil CO<sub>2</sub> emission and soil moisture in plots CPnc, SMwc, SUBwc and MPnc in the second-year experiment, while the best correlation was observed in the MPnc plot ( $r = 0.74$ ;  $p < 0.002$ ).

### Conclusions

The presence of crop residues on the soil surface influenced the magnitude of soil CO<sub>2</sub>-C emission for some tillage systems, especially in the first four days of the study, when emissions in tilled plots were higher/lower from no-till emissions. The total emission indicates that some tillage systems could exert even negative effects on short-term soil CO<sub>2</sub> emissions. In contrast, when sugarcane residues were present, tillage induced emissions were always positive. By taking into account the carbon contents of the sugarcane crop residues, it was possible to derive multiple tillage factors related to the separate C losses from crop residues induced by tillage.

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Table 3 – Mean and standard error of mean (St. Error) of soil temperature and soil moisture for treatments in two experimental years, during the experimental periods.

Treatment	Experiment year 2008				
	Soil Temperature (°C)		Soil Moisture (m <sup>3</sup> m <sup>-3</sup> )		
	Mean	St. Error	Mean	St. Error	
NTnc	20.6	1.18	13.1	0.31	
HOnc	22.1	1.25	8.2	0.18	
HOwc	34.3	1.15	8.3	0.22	
CPnc	23.3	1.07	7.5	0.15	
CPwc	33.5	0.90	7.2	0.20	
RTnc	24.8	0.99	8.4	0.19	
RTwc	30.4	0.88	10.4	0.30	
SMnc	27.1	0.88	7.3	0.13	
SMwc	28.9	0.78	7.4	0.16	
Treatment	Experiment year 2009				
	NTnc	20.0	0.11	33.4	2.63
	MPnc	20.1	0.17	18.4	1.12
	MPwc	20.4	0.12	15.9	1.16
	CPnc	20.0	0.13	17.3	0.68
	CPwc	20.0	0.11	18.0	0.46
	RTnc	20.4	0.10	13.4	0.87
	RTwc	20.1	0.13	15.8	0.88
	SMnc	19.9	0.12	15.8	0.88
	SMwc	19.9	0.11	19.2	0.85
	SUBnc	20.1	0.12	22.7	1.49
	SUBwc	19.7	0.10	26.8	0.90

NTnc = no-till without crop residues; HOnc = disk harrow + by offset disk harrow without crop residues; HOwc = disk harrow + by offset disk harrow with crop residues; CPnc = chisel plow without crop residues; CPwc = chisel plow with crop residues; RTnc = rotary tiller without crop residues; RTwc = rotary tiller with crop residues; SMnc = sugarcane mill tillage system without crop residues; SMwc = sugarcane mill tillage system with crop residues; MPnc = moldboard plowing without crop residues; MPwc = moldboard plowing with plot residues; SUBnc = subsoiler without crop residues; SUBwc = subsoiler with crop residues.

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