

Soil carbon dioxide emission associated with soil porosity after sugarcane field reform

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Abstract This study aimed to characterize soil carbon dioxide (CO₂) emission associated with soil pore distribution in an Oxisol and Ultisol under chiseling in the planting row and in total area for sugarcane (*Saccharum officinarum*) cultivation. The experimental design was a large paired-plot design. Treatments consisted of chiseling in the planting row (CPR) and chiseling in total area (CTA) in an Oxisol and Ultisol. Soil CO₂ emission, soil temperature, and soil moisture were assessed over 12 days in the Oxisol and 11 days in the Ultisol at a depth of 0–0.10 m. Organic carbon associated with minerals (OCAM) and particulate organic carbon (POC) were also assessed. OCAM, pore class C2 (0.05 ≤ ϕ < 0.1 mm), soil moisture, and soil temperature explained 72 and 53% of the variability of soil CO₂ emission in CPR and CTA, respectively. In the Ultisol, pore class C1 (ϕ ≥ 0.1 mm) and OCAM explained 82% of the variability of soil CO₂ emission in CPR. In CTA, soil moisture, OCAM, and POC explained 67% of the variability of soil CO₂ emission. In the Oxisol, CPR and CTA affected soil structure, causing changes in both soil porosity and soil CO₂ emission. In the Oxisol, the lowest average value of soil CO₂ emission (2.8 $\mu\text{mol m}^{-2} \text{s}^{-1}$) was observed in CPR whereas its highest value (3.4 $\mu\text{mol m}^{-2} \text{s}^{-1}$) was observed in CTA. In the Ultisol, soil tillage (CPR and CTA) did not affect soil CO₂ emission. These results indicate that the intensity of soil tillage in more clayey textured soils favors soil CO₂ emission possibly due to a higher carbon availability for microbial activity when compared to more sandy textured soils. A less intensive soil tillage can be considered as an efficient strategy to reduce soil CO₂ emission and hence soil organic carbon losses. Thus, this management strategy proved to be efficient in terms of mitigating greenhouse gas emissions, reducing the contribution of agriculture to global climate change.

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1 Introduction

Agriculture is an important source of CO₂ emission to the atmosphere (IPCC 2014), standing out agricultural practices related to changes in land use and soil management that contribute to increasing its concentrations (Cerri et al. 2007; Iamaguti et al. 2015). Carbon dioxide is one of the greenhouse gases that have contributed the most to the additional greenhouse effect over the last 200 years (IPCC 2014). In this sense, soil CO₂ emission process is associated with the microbial activity, root respiration, plant residue decomposition, and soil organic matter oxidation (Lal 2009). This process is influenced by soil texture, soil structure, soil temperature, and soil moisture (Ussiri and Lal 2009).

Agricultural practices affect soil physical, chemical, and biological attributes (La Scala et al. 2006; Schwartz et al. 2010). In fact, many studies have assessed soil CO₂ emission in agricultural areas and observed that soil attributes such as macro and microporosity (Panosso et al. 2011), organic matter (Lal 2009), and organic carbon (Costa et al. 2008; Lal 2009) can directly affect the emission dynamics since these soil attributes control CO₂ production in the soil and its transport to the atmosphere.

Soil tillage systems, such as the conventional tillage, contribute to the increased CO₂ emission to the atmosphere (La Scala et al. 2006; Iamaguti et al. 2015). In this sense, soil disaggregation due to the disturbance caused by tillage interferes with soil CO₂ emission. Considering that, a less intense soil tillage such as the reduced tillage and no-tillage systems in agricultural production areas has been replacing more intense soil tillage systems such as the conventional tillage (Mazurana et al. 2011). Therefore, studies on the use of agricultural practices with less soil mobilization are promising in reducing soil CO₂ emission due to soil disaggregation. Thus, chiseling in the planting row stands out as an alternative to the chiseling in total area aiming at reducing soil CO₂ emission.

Chiseling promotes soil disaggregation at a depth of 30 cm. In this operation, the soil is moved sideward, forward, and upward, favoring soil aggregate rupture and the exposure of the previously protected organic carbon, creating an environment with a good oxygenation for microbial activity. Carbon is a source of energy for microorganisms and its decomposition favors carbon loss from soil to the atmosphere. When studying soil CO₂ flux after plowing and chiseling, Teixeira et al. (2010) observed that the soil submitted to disk plow and disk harrow emitted a higher value of CO₂ (260.7 g CO₂ m⁻²) over a 14-day assessment period when compared to the soil submitted to chiseling without declodding roller (82.3 g CO₂ m⁻²).

According to Mangalassery et al. (2013), studies on CO₂ emission dynamics associated with soil pore distribution are incipient in Oxisols and Ultisols. These authors observed that both texture and aggregate size influences soil CO₂ emission to the atmosphere. This fact is important to understand how agricultural operations that disturb soils with a lesser intensity have a direct impact on CO₂ emission. Different pore characteristics (size, continuity, and shape) interfere with gas transport (Luo et al. 2010) and soil microbial activity (Mangalassery et al. 2013). In its turn, these pore characteristics are affected by soil texture (Mooney and Morris 2008) and agricultural activities related to soil management (Zhou et al. 2008).

This study tests the hypothesis that chiseling in the planting row and in total area interfere directly with soil structure, altering its porosity and causing changes in soil CO₂ emission. Thus, the aim of this study was to characterize soil CO₂ emission associated with pore

distribution in an Oxisol and Ultisol under chiseling in the planting row and in total area for sugarcane (*Saccharum officinarum*) cultivation.

2 Material and methods

2.1 Characterization of the study areas

The experiment was carried out in two agricultural areas with a distance of 27 km between each other. The first area was located in Guariba, SP, Brazil, at the geographical coordinates of 21° 24' S and 48° 12' W, with an average altitude of 618 m and soil characterized as an Oxisol. The second area was located in Monte Alto, SP, Brazil, at the geographical coordinates of 21° 15' S and 48° 25' W, with an average altitude of 735 m and soil characterized as an Ultisol.

Regional climate is classified as Aw according to the Köppen classification, indicating a mesothermal region with a dry winter and temperatures for the warmest and coldest months exceeding 22 and 18 °C, respectively. The average annual precipitation is 1400 mm, concentrated from October to March and a dry season between April and September. Both areas were destined for mechanized sugarcane production for more than 20 years.

Soil texture characterization was performed by means of particle size analysis in the layer of 0.0–0.10 m, as in Claessen (1997). Concentrations of clay, sand, and silt were 550, 392, and 58 g kg⁻¹, respectively, in the Oxisol and 130, 809, and 61 g kg⁻¹, respectively, in the Ultisol. Organic carbon content (OC) was, on average, 17.94 and 7.00 g kg⁻¹ in the Oxisol and Ultisol, respectively. The Oxisol presented a soil bulk density (Ds) of 1.24 g cm⁻³, mean weight diameter of aggregates (MWD) of 3.46 mm, total porosity (Pt) of 0.53 m³ m⁻³, macroporosity (Macro) of 0.15 m³ m⁻³, and microporosity (Micro) of 0.38 m³ m⁻³. In its turn, the Ultisol presented a Ds of 1.71 g cm⁻³, MWD of 1.72 mm, Pt of 0.32 m³ m⁻³, Macro of 0.07 m³ m⁻³, and Micro of 0.25 m³ m⁻³.

The Oxisol area is located close to a sandstone-basalt transition, with sandstone from Rio do Peixe Valley, old Bauru Group, Adamantina Formation, and basalt from Serra Geral Formation (IPT 1981). The Ultisol geology is a sandstone from Rio do Peixe Valley, old Bauru Group, Adamantina Formation. The values of kaolinite (Kt) to gibbsite (Gb) ratio were 0.50 and 0.65, and the contents of iron oxide extracted by dithionite-citrate-bicarbonate (Fe_d) were 80.32 and 18.5 g kg⁻¹ for Oxisol and Ultisol, respectively (Jackson 1985; Mehra and Jackson 1960).

2.2 Experimental design and tillage activities conducted in the areas

The experimental design was a large paired-plot design (Perecin et al. 2015; Souza et al. 2017) with treatments consisting of chiseling in the planting row (CPR) and chiseling in total area (CTA). Before soil tillage, the mechanical removal of sugarcane ratoon was conducted in the Oxisol area in November 2014 by using a mechanical ratoon eliminator; in the Ultisol area, this agricultural practice was conducted in January 2015 using 4 L ha⁻¹ of glyphosate (N-(phosphonomethyl)glycine). Soil correction was performed in December 2014 in the Oxisol area using 1.5 t ha⁻¹ of lime and 1 t ha⁻¹ of gypsum (CaSO₄ 2H₂O); in the Ultisol area, 3 t ha⁻¹ of lime and 1 t ha⁻¹ gypsum were applied in January 2015.

CPR and CTA were performed in the Oxisol on January 31, 2015, with a soil moisture of 0.18 g g⁻¹, and in the Ultisol on February 17, 2015, with a soil moisture of 0.11 g g⁻¹. In both areas,

soil moisture was measured at a depth of 0–0.12 m. CPR was conducted by means of a chisel plow with two rollers and two pairs of tynes spaced at 1.5 m considering the sugarcane spacing planting. The distance between tynes of each pair was 0.50 m. CTA was conducted using a chisel plow with two rollers and five tynes spaced at 0.50 m. For both chisel plows, the tyne length was 0.8 m with points of 0.25-m long and 0.04-m wide, allowing a working depth of 0.30 m.

The experimental areas had approximately 10 ha (Oxisol) and 9 ha (Ultisol) and were divided into 20 plots with sizes of approximate 0.5 ha for the Oxisol and 0.45 ha for the Ultisol. These 20 plots were equally divided into two tillage treatments, i.e., chiseling in the planting row and in total area for both soils.

2.3 Determination of soil attributes to characterize the study area

Soil samples were collected after chiseling operations at a depth of 0.0–0.10 m. Disturbed soil samples were collected using a Dutch auger and used for determining organic carbon associated with minerals (OCAM) and particulate organic carbon (POC) (Cambardella and Elliott 1992). Undisturbed soil samples were collected using an Uhland auger and volumetric rings (0.05 × 0.05 m) and used for determining macroporosity (Macro) and microporosity (Micro) (Claessen 1997), in addition to pore size distribution. Two samples were collected at each plot aiming at characterizing the study area: one in the sugarcane row and another between rows (Table 1), totaling 20 sample points at each of the 10 plots.

Pore size distribution was determined by the relation between the tension (0, 30, 60, and 80 cm of water column) of water retained in capillary tubes and the pore diameter, as shown in Eq. (1):

$$d = \frac{0.3}{h} \quad (1)$$

where d is the pore diameter (cm) and h is the height of water column (cm) equivalent to the applied tension (Brady and Weil 2013). The volume ($\text{m}^3 \text{m}^{-3}$) equivalent to the pore diameter at each applied tension was obtained by the difference between the volume of water corresponding to the previously applied tension and the volume corresponding to the applied tension divided by the total volume of the sample. Thus, four pore classes were determined, two of them corresponded to the macropores, i.e., C1 ($\phi \geq 0.1$ mm) and C2 ($0.05 \leq \phi < 0.1$ mm), and the other two corresponded to the micropores, i.e., C3 ($0.0375 \leq \phi < 0.05$ mm) and C4 ($\phi < 0.0375$ mm).

2.4 Assessment of soil CO₂ emission, soil temperature, and soil moisture

For the assessment of soil CO₂ emission, 40 points (20 points in CPR and 20 points in CTA) at minimum distances of 5 m were chosen in each experimental area and PVC collars were inserted into

Table 1 Multiple regression model of the average soil CO₂ emission as a function of soil attributes in the chiseling in the planting row (CPR) in the Oxisol

Attribute	Parameter	SE	<i>p</i>	<i>R</i> ²
Intercept	−6.5844	1.86209	0.0054	
OCAM	0.61845	0.12426	0.0006	0.5595
C2	33.82357	14.19456	0.0384	0.7190

SE = standard error of the parameter estimation; *R*² = coefficient of determination; OCAM = organic carbon associated with minerals; C2 ($0.05 \leq \phi < 0.1$ mm)

the soil of the sugarcane row and between rows. PVC collars were inserted into the soil before and immediately after chiseling in the planting row and in total area at the same positions since each point was georeferenced. Soil CO₂ emission values were obtained from the average emissions assessed in the sugarcane row and between rows. In the Oxisol area, one measurement was conducted before chiseling (January 18, 2015) and 10 measurements after chiseling over a period of 12 days (February 1, 2, 3, 5, 6, 7, 8, 10, 11, and 12, 2015). In the Ultisol area, one measurement was also performed before chiseling (February 1, 2015) and 10 after chiseling over a period of 11 days (February 19, 20, 21, 22, 23, 24, 26, 27, and 28 and March 1, 2015).

Assessments were carried out in the morning from 7:00 to 9:00 h. Soil CO₂ emission varies within the same day according to temperature variations mainly due to air temperature that influences soil temperature. Other studies designed to assess soil CO₂ emission over the days were also conducted in the same period so that the assessments could start and finish with small soil temperature fluctuations (Panosso et al. 2011; Iamaguti et al. 2015). No measurements were conducted on the days that precipitations coincided with the assessment time. However, soil CO₂ emission was conducted when precipitations occurred on the afternoon of the day before the measurements.

Soil CO₂ emission was measured using an LI-8100A system (LI-COR, Lincoln, NE, USA), which consists of a closed chamber with an internal volume of 854.2 cm³ and a soil contact area of 83.7 cm². The chamber was coupled to PVC collars, which presented a diameter of 0.10 m, a height of 0.05 m, and were inserted 0.03 mm deep in the soil. This system analyzes the CO₂ concentration in the closed chamber using optical absorption spectroscopy in the infrared spectrum (infrared gas analyzer (IRGA)). The total measurement period at each point was 90 s. Simultaneously with the measurements of soil CO₂ emission, soil temperature (T_{soil}) and soil moisture (M_{soil}) were determined. T_{soil} was monitored using a temperature sensor, which contained a 0.12-m probe that was inserted into the soil near the PVC collars. In its turn, M_{soil} was obtained using a Time Domain Reflectometry (TDR) system (Hydrosense TM, Campbell Scientific Inc., Logan, UT, USA), which was inserted into the soil in the layer of 0.0 to 0.12 m, also near the PVC collars. Precipitation was measured daily by plastic rain gauges installed at both sites. For the Oxisol, precipitations occurred in the afternoon of the fourth (10 mm), fifth (35 mm), sixth (2 mm), seventh (6 mm), eighth (51 mm), and 11th (45 mm) days after tillage. In its turn, in the Ultisol, precipitations occurred in the afternoon of day 0 (28 mm), 2 (6 mm), 6 (45 mm), 9 (13 mm), and 10 (6 mm).

2.5 Data processing and statistical analysis

Mean comparison of soil attributes was performed using the 95% confidence interval described by Gabriel (1978) and processed in the program STATISTICA 7.0 (StatSoft Inc., Tulsa, OK, USA). The multiple regression analysis was performed using the SAS system version 9.1 (SAS Institute, Cary, NC, USA) (SAS Institute 1987) for CPR and CTA by using the stepwise method of variable selection. Thus, this method was applied in each area with different chiseling, for different subsets of attributes, soil temperature, and soil moisture. In this method, a significance level of 10% ($p = 0.10$) was used in the F test in order to choose the variables for the model. In addition, simultaneously with the statistical analyses, the basic assumptions of the analysis of variance, multiple regression, error normality, variance homogeneity, additivity, and error independence were tested for the assessed attributes. The accumulated soil CO₂ emission over the study period was estimated by the area under the emission curve by using the software R (R Development Core Team 2011).

3 Results and discussion

3.1 Soil CO₂ emission and soil attributes in the Oxisol

The lowest average value of soil CO₂ emission ($2.8 \mu\text{mol m}^{-2} \text{s}^{-1}$) was observed in CPR whereas its highest value ($3.4 \mu\text{mol m}^{-2} \text{s}^{-1}$) was observed in CTA (Fig. 1). This is due to the smaller area of soil mobilized by the chiseling in the planting row when compared to the chiseling in total area, hampering gas diffusion, i.e., the entry of O₂ into the soil and the release of CO₂ to the atmosphere. Thus, the exposure of soil organic matter to microbiological attack contributes to this process of increasing its mineralization (Schwartz et al. 2010), mainly in agricultural practices that promote a greater soil mobilization.

La Scala et al. (2006) observed that the conventional (plowing + harrowing) and reduced (chiseling) tillage systems favored an increase in soil CO₂ emission when compared to the soil without tillage. Iamaguti et al. (2015) also observed in an Oxisol that the conventional tillage presented a higher average value of soil CO₂ emission when compared to the conventional subsoiling and localized subsoiling. According to the authors, this fact shows that soil CO₂ emission is a complex phenomenon and its understanding is challenging due to the great variability of this variable.

The lower soil CO₂ emission in the Oxisol under CPR is also due to the lower decomposition rate of organic carbon present in the planting row when compared to CTA, which is

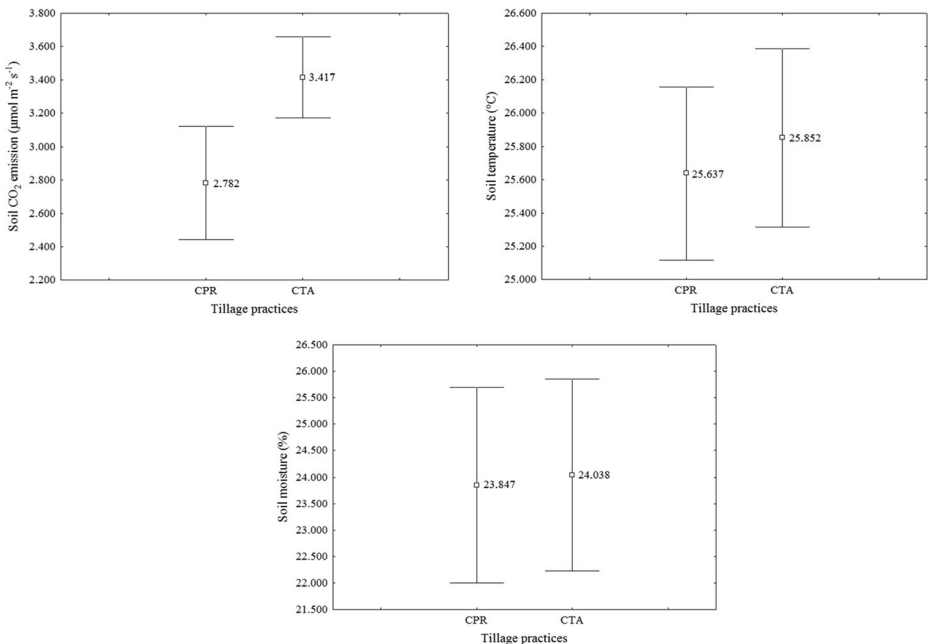


Fig. 1 Average values of soil CO₂ emission, soil temperature, and soil moisture as a function of chiseling in the planting row (CPR) and chiseling in total area (CTA) in the Oxisol. Vertical bars indicate the confidence interval. When upper and/or lower limits of the confidence interval overlap, no statistically significant difference ($p < 0.05$) is observed between CPR and CTA

explained by the smaller mobilized area provided by CPR since chiseling occurred only in the planting row, favoring a smaller soil disaggregation. Thus, the soil submitted to CPR presents a higher capacity to store and conserve soil carbon when compared to that submitted to CTA. In addition, CTA provided a greater soil disaggregation, unprotecting POC and favoring soil microbial activity.

POC differed as a function of chiseling, i.e., CPR presented lower values (2.8 g kg^{-1}) when compared to CTA (4.8 g kg^{-1}) (Fig. 2). This behavior may have occurred due to the mineralization of organic carbon that was readily oxidizable in the area under CTA, since its decomposition leads to an increase in soil CO_2 emission. In addition, in the tillage systems where the soil is mobilized more intensely, organic matter is distributed in the arable layer, favoring its decomposition. CPR and CTA did not affect soil temperature and soil moisture (Fig. 1) because these variables are not normally limiting in tropical regions. Furthermore, CPR and CTA did not affect OCAM (Fig. 2). This organic matter fraction is related to the particles of silt and clay, which is under colloidal protection (Christensen 1996).

Moreover, soil tillage (CPR and CTA) did not affect the pore classes C1, C2, and C3 (Fig. 3). However, a statistical difference ($p < 0.05$) was observed for the pore class C4, whose lower average value ($0.332 \text{ m}^3 \text{ m}^{-3}$) was observed in CPR comparatively to CTA ($0.395 \text{ m}^3 \text{ m}^{-3}$) (Fig. 3). This result may be due to the greater disaggregation that occurred in CTA, leading to a higher compression of soil particles, disaggregating the largest pores and contributing to the formation of small pores. In a clayey soil whose structure was changed, Souza and Alves (2003) observed that the spaces occupied by large pores were affected by an increase in the mass of soil particles per unit volume, favoring the formation of small pores.

Chiseling in the planting row is a characteristic of the recent management techniques adopted by the sugarcane sector, in which soil mobilization occurs in a localized and combined manner by using agricultural implements that simultaneously perform deep subsoiling, application and incorporation of soil correctives, straw windrowing, and soil declodding, such as in bed formation. When soil tillage occurs localized in the planting row, machinery traffic occurs in a controlled manner, providing a lower accumulation of contact pressures generated by the wheels of agricultural machines, which contributes to reduce soil compaction and leads to production, reducing the operational cost related to soil tillage by up to 30% (Souza et al. 2014). In addition, the localized soil tillage leads to a reduction in fuel consumption and hence in greenhouse gas emissions associated with fuel burning. Thus, management practices related

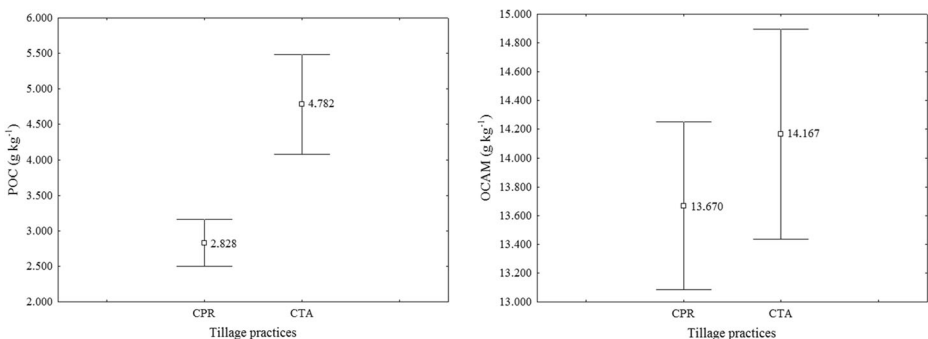


Fig. 2 Average values of particulate organic carbon (POC) and organic carbon associated with minerals (OCAM) as a function of chiseling in the planting row (CPR) and chiseling in total area (CTA) in the Oxisol. Vertical bars indicate the confidence interval. When upper and/or lower limits of the confidence interval overlap, no statistically significant difference ($p < 0.05$) is observed between CPR and CTA

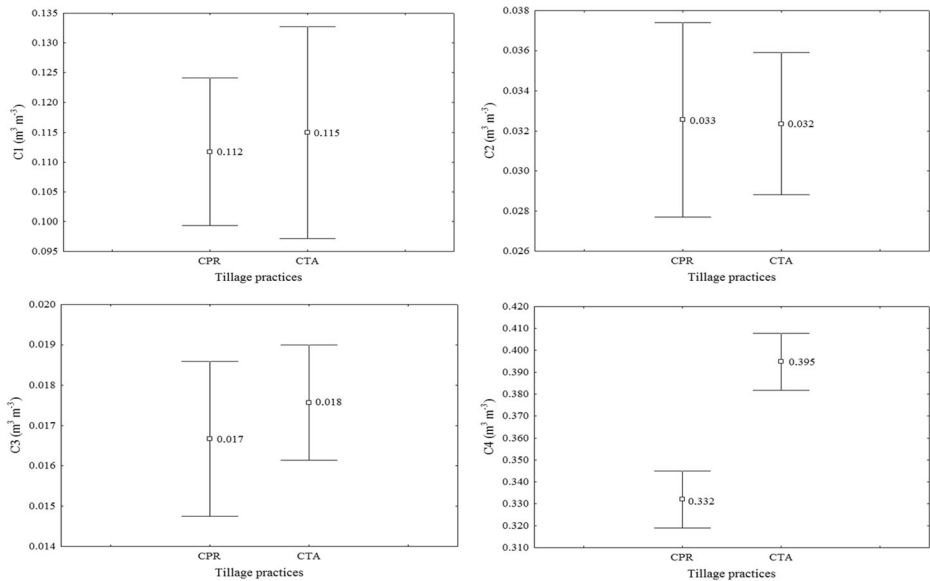


Fig. 3 Average values of water volume ($\text{m}^3 \text{m}^{-3}$) corresponding to C1 ($\phi \geq 0.1$ mm), C2 ($0.0375 \leq \phi < 0.05$ mm), and C4 ($\phi < 0.0375$ mm) as a function of chiseling in the planting row (CPR) and chiseling in total area (CTA) in the Oxisol. Vertical bars indicate the confidence interval. When upper and/or lower limits of the confidence interval overlap, no statistically significant difference ($p < 0.05$) is observed between CPR and CTA

to localized soil tillage for sugarcane planting are effective strategies for mitigating greenhouse gas emissions in agriculture, allowing sugarcane to increasingly stand out as an environmentally viable energy matrix.

In order to understand the behavior of soil CO_2 emission as a function of the studied soil attributes, a multiple regression analysis was performed for each soil tillage considering both soil classes. Multiple regression models showed that OCAM and C2 explained 72% of the variability of soil CO_2 emission ($R^2 = 0.72$) (Table 1). In addition, the parameters estimated by the multiple regression for OCAM and C2 were positive, indicating individual correlations between these variables and soil CO_2 emission in CPR, i.e., as OCAM and C2 increased soil CO_2 emission also increased. This positive signal for both variables may be related to the larger pores, which favor an increase in soil CO_2 flux. Chiseling in the planting row leads to a less soil mobilization, favoring OCAM protection and preserving larger pores such as C2. This result occurred, because the area under CPR preserved the large pores. Moreover, although OCAM has less exposure, the microorganisms act in its decomposition, favoring the emission of CO_2 through the pores.

Chiseling in the planting row and in total area initially increase soil CO_2 emission due to soil disaggregation, which favors the mineralization of carbon that was physically protected in the aggregates (Schwartz et al. 2010). Thus, soil management systems that provide a reduction in CO_2 emissions present a greater potential for soil carbon conservation when compared to systems with a higher CO_2 emission (Costa et al. 2008). In addition, larger pores favor an

environment with a high oxygenation for CO₂ production by microorganisms. In our study, CTA mobilized a larger area, creating an environment that favored both microbial activity and particle accommodation, leading to the formation of small pores, although they did not govern soil CO₂ emission in CPR.

Multiple regression models for CTA showed that M_{soil} and T_{soil} explained 53% of the variability of soil CO₂ emission ($R^2 = 0.53$) (Table 2). In this case, CTA provided a greater soil disaggregation, causing the soil CO₂ emission to be influenced only by soil moisture and soil temperature. The parameters estimated in this analysis for M_{soil} and T_{soil} were also positive, showing individual correlations between these variables and soil CO₂ emission. Soil CO₂ emission was related to M_{soil} and T_{soil} only in CTA, since this tillage operation promotes a greater soil disturbance and affects both variables, which are directly related to each other and sensitive to soil structure modification. In a study conducted in an Oxisol under conventional (plowing + harrowing) and reduced (chiseling) tillage systems, La Scala et al. (2006) also observed a positive correlation between soil CO₂ emission and soil moisture, but not significant with soil temperature. Iamaguti et al. (2015) found a significant and negative correlation between soil CO₂ emission and soil temperature for conventional tillage, different from that observed in our study. In addition, these authors did not find a correlation between soil CO₂ emission and soil moisture in the conventional tillage (two harrowing), conventional subsoiling (subsoiling in total area), and localized subsoiling (subsoiling in the planting row). Ussiri and Lal (2009) observed a significant and positive correlation between soil temperature and soil CO₂ emission after soil tillage (moldboard plowing, chiseling, and no tillage).

The total soil CO₂ emission accumulated in the Oxisol was calculated and presented a value of 1336.3 kg CO₂ ha⁻¹ for CTA and 1042.6 kg CO₂ ha⁻¹ for CPR. Thus, CTA emitted, from soil to the atmosphere, 293.7 kg CO₂ ha⁻¹ more than CPR in a 12-day period, which is equivalent to a loss of 80 kg C ha⁻¹ (C-CO₂) due to a greater soil mobilization in CTA. Oxisols and Ultisols occupy 58% of the total area of Brazil, 32% of which represented only by Oxisols (Santos et al. 2013). Thus, determining soil management that reduces carbon loss is essential in the face of the challenges of global agriculture to increase the efficiency of conventional management practices, integrating and/or replacing them with more sustainable alternatives (FAO 2014) since carbon loss is detrimental both due to environmental factors related to climate change and to agronomic factors related to the decrease of organic matter that affects the structure and fertility of soils and, consequently, food production.

3.2 Soil CO₂ emission and soil attributes in the Ultisol

In the Ultisol, soil tillage (CPR and CTA) did not affect soil CO₂ emission, T_{soil} , M_{soil} , OCAM, POC (Figs. 4 and 5), C1, C2, C3, and C4 (Fig. 6). This difference may be due to the higher

Table 2 Multiple regression model of the average soil CO₂ emission as a function of soil attributes in the chiseling in total area (CTA) in the Oxisol

Attribute	Parameter	SE	<i>p</i>	R^2
Intercept	-13.54845	5.21824	0.0267	
M_{soil}	0.10843	0.04438	0.0347	0.2826
T_{soil}	0.55328	0.16707	0.0079	0.5265

SE = standard error of the parameter estimation; R^2 = coefficient of determination; M_{soil} = soil moisture; T_{soil} = soil temperature

sand content (809.30 g kg^{-1}) and Ds (1.71 g cm^{-3}) and the lower MWD (1.72 mm), Pt ($0.32 \text{ m}^3 \text{ m}^{-3}$), Macro ($0.07 \text{ m}^3 \text{ m}^{-3}$), Micro ($0.25 \text{ m}^3 \text{ m}^{-3}$), and OC (7.00 g kg^{-1}) found in the Ultisol when compared to the sand content (392.00 g kg^{-1}), Ds (1.24 g cm^{-3}), MWD (3.46 mm), Pt ($0.53 \text{ m}^3 \text{ m}^{-3}$), Macro ($0.15 \text{ m}^3 \text{ m}^{-3}$), Micro ($0.38 \text{ m}^3 \text{ m}^{-3}$), and OC (17.94 g kg^{-1}) found in the Oxisol. When studying the attributes of a soil submitted to chiseling in the planting row and in total area in the same experimental area of our study, Souza (2016) observed a higher soil density in the Ultisol for both chiseling (CPR of 1.73 g cm^{-3} and CTA of 1.69 g cm^{-3}) when compared to the Oxisol (CPR of 1.30 g cm^{-3} and CTA of 1.18 g cm^{-3}). Moreover, this author observed lower values of soil porosity in the Ultisol (CPR of $0.31 \text{ m}^3 \text{ m}^{-3}$ and CTA of $0.33 \text{ m}^3 \text{ m}^{-3}$) when compared to the Oxisol (CPR of $0.49 \text{ m}^3 \text{ m}^{-3}$ and CTA of $0.56 \text{ m}^3 \text{ m}^{-3}$) at a depth of 0–0.10 m. Sandy textured soils favor a porosity decrease, leading to a reduction in soil CO_2 diffusion (Shestak and Busse 2005), since a lower total porosity provides an anaerobic environment (with little oxygenation), restricting soil microbial activity.

Li et al. (2002) observed that at environments with low porosity and oxygenation, there is a decrease of up to one third of the number of microorganisms that live in the soil (bacteria and fungi), thus reducing the emission of CO_2 to the atmosphere. Da Silva et al. (2004) assessed the physical attributes of an Ultisol under different soil tillage (conventional tillage, reduced tillage, and no tillage) and verified that soil disturbance did not influence attributes such as pore size distribution and total porosity. In addition, in the Ultisol, the average values of soil CO_2 emission were not significant. This result is probably due to the intrinsic characteristics of

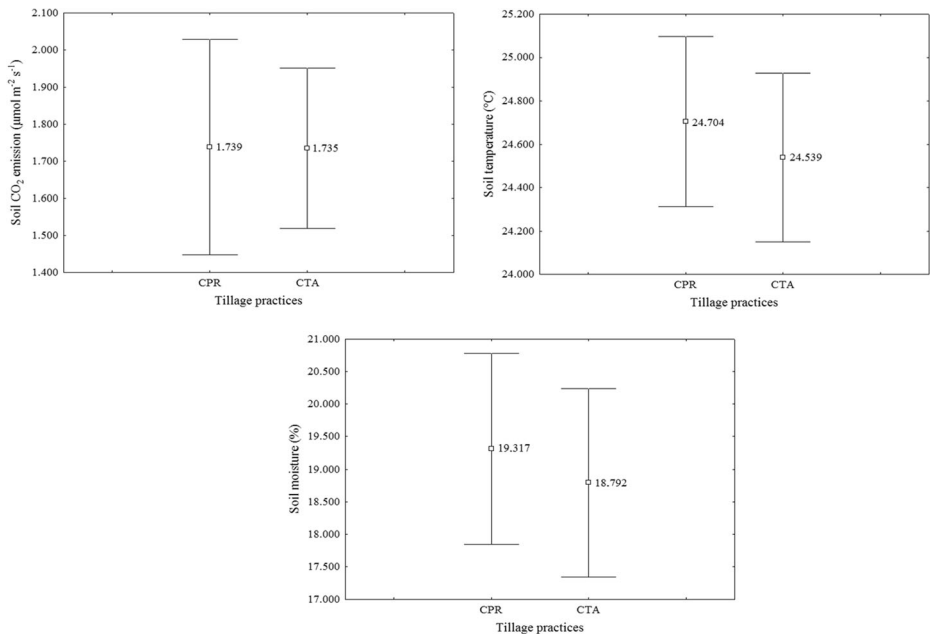


Fig. 4 Average values of soil CO_2 emission, soil temperature, and soil moisture as a function of chiseling in the planting row (CPR) and chiseling in total area (CTA) in the Ultisol. Vertical bars indicate the confidence interval. When upper and/or lower limits of the confidence interval overlap, no statistically significant difference ($p < 0.05$) is observed between CPR and CTA

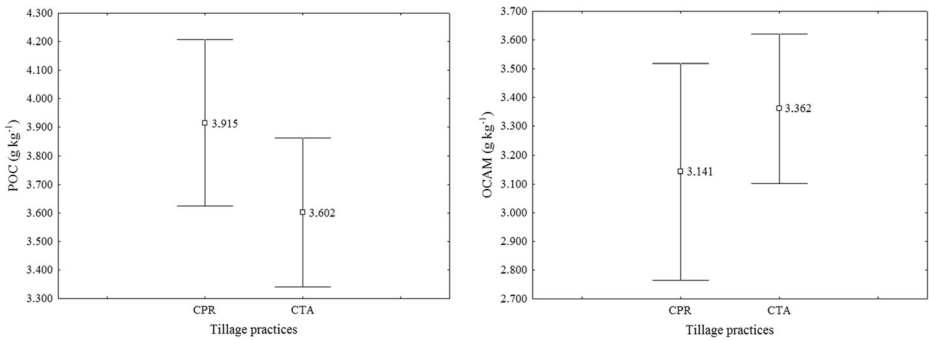


Fig. 5 Average values of particulate organic carbon (POC) and organic carbon associated with minerals (OCAM) as a function of chiseling in the planting row (CPR) and chiseling in total area (CTA) in the Ultisol. Vertical bars indicate the confidence interval. When upper and/or lower limits of the confidence interval overlap, no statistically significant difference ($p < 0.05$) is observed between CPR and CTA

the Ultisol, because soils that present a sandy texture in the superficial layer can promote a greater particle reorganization, with reduced pore volumes, and are more resistant to external forces (Braga et al. 2015).

The Ultisol presented lower values of OC when compared to the Oxisol, resulting in lower average values of soil CO₂ emission in CPR and CTA. In general, the Oxisol presents a greater

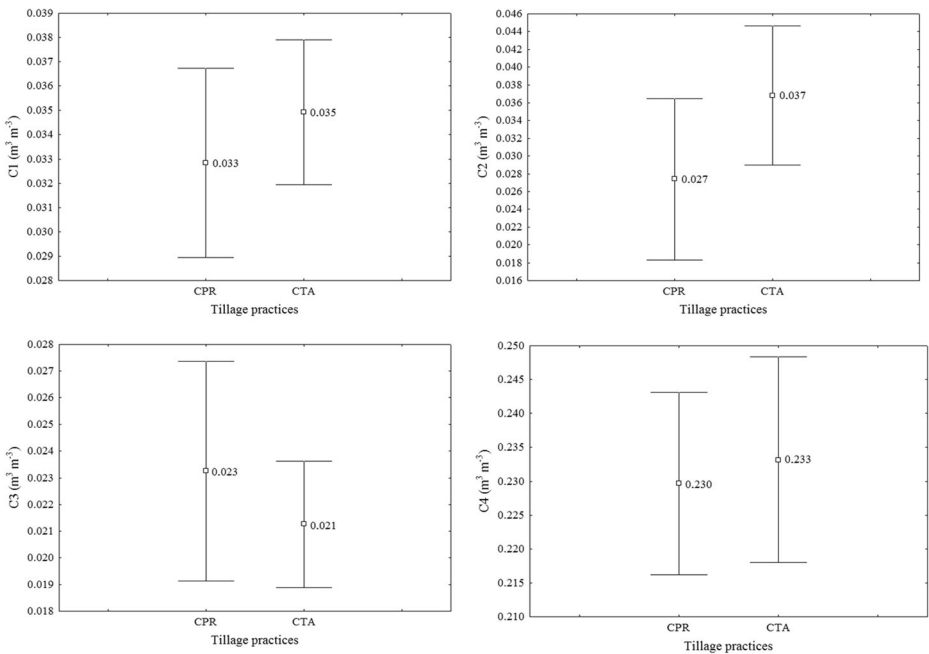


Fig. 6 Average values of water volume (m³ m⁻³) corresponding to C1 ($\phi \geq 0.1$ mm), C2 ($0.05 \leq \phi < 0.1$ mm), C3 ($0.0375 \leq \phi < 0.05$ mm), and C4 ($\phi < 0.0375$ mm) as a function of chiseling in the planting row (CPR) and chiseling in total area (CTA) in the Ultisol. Vertical bars indicate the confidence interval. When upper and/or lower limits of the confidence interval overlap, no statistically significant difference ($p < 0.05$) is observed between CPR and CTA

physical protection to the organic matter inside its aggregates, reducing the microbial activity and hence the mineralization of organic residues in the soil, in addition to favoring an increase in its carbon stock.

No significant difference was observed for the average values of soil CO₂ emission and tillage operations in the Ultisol. However, by calculating the total soil CO₂ emission accumulated over the assessment period and comparing CTA (702.8 kg CO₂ ha⁻¹) and CPR (659.1 kg CO₂ ha⁻¹), an additional emission of 43.7 kg CO₂ ha⁻¹ was observed in only 11 days of assessments, i.e., a loss of 12 kg C ha⁻¹ (C–CO₂) occurred in this short period due to the more intense soil mobilization in CTA. Therefore, considering that the Ultisol naturally presents a lower carbon content due to its sandy texture when compared to the Oxisol, which presents a more clayey texture, any carbon loss can be considered significant and may have a consequence on its soil structure.

In the multiple regression analysis, M_{soil} , C1, and OCAM explained 82% ($R^2 = 0.82$) of the variability of soil CO₂ emission in CPR (Table 3) whereas, in CTA, M_{soil} , OCAM, and POC explained 67% ($R^2 = 0.67$) of this variability (Table 4). The greater soil disaggregation provided by CTA explains the lower variability of soil CO₂ emission when compared to CPR, since a greater disaggregation favors a good environment for microbial activity, leading to the organic matter decomposition and favoring carbon loss as CO₂. Thus, in CPR and CTA, M_{soil} is negatively related to soil CO₂ emission, which is possibly due to the occurrence of rain in the experimental area over the experimental period. According to Lier (2001), an increase in soil moisture reduces the flow of gases in the soil. When studying soil CO₂ emission in an Ultisol at a depth of 0–0.05 m under conventional (plowing + harrowing) and no-tillage systems, Costa et al. (2008) also found similar results. La Scala et al. (2006) also found similar results.

Furthermore, OCAM and C1 were positively related to soil CO₂ emission in CPR. In this case, a less soil mobilization led to a greater preservation of larger pores and OCAM. Large pores favor the flow of gases in the soil, contributing to soil CO₂ emission. In addition, OCAM is a source of energy for microorganisms, favoring the emission of carbon as CO₂. OCAM and POC were negatively related to soil CO₂ emission in CTA. Although chiseling in the planting row and in total area are not distinct from each other, CTA provides a greater soil mobilization when compared to CPR. Sandy textured soils provide a low binding power of the organic constituents with colloidal components, resulting in a less physical protection of the organic matter, which favors a greater decomposition by microorganisms (Bayer et al. 2000). Thus, soil CO₂ emission is favored by the mineralization of organic matter that was unprotected due to the rupture of aggregates caused by chiseling.

In our study, the Ultisol presented a higher average value of Ds (1.71 g cm⁻³) and lower average values of Pt (0.32 m³ m⁻³), Macro (0.07 m³ m⁻³), Micro (0.25 m³ m⁻³), and OC (7.00 g kg⁻¹) when

Table 3 Multiple regression model of the average soil CO₂ emission as a function of soil attributes in the chiseling in the planting row (CPR) in the Ultisol

Attribute	Parameter	SE	<i>p</i>	R^2
Intercept	3.06366	0.73855	0.0014	
M_{soil}	-0.16642	0.02816	< 0.0001	0.5583
C1	29.17442	9.28408	0.0085	0.7204
OCAM	0.29565	0.11802	0.0277	0.8164

SE = standard error of the parameter estimation; R^2 = coefficient of determination; M_{soil} = soil moisture; C1 ($\phi \geq 0.1$ mm); OCAM = organic carbon associated with minerals

Table 4 Multiple regression model of the average soil CO₂ emission as a function of soil attributes in the chiseling in total area (CTA) in the Ultisol

Attribute	Parameter	SE	<i>p</i>	<i>R</i> ²
Intercept	5.88067	0.86838	< 0.0001	
<i>M</i> _{soil}	−0.09494	0.02539	0.0025	0.4084
OCAM	−0.39862	0.13997	0.0137	0.5670
POC	−0.26623	0.13210	0.0450	0.6701

SE = standard error of the parameter estimation; *R*² = coefficient of determination; *M*_{soil} = soil moisture; OCAM = organic carbon associated with minerals; POC = particulate organic carbon

compared to the Oxisol (Ds of 1.24 g cm^{−3}, Pt of 0.32 m³ m^{−3}, Macro of 0.15 m³ m^{−3}, Micro of 0.38 m³ m^{−3}, and OC of 17.94 g kg^{−1}). This result could explain the lower soil CO₂ emission in the Ultisol since higher values of soil bulk density and a low total porosity favor an environment with little oxygenation, limiting soil microbial activity. In addition, the Ultisol presents a less aggregation, i.e., the aggregates are broken easily because of their less stable structure. Thus, with aggregate disruption, carbon is released as CO₂, leading to a lower soil CO₂ emission in the Ultisol. This behavior can also be explained by the higher content of Fe_d (80.32 g kg^{−1}) found in the Oxisol when compared to the Ultisol (18.5 g kg^{−1}). Clayey textured soils, with high contents of Fe and Al oxides and hydroxides, contribute to increasing organic carbon stability in the form of organomineral complexes (Roscoe and Buurman 2003).

Another factor that may explain the lower soil CO₂ emission in the Ultisol is the low microporosity when compared to the Oxisol. This low microporosity reduces water adsorption in the pores, making it an environment limiting for the survival of microorganisms that act in the organic matter decomposition, because water is essential for their life. Thus, as the microbial activity decreases, carbon loss in the form of CO₂ also decreases. Souza et al. (2017) studied soil CO₂ emission in an Oxisol and Ultisol and observed that the total soil CO₂ emission was, on average, higher in the Oxisol (1178.60 kg CO₂ ha^{−1}) when compared to the Ultisol (618.15 kg CO₂ ha^{−1}).

Soil CO₂ emission presents a different behavior as a function of soil texture, soil management, and climatic conditions due to its variability and dependence of climatic conditions of each environment by the variables that are involved in both CO₂ production and emission processes. Thus, more studies are needed to understand the behavior of soil CO₂ emission in different soil textural classes, soil management, and climatic conditions since its characterization is challenging due to its great variability.

4 Conclusions

In the Oxisol, chiseling in planting row and in total area directly affected soil structure, causing changes in soil porosity and in soil CO₂ emission. On the other hand, in the Ultisol, soil CO₂ emission was not affected regardless of the chiseling.

Chiseling in the planting row favored the formation of small pores in the Oxisol, contributing to a reduction in soil CO₂ emission. In the Ultisol, soil pores did not influence soil CO₂ emission regardless of the chiseling.

In the chiseling in planting row, macropores and organic carbon associated with minerals interfered with soil CO₂ emission in the Oxisol whereas, in the Ultisol, macropores, soil moisture, and organic carbon associated with minerals interfered with soil CO₂ emission.

The results indicate that in addition to soil tillage intensity, soil texture to which the tillage operation will be applied must be taken into account in the adoption of soil management strategies aiming at reducing greenhouse gas emissions. Thus, in order to mitigate CO₂ emission and, consequently, carbon preservation, agricultural soils that present a more clayey texture require tillage practices that allow less mobilization when compared to soils with a more sandy texture. Improved soil management practices and strategies can help address a variety of global change challenges.

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