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# On the spatial and temporal dependence of $CO_2$ emission on soil properties in sugarcane (*Saccharum* spp.) production

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ABSTRACT

$CO_2$ production in soil is the result of biological processes, such as the decomposition of organic matter and the respiration of roots and soil organisms. It also depends on the physical, chemical and biological properties and their interactions. Such properties exhibit variability in space and time, which provides a high degree of complexity on soil $CO_2$ emission ($FCO_2$). However few studies discuss the spatial and temporal component of $FCO_2$, jointly. The objective of this study was to characterize the spatial and temporal variability of $FCO_2$ and its relationship to the edaphoclimatic properties of the soil in sugarcane fields. The LI-8100 system, which monitors changes in $CO_2$ concentrations within a portable chamber, was used to assess the $FCO_2$. The $CO_2$ flux measurements, soil temperature (0–20 cm, thermometer of LI-8100) and soil water content (0–12 cm, TDR device) were evaluated concomitantly. Overall, the mean values for $FCO_2$, soil temperature and soil water content were 2.8 $\mu$mol m$^{-2}$ s$^{-1}$, 19.48 °C and 17.20 m$^3$ m$^{-3}$, respectively. The $FCO_2$ was positively correlated with the soil organic matter content (SOM) ($r = 0.67$, $p < 0.001$), the air-filled porosity (AFP) ($r = 0.71$, $p < 0.001$) and the available phosphorus ($r = 0.28$, $p < 0.05$) but negatively correlated with the soil C/N ratio ($r = -0.75$, $p < 0.001$) and soil water content ($r = -0.29$, $p < 0.05$). The air-filled porosity was the last property added to the multiple regression model and explained 77% of the spatial variability in soil $CO_2$ emission. The largest temporal variations in $CO_2$ emissions over the study period were explained by changes in soil water content, especially after rainfall. Spatially, the $CO_2$ emission is modeled by chemical (organic matter and soil C/N ratio) and physical (air-filled porosity) soil properties which are associated to production and transport of $CO_2$ in soil.



## 1. Introduction

The concentrations of carbon dioxide ($CO_2$) and other greenhouse gases, such as methane ($CH_4$), nitrous oxide ($N_2O$) and chlorofluorocarbons (CFCs), in the atmosphere have increased considerably since the Industrial Revolution. This phenomenon caused serious climate changes by enhancing the greenhouse effect and raising the mean temperature of the planet (IPCC, 2007). The strategies employed to reduce carbon emissions include increased energy efficiency, the use of renewable sources primarily generated by hydropower and biofuels, and the development of technologies that promote the storage of carbon by different terrestrial ecosystems. Sugarcane (*Saccharum* spp.) has become the second most important source of energy in Brazil behind oil. Brazil is the world's largest sugarcane producer and accounts for 54% of the ethanol sold in the world (CONAB, 2012).

Sugarcane production areas are expanding in Central Brazil, which is the focus of numerous studies that have indicated the potential of sugarcane to capture atmospheric $CO_2$ and promote soil carbon sequestration (La Scala et al., 2001; Razafimbelo et al., 2006; Cerri et al., 2007; Silva-Olaya et al., 2013). In addition, with the adoption of mechanized harvest systems that circumvent the need for burning, the soil $CO_2$ flux to the atmosphere is reduced (Panosso et al., 2009; La Scala et al., 2012) by avoiding the release of significant amounts of carbon that are stored in the surface soil layers (Galdos et al., 2009).

Soil $CO_2$ production is directly related to biological activity, such as the respiration of roots and the decomposition of soil organic

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matter (SOM) by microbial activity, and is influenced by temperature and soil water content (Epron et al., 2006; Lal, 2009; Herbst et al., 2009). Within the soil, $CO_2$ moves by two mechanisms: (1) displacement from a greater concentration zone to a lower concentration zone (diffusion) and (2) by convective flow, in which the gas moves with the air that is mixed following a pressure gradient, which varies depending on the texture, structure and soil water content (Ball and Smith, 1991).

Thus, it is expected that different soil types will display different $CO_2$ emissions due to their different physical, chemical and biological properties, such as the soil organic matter content (Lal, 2009), the microorganism population density in the rhizosphere (Duiker and Lal, 2000), the dry bulk soil density (Xu and Qi, 2001; Teixeira et al., 2012), the soil pH (Reth et al., 2005; Fuentes et al., 2006), the available phosphorus (Nordgren, 1992; Duah-Yentumi et al., 1998), the texture (Dilustro et al., 2005) and the water filling status of pores (Smart and Peñuelas, 2005). Changes in soil use and management as well as anthropogenic factors also determine the intensity of the emission process (Cerri et al., 2007).

Soil properties vary considerably in space due to pedogenic factors (Epron et al., 2006; Fiener et al., 2012; Ngao et al., 2012). Meanwhile, temperature and soil water content display more temporal than spatial variability. Thus, the influence of these two sets of variables on soil $CO_2$ emissions results in large spatial and temporal variations in emissions.

Organic matter is the primary source of energy that soil microorganisms use for metabolic processes that produce carbon dioxide ($CO_2$). Therefore, the microbial community is a key factor in SOM dynamics and soil $CO_2$ emission, which control the availability of nutrients and carbon release or accumulation in the soil (Six et al., 2006).

In this context, the C/N ratio is an important regulator of SOM decay and provides information about its humification state (Lamparter et al., 2009). Hence, depending on the values of this ratio, we can infer whether the microbial activity is more or less intense (Ngao et al., 2012). The lignin content controls SOM decay (Parton et al., 1987), but the C/N ratio is most commonly used as an indicator of the potential mineralization (Potter and Klooster, 1997).

Variables such as the soil temperature and soil water content influence the $FCO_2$ (Duiker and Lal, 2000). The soil temperature directly affects microbial activity and root respiration (Silva-Olaya et al., 2013). According to Davidson et al. (2000), the soil respiration increases exponentially with increasing temperature, explaining why higher emissions are observed in tropical regions. Soil respiration is also affected by soil water content (Herbst et al., 2009), which can either promote or inhibit the $CO_2$ production in the soil as it affects microbial activity and gas diffusion (Lal, 2001). These effects are primarily due to the soil water content. The $CO_2$ concentration in soil pores is approximately 10–100 times higher than that in the atmosphere (Varella et al., 2004). Increased soil water content due to rainfall favors the removal of significant quantities of $CO_2$ from the soil as water enters the pore space (Smart and Peñuelas, 2005).

Under the assumption that soil $CO_2$ emission is influenced by inherent soil properties and environmental factors, which exhibit spatial and temporal variability, respectively, the objective of this study was to characterize the spatial and temporal behavior of soil $CO_2$ emission and its relationship to the edaphoclimatic properties of the soil in sugarcane areas in Dourados, Mato Grosso do Sul State, Central Brazil.

## 2. Materials and methods

### 2.1. Study site

The study was conducted in the experimental area of Embrapa Agropecuária West (CPAO) in Dourados, Mato Grosso do Sul State, in Central Brazil. The area is located at 22°14′ Southern latitude, 54°49′ Western longitude and 452 m above sea level. The soil is classified as Dystroferric Red Latosol (Haplustox, USDA Soil Taxonomy), and the slope was determined to be 3%.

According to the Thornthwaite classification, the climate was defined as B1rB′4a′ humid mesothermal, with little or no water deficiency, and a summer evapotranspiration of less than 48% of the annual evapotranspiration. The mean annual temperature ranges from 20 °C to 22 °C with a mean annual rainfall of 1550 mm, with November–January representing the wettest months.

### 2.2. Experimental design

Sugarcane was planted on November 28, 2009, with density of 18 plants $m^{-1}$, covering an area of 3000 $m^2$. Fertilization was performed one day before the sugarcane was planted by applying 2 t $ha^{-1}$ of organic compost to the plantation immediately beneath the sugarcane culms. Prior to sugarcane, the area was planted with green manure, especially oat (*Avena stringosa*), and this was the first sugarcane planting in the study area. *Avena stringosa* is a grass recommended for green manure in the winter. It has been used with success in the rotation and succession of crops.

Assessments and soil sampling were performed in the sugarcane interrows prior to harvest. Those samplings were distributed randomly in 60 sample points separated by at least 5 m distance.

### 2.3. Soil $CO_2$ emission, soil temperature and soil water content

The soil $CO_2$ emission ($FCO_2$) was recorded using a portable LI-COR system (LI-8100, Nebraska, USA). This system consisted of a closed 10-cm-diameter chamber that was attached to the soil collars previously inserted into the soil. In measurement mode, the system monitors changes in the $CO_2$ concentration over time within the chamber via optical absorption spectroscopy in the infrared region (IRGA–infrared gas analyzer). The $FCO_2$ captured by the LI-COR system was the result of soil $CO_2$ emission by autotrophic (roots of plants) and heterotrophic (microorganisms) respiration. In this study, although autotrophic respiration is present, this factor was disregarded during analysis due to the homogeneity of the plants in the study area. Thus, because all plants present in the area were in the same phenological stage, the autotrophic component of the emission was considered similar throughout the area, and the observed differences in $FCO_2$ in time and space were attributed to the inherent soil properties and to environmental factors (soil temperature and soil water content).

Concurrent with the soil $CO_2$ emission evaluations, the soil temperature (TS) at 18 cm depths was recorded using a thermometer (thermistor laptop), which is part of the system attached to the LI-COR instrument. The soil water content (SWS) was also evaluated at all sampling locations using a portable TDR system (Campbell, Hydrosense, Campbell Scientific, Australia), which assessed the soil water content ($m^3\,m^{-3}$) in a 0–12 cm layer.

Measurements were performed on 10 different days during a 20-day total period (15, 16, 19, 21, 22, 26, 27 and 30 September, 2011 and 03 and 04 October, 2011) in the morning from 8 to 10 h. Using the Julian day calendar, these dates correspond to days 258, 259, 262, 264, 265, 269, 270, 273, 276 and 277, 2011.

### 2.4. Analysis of chemical and physical properties of the soil

After 10 measurements the $CO_2$ flux, 60 soil samples were taken at 0–20 cm depths to determine the base saturation (BS), sum of bases (SB), hydrogen potential (pH), calcium (Ca), magnesium (Mg), potassium (K), phosphorus (P), cation exchange capacity

(CEC) and potential acidity (H + Al) following the methods proposed by EMBRAPA (1997). An analysis of the total organic carbon (TOC) was performed with a Total Organic Carbon Analyzer (TOC-V, Shimadzu Labs) coupled with a Solid Sample Module (model SSM-5000, Shimadzu Labs). The TOC values were multiplied by 1.72 to transform them into the soil organic matter content (SOM). The analysis of total nitrogen was performed by the Kjeldahl method. In this method, N is converted to ammonium sulfate by oxidation with a mixture of $CuSO_4$, $H_2SO_4$ and $Na_2SO_4$. Subsequently, in an alkaline medium, the converted ammonium sulfate releases ammonia, is complexed with a solution of boric acid containing a mixed indicator in a diffusion chamber and is finally determined by acidimetry ($H_2SO_4$ or HCl) (EMBRAPA, 1997).

The soil dry bulk density (BD), macroporosity (macro), microporosity (micro) and the total pore volume (TPV) were evaluated in undisturbed soil samples extracted with steel rings that had an internal volume of 50 $cm^3$ and in samples collected near the collars at 0–20 cm depths. The air-filled porosity (AFP in $m^3 m^{-3}$) fraction was calculated as the difference between the total porosity (TP in $m^3 m^{-3}$) and the soil water content (SWC in $m^3 m^{-3}$) (Panosso et al., 2011).

### 2.5. Statistical analyses

#### 2.5.1. Temporal variability

$FCO_2$, temperature and soil water content were measured on 10 different days, considering 60 sampling points. For each of the 10 days were calculated, the mean, standard deviation, standard error and coefficient of variation.

#### 2.5.2. Spatial variability

The soil $CO_2$ emission (Fmean), temperature (TSmean) and soil water content (SWC mean) were spatially analyzed considering the average for each of the 60 sampling points, being calculated from the 10 respective measurements over time. This procedure was used by several authors to perform spatial analyses (Panosso et al., 2009; Teixeira et al., 2012). The correlation analysis was performed between the mean values of $CO_2$ emission over time (Fmean) and physical and chemical soil properties, considering 60 samples for each property.

The data were analyzed by descriptive statistics (mean, standard error of mean, maximum, minimum and coefficient of variation). Correlation analyses were performed to determine the degree of relationship between the $FCO_2$ and the related properties.

A multiple regression analysis was performed using stepwise variable selection. In this method, the significance levels of the *F* test used to judge the input and/or output variables in the model were equal to 1% ($p < 0.001$). Simultaneously with the statistical analyses, the basic assumptions of analysis of variance, multiple regression, normality of error and homogeneity of variances were tested for all the properties. The statistical analyses were conducted in SAS (SAS version 9, SAS institute, Cary, NC, USA) programs.

## 3. Results and discussion

### 3.1. Temporal variability

The mean $FCO_2$ during the study period ranged from 1.89 to 2.32 $\mu mol\ m^{-2} s^{-1}$, as recorded on days 258 and 276, respectively (Table 1). The range of values were similar to those reported by other authors in studies conducted in areas under sugarcane cultivation (Panosso et al., 2011; Silva-Olaya et al., 2013). The $FCO_2$ spatial mean values increased between days 270 and 277 following the precipitation events recorded on days 269 (27.8 mm), 274 (7.8 mm) and 275 (0.2 mm). La Scala et al. (2001) observed that precipitation influenced $FCO_2$, and the pattern of the emission was changed immediately after a rain period. The same phenomenon was observed by Panosso et al. (2009), where emissions reached values as high as 5.11 $\mu mol\ m^{-2} s^{-1}$ on days following rainfall events.

Precipitation can affect soil respiration in different ways depending on the environmental conditions and the soil. Precipitation after a prolonged dry spell (conditions similar to this experiment) promote microbial activity, whereas in more humid periods, precipitation can cause total expulsion of the oxygen present in the soil, giving rise to an anaerobic microenvironment (Smart and Peñuelas, 2005) and reducing soil $CO_2$ emissions. During precipitation, significant amounts of $CO_2$ are expelled out the soil due to the infiltration of water, which causes the air in the soil pores to be replaced by water (Varella et al., 2004).

The soil water content (SWC) also varied considerably during the study period, ranging from 8.00 $m^3 m^{-3}$ to 32.22 $m^3 m^{-3}$ (Table 1), with the highest mean (32.22 $m^3 m^{-3}$) also recorded after rainfall events and representing a 50% increase compared to the previous day. Because $FCO_2$ and SWC changes were observed after rainy events, we performed a linear correlation analysis between those variables and observed a positive correlation ($r = 0.66$, $p < 0.05$), which indicated that the soil water content affected the temporal evolution of $FCO_2$ during the study period. Conversely, a significant correlation was not observed between the $FCO_2$ and the soil temperature ($p > 0.05$) over the experimental period. The low TS variability (minimum of 18.2 °C on day 269 and maximum of 21.0 °C on day 273) during the study period possibly contributed to this lack of correlation between the variables.

The coefficient of variation (CV) for SWC ranged from medium (12% < CV < 24%) to high (CV > 24%) according to the classification

**Table 1**
Descriptive statistics of soil $CO_2$ emissions ($FCO_2$), soil temperature (TS) and soil water content (SWC) during the study period, and accumulated rainfall. Statistics are given for spatial means at 10 different days.

| Day | $FCO_2$ ($\mu mol\ m^{-2} s^{-1}$) | | | | TS (°C) | | | | SWC ($m^3 m^{-3}$) | | | | Accumulated rainfall (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD | SE | CV | Mean | SD | SE | CV | Mean | SD | SE | CV | |
| 258 | 1.89 | 0.70 | 0.09 | 37.04 | 19.11 | 1.92 | 0.25 | 10.05 | 8.69 | 3.39 | 0.44 | 39.01 | 0 |
| 259 | 1.92 | 0.70 | 0.09 | 36.46 | 19.50 | 0.55 | 0.07 | 2.82 | 8.00 | 1.80 | 0.23 | 22.50 | 0 |
| 262 | 1.97 | 0.71 | 0.09 | 36.04 | 20.13 | 0.42 | 0.05 | 2.09 | 10.66 | 2.66 | 0.35 | 24.95 | 0 |
| 264 | 2.05 | 0.79 | 0.10 | 38.54 | 19.55 | 0.50 | 0.06 | 2.56 | 15.39 | 4.84 | 0.63 | 31.45 | 0 |
| 265 | 2.02 | 0.74 | 0.10 | 36.63 | 18.43 | 0.58 | 0.08 | 3.15 | 14.25 | 3.59 | 0.47 | 25.19 | 0 |
| 269 | 1.96 | 0.85 | 0.11 | 43.37 | 18.24 | 0.79 | 0.10 | 4.33 | 21.69 | 3.57 | 0.46 | 16.46 | 27.8 |
| 270 | 2.16 | 0.97 | 0.13 | 44.91 | 18.44 | 0.75 | 0.10 | 4.07 | 32.22 | 8.37 | 1.09 | 25.98 | 27.8 |
| 273 | 2.25 | 0.99 | 0.13 | 44.00 | 21.07 | 0.71 | 0.09 | 3.37 | 17.08 | 3.21 | 0.42 | 18.79 | 27.8 |
| 276 | 2.32 | 0.99 | 0.13 | 42.67 | 20.30 | 0.67 | 0.09 | 3.30 | 24.14 | 4.53 | 0.59 | 18.77 | 36.0 |
| 277 | 2.11 | 0.80 | 0.10 | 37.91 | 20.03 | 0.64 | 0.08 | 3.20 | 20.12 | 3.54 | 0.46 | 17.59 | 36.0 |

$N = 60$. SD, standard deviation; SE, standard error of the mean; CV, coefficient of variation (%).

criteria proposed by Warrick and Nielsen (1980). For the $FCO_2$, the CV was high for all studied days; however, the CV values were similar to those observed in forest areas (Epron et al., 2006; Tedeschi et al., 2006) and in areas cultivated with sugarcane (Panosso et al., 2009). Brito et al. (2009) investigated sugarcane areas in São Paulo and evaluated the effect of different topographic positions and soil properties on the $FCO_2$, observing higher CV values for $FCO_2$ (55.2%) and soil water content (28.7%) and medium CV values for soil temperature (16.4%).

The increase in the CV value for $FCO_2$ after rainy events (day 269) indicates that rainfall promotes variability in soil respiration. However, for soil water content the opposite trend occurred, and the CV value decreased after rains (Table 1).

### 3.2. Spatial variability

The total mean over the studied period was 2.08 $\mu mol\ m^{-2}\ s^{-1}$, 19.48 °C and 17.20 $m^3\ m^{-3}$ for Fmean, TSmean and WSCmean (Table 2), respectively, which were higher than those reported by Brito et al. (2009) under similar conditions of studies in areas of sugarcane in the state of São Paulo, where the crop was at the initial cycle.

Using simple linear correlation analysis, we observed a weak positive relationship between Fmean and WSCmean ($r = 0.29$, $p < 0.05$) in space (Table 3), which differed from previous reports that performed the same analysis with the daily average of the two variables. Thus, we can see that although the soil water content influenced $CO_2$ emission both in space and in time, there was an approximately two fold higher correlation for temporal variability. These observations were also noted by Panosso et al. (2009). A significant correlation between Fmean and TSmean ($p > 0.05$) was not detected. In tropical conditions, no spatial relationship between temperature and $FCO_2$ is typically found, primarily because of the low spatial variability in the soil temperature (CV = 6.26%) (Table 2).

The Fmean and SOM were positively correlated ($r = 0.67$, $p < 0.001$) (Table 3). The SOM, which is the largest land reserve of organic carbon, is closely connected to soil respiration because it is the primary source of energy for soil microorganisms (Galdos et al., 2009; Lal, 2009). Furthermore, the ease with which the carbon present in soil is decomposed by microorganisms is measured by the C/N ratio, which also influences soil $CO_2$ emission (Razafimbelo et al., 2006).

**Table 2**
Descriptive statistics for mean values of $CO_2$ emission, temperature and soil water content over time, along with the physical and chemical properties of the soil.

| Property | Mean | SD | SE | Min | Max | CV (%) |
|---|---|---|---|---|---|---|
| Fmean ($\mu mol\ m^{-2}\ s^{-1}$) | 2.08 | 0.84 | 0.03 | 0.24 | 6.49 | 40.38 |
| TSmean (°C) | 19.48 | 1.22 | 0.05 | 15.70 | 24.50 | 6.26 |
| SWCmean ($m^3\ m^{-3}$) | 17.20 | 8.31 | 0.34 | 3.00 | 49.00 | 48.31 |
| pH ($H_2O$) | 6.10 | 0.15 | 0.02 | 5.80 | 6.41 | 2.46 |
| H + Al ($mmol\ dm^{-3}$) | 44.14 | 7.33 | 0.95 | 30.12 | 61.77 | 16.61 |
| Mg ($mmol\ dm^{-3}$) | 19.07 | 2.79 | 0.35 | 14.50 | 28.00 | 14.63 |
| Ca ($mmol\ dm^{-3}$) | 55.54 | 6.89 | 0.89 | 42.50 | 79.00 | 12.41 |
| K ($mmol\ dm^{-3}$) | 4.74 | 2.19 | 0.28 | 1.47 | 9.59 | 46.20 |
| P ($mg\ dm^{-3}$) | 20.14 | 7.46 | 0.96 | 9.95 | 47.95 | 37.04 |
| SB ($mmol\ dm^{-3}$) | 79.35 | 9.76 | 1.26 | 60.36 | 109.88 | 12.30 |
| CEC ($mmol\ dm^{-3}$) | 123.49 | 6.82 | 0.88 | 108.60 | 151.29 | 5.52 |
| BS (%) | 64.09 | 6.01 | 0.78 | 49.46 | 77.08 | 9.38 |
| SOM ($g\ dm^{-3}$) | 27.60 | 2.26 | 0.29 | 20.80 | 31.98 | 8.19 |
| C/N | 12.83 | 2.12 | 0.27 | 9.11 | 18.44 | 16.52 |
| BD ($g\ cm^{-3}$) | 1.32 | 0.08 | 0.01 | 1.17 | 1.48 | 6.06 |
| Macro ($m^3$) | 17.54 | 3.54 | 0.46 | 9.01 | 24.70 | 20.18 |
| Micro ($m^3$) | 37.36 | 5.71 | 0.74 | 25.63 | 49.07 | 15.28 |
| TPV ($m^3$) | 54.90 | 4.28 | 0.55 | 45.80 | 66.34 | 7.80 |
| AFP ($m^3\ m^{-3}$) | 37.71 | 4.36 | 0.56 | 28.91 | 49.24 | 11.56 |

D, standard deviation; SE, standard error of the mean; Min, minimum; Max, maximum; CV, coefficient of variation (%); Fmean, mean values of soil $CO_2$ emission over time; TSmean, mean values of soil temperature over time; SWCmean, mean values of soil water content over time; pH, hydrogen potential; Ca, calcium; Mg, magnesium; H + Al, potential acidity; K, potassium; P, phosphorus; SB, sum of bases; CEC, cation exchange capacity; BS, base saturation; SOM, soil organic matter; C/N, relationship carbon/nitrogen the soil; BD, soil bulk density; macro, macroporosity; micro, microporosity; TPV, total pore volume; AFP, air-filled porosity.

**Table 3**
Linear correlation coefficient between the spatial mean values of $CO_2$ emission over time (Fmean) and physical and chemical properties of the soil.

| Property | r | Property | r |
|---|---|---|---|
| TSmean | 0.20 | CEC | 0.08 |
| SWCmean | 0.29[a] | BS | 0.22 |
| pH | 0.16 | SOM | 0.67[a] |
| H + Al | −0.21 | C/N | −0.75[a] |
| Mg | 0.20 | BD | 0.16 |
| Ca | 0.22 | Macro | 0.06 |
| K | 0.01 | Micro | −0.11 |
| P | 0.28[a] | TPV | 0.59[a] |
| SB | 0.21 | AFP | 0.71[a] |

TSmean, mean values of soil temperature over time; SWCmean, mean values of soil water content over time; pH, hydrogen potential; Ca, calcium; Mg, magnesium; H + Al, potential acidity; K, potassium; P, phosphorus; SB, sum of bases; CEC, cation exchange capacity; BS, base saturation; SOM, soil organic matter; C/N, relationship carbon/nitrogen the soil; BD, soil bulk density; macro, macroporosity; micro, microporosity; TPV, total pore volume; AFP, air-filled porosity.
[a] Values significant of the correlation coefficient of Pearson ($p < 0.05$).

Thus, the balance between the input and output of carbon in the soil through the addition and decomposition of organic litter depends on many factors, including the dynamics of microbial activity regulated by the C/N ratio (Six et al., 2006).

The C/N ratio of 12.83 (Table 2) is in agreement with characterizations of other agricultural soils (Ngao et al., 2012; Wick et al., 2012). The Fmean was negatively correlated with the C/N ratio of the soil ($r = -0.75$, $p < 0.001$), which influenced the residual quality and its distribution in the study area. The soil C/N ratio strongly influenced the flow of $CO_2$ because, depending on its value (high or low), the C/N ratio can impede or facilitate SOM decomposition. The nitrogen (N) content is also an important factor because nitrogen can increase or decrease the soil carbon input, where low nitrogen inhibits biological activity by limiting the humification process (Lamparter et al., 2009).

Ngao et al. (2012) studied forest soils and observed a more significant coefficient of correlation ($r = 0.86$, $p < 0.05$) between the $CO_2$ flux and the soil C/N ratio. High correlations in forest soils are expected due to the large diversity of organic inputs; however, this correlation was only slightly higher than the one found in the cane fields in our study (Table 3). We therefore also checked the impact of this property on $CO_2$ emissions though the C/N content stems only from sugarcane (no diversity), but it was nonetheless one of the main factors controlling the $FCO_2$.

With respect to soil aeration and soil $CO_2$ emissions, the soil pore system is very important because it allows the storage and movement of water and gas (Wick et al., 2012). The AFP exhibited a positive and significant relationship with the Fmean ($r = 0.71$, $p < 0.001$) (Table 3). The BD, together with the air-filled porosity (AFP), directly affected the gas diffusion within the soil in terms of both the entrance of oxygen, which is required for the aerobic activity of microorganisms, as in the exit of $CO_2$, which is a byproduct of this activity (Teixeira et al., 2012). In this study, the BD values were not linearly correlated with the Fmean ($p > 0.05$), most likely due to the medium density (1.32 $g\ cm^{-3}$) in the area (Table 2), indicating that the density factor did not affect the total porosity of the soil nor the $CO_2$ transport.

For Wick et al. (2012), soil properties, especially those that influence the porosity (macroporosity and microporosity), helped to explain the emission of greenhouse gases, particularly $CO_2$, indicating the importance of including soil porosity when studying $FCO_2$ variability. In studies conducted in sugarcane areas in São Paulo State, Brazil, Teixeira et al. (2012) observed a weak ($r = 0.27$) but significant ($p < 0.01$) relationship between the AFP and $FCO_2$. However, when the spatial estimates were considered, the AFP became the main variable responsible for the spatial characteristics of soil respiration.

The available phosphorus (P) content in the soil was weakly correlated with the Fmean ($r = 0.28$, $p < 0.05$) (Table 3). Phosphorus is a chemical element that participates in soil microbial activity and influences the intensity of microorganism metabolism (Nordgren, 1992; Duah-Yentumi et al., 1998).

In this study, the various soil properties, including the pH, Ca, Mg, H + Al, CEC, BS, SB and BD, were not linearly related ($p > 0.05$) with $FCO_2$ in space (Table 3). However, other studies have indicated that these properties are related to $FCO_2$ because of its direct relationship with the SOM, which mediates the cycling and retention of soil nutrients and the aggregation rate and water dynamics in the soil (Six et al., 2006), thereby limiting microbial growth and respiration rate (Lamparter et al., 2009).

The mean values observed for the pH (6.10) and H + Al (44.14 mmol $dm^{-3}$) indicate low soil acidity (Table 2). Silva-Olaya et al. (2013), investigating the soil $CO_2$ emission in sugarcane areas under different management systems, obtained similar results when evaluating these properties in the upper soil layers (0–10 and 10–20 cm) and also did not obtain a correlation with $FCO_2$. The pH values, near neutral, were not limiting for microbial activity and consequently had no influence on the observed $FCO_2$ values in this study, as in the study by Silva-Olaya et al. (2013).

According to Fuentes et al. (2006) the pH affects the quantity and diversity of the soil microorganisms, fungi development favors environments with pH < 5, but bacteria prefer environments with pH values of 6–8.

Multiple regression analysis identified the properties that most influenced the spatial variability in the soil $CO_2$ emission. In the model, the Fmean was correlated with the SOM, C/N and AFP. The first property selected was SOM, which explained 62% of the $FCO_2$ variability. When the C/N was included in the model, the amount of variance explained increased by 10%. Finally, when the AFP was selected, an additional 5% of the variance was explained, totaling 77% of the $FCO_2$ variability ($R^2 = 0.77$) (Table 4).

First, the Fmean was influenced by variables related to $CO_2$ production, such as the SOM and C/N (the first variables selected by the model), and second, the variable involved in the process of transporting $CO_2$ (AFP) explained the remaining spatial variability in $FCO_2$.

The contrast between the SOM and the C/N ratio of the soil was expected because it provides information about the quality and availability of this nutrient for microorganisms, so the C/N rate is an important indicator of microbial activity, of degree of humification and stability of soil organic matter (Lamparter et al., 2009).

Panosso et al. (2011) also noted the relationship between the AFP and $FCO_2$. The air-filled porosity was present in all models obtained using multiple linear regression analysis and was the property that explained most of the spatial $FCO_2$ variation (46% in the cane green harvest system and 75% in the burned cane system).

**Table 4**
Multiple regression model of the mean values of $CO_2$ emission over time ($\mu$mol $m^{-2}\,s^{-1}$) in function of soil chemical properties in the studied period.

| Property | Parameter | SE | *p* | $R^2$ |
|---|---|---|---|---|
| Intercept | −0.52657 | 0.44857 | 0.2454 | |
| SOM ($g\,dm^{-3}$) | 0.04203 | 0.01058 | 0.0002 | 0.6235 |
| C/N | −0.06138 | 0.01279 | 0.0001 | 0.7231 |
| AFP ($m^3\,m^{-3}$) | 0.02225 | 0.00592 | 0.0004 | 0.7789 |

SE, standard error of the estimated parameters; $R^2$, coefficient of determination; SOM, soil organic matter; C/N, relationship carbon/nitrogen the soil; AFP, air-filled porosity.

## 4. Conclusions

The soil $CO_2$ emission in the sugarcane area was influenced by edaphoclimatic conditions. The largest temporal variations in $CO_2$ emissions over the study period were explained by changes in soil water content, especially after rainfall. Spatially, the $CO_2$ emission was influenced by chemical (organic matter and soil C/N ratio) and physical (air-filled porosity) soil properties which were associated with production and transport of $CO_2$ in soil.

Soil C/N ratio, although not intensively studied, has a great potential to integrate models to estimate the soil $CO_2$ emission. Brazil, the world's largest producer of sugarcane, uses sugarcane varieties with different vegetable supply (C/N ratio) and consequently show potential for different soil C/N ratio. The agricultural inventories do not include estimates of soil $CO_2$ emission due to the complexity in its determination. Hence, inventories of agricultural emissions that integrate the soil C/N ratio in their models could estimate the $CO_2$ emissions with more accuracy, allowing the construction of state or national inventories with greater reliability.

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