

Soil Greenhouse Gases: Relations to Soil Attributes in a Sugarcane Production Area

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The production of the main soil greenhouse gases (GHG: carbon dioxide [CO_2], methane [CH_4] and nitrous oxide [N_2O]) is influenced by agricultural practices that cause changes in soil physical, chemical, and biological attributes, directly affecting their emission to the atmosphere. The aim of this study was to investigate the infield soil carbon dioxide emissions (F_{CO_2}) and soil CO_2 , methane, and nitrous oxide production potentials (P_{CO_2} , P_{CH_4} , and $P_{\text{N}_2\text{O}}$, respectively) under laboratory conditions and their relationship to soil attributes in a mechanically harvested sugarcane area. Soil carbon dioxide emissions presented an infield average emission value of $1.19 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, while GHG production in the laboratory was $2.34 \mu\text{g C-CO}_2 \text{ g}^{-1} \text{ soil d}^{-1}$ and $0.20 \text{ ng N-N}_2\text{O g}^{-1} \text{ soil d}^{-1}$ for P_{CO_2} and $P_{\text{N}_2\text{O}}$, respectively. No significant production or oxidation was observed for CH_4 . Factor analysis showed the formation of two independent processes that explained almost 72% of the total variance observed in the data. The first process was related to F_{CO_2} transport and its relation to soil physical attributes such as microporosity, macroporosity, the C/N ratio, soil moisture, and soil bulk density, showing the dependence between F_{CO_2} and soil porosity. The second process was related to soil CO_2 and N_2O production potentials under laboratory conditions and their relation to soil chemical attributes such as the sum of bases, pH, and available phosphorus, which affect microbial activity and contribute to GHG production. Although presented as independent, these processes are coupled and occur simultaneously in the soil, in addition to providing information about their variability and showing if the infield emissions are due to gas transport processes or soil carbon levels and their quality.

Abbreviations: AFPS, air-filled pore space; Bases, sum of bases; C/N, carbon to nitrogen ratio; CEC, cation exchange capacity; Clay, clay content; C_{stock} , soil carbon stock; D_s , soil bulk density; F_{CO_2} , soil carbon dioxide emissions; GHG, greenhouse gases; Macro, macroporosity; Micro, microporosity; M_s , soil moisture; N, total soil nitrogen content; P, available phosphorus; PCA, principal component analysis; P_{CH_4} , soil methane production potentials; P_{CO_2} , soil carbon dioxide production potentials; $P_{\text{N}_2\text{O}}$, soil nitrous oxide production potentials; Sand, sand content; Silt, silt content; SMB, soil microbial biomass; SOM, soil organic matter; TPV, total pore volume; T_s , soil temperature.

Core Ideas

- The production of the main soil greenhouse gases (CO_2 , CH_4 and N_2O) is influenced by agricultural practices.
- The soil bulk density and micropores showed negative correlation with soil CO_2 emission.
- The factor analysis showed the formation of two independent processes that explained almost 72% of the total variance observed in the data.
- The soil moisture is a controlling factor of soil CO_2 emission.

Anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have increased since the preindustrial era. The concentration of CO_2 in the atmosphere increased from 278 ppm (278 mg kg^{-1}) in 1750 to 390.5 ppm (390.5 mg kg^{-1}) in 2011; during the same period, an increase from 722 ppb (0.722 mg kg^{-1}) to 1803 ppb (1.803 mg kg^{-1}) was observed in the atmospheric concentration of CH_4 ; N_2O concentrations also increased, reaching values from 271 ppb (0.271 mg kg^{-1}) in 1750 to 324.2 ppb (3.241 mg kg^{-1}) in 2011 (Ciais et al., 2013). These greenhouse gases (GHG) are mainly related to burning fossil fuels, land use, and land-use change, especially

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in agriculture, and are primarily responsible for climate change (Schneider et al., 2001).

In Brazil, net anthropogenic CO₂ emissions were estimated at 739.7 Tg in 2010, a reduction of 82.7% in relation to 2005. The sectors of land use, land-use change, and forestry, accounted for 42% of these emissions (Brazil Ministry of Science, Technology and Innovation, Secretariat of Policies and Programs of Research and Development, General Coordination on Climate Change, 2016). The emissions related to the lime application in soils are included in this total and accounted for 10.4 Tg of CO₂. The emissions of CH₄ were estimated at 16.7 Tg, primarily attributed to the agricultural sector, which accounted for 74.4% of the total CH₄ emission and showed an increase of 0.5% in relation to 2005 (Brazil Ministry of Science, Technology and Innovation, Secretariat of Policies and Programs of Research and Development, General Coordination on Climate Change, 2016). Similarly, net N₂O emissions were estimated at 560.5 Gg, which represents an increase of 10% in relation to 2005, with the agricultural sector accounting for 84.2% of the total N₂O emissions (Brazil Ministry of Science, Technology and Innovation, Secretariat of Policies and Programs of Research and Development, General Coordination on Climate Change, 2016).

Agricultural activities, such as soil tillage, influence GHG emission from soil to the atmosphere since agricultural management practices in the production systems result in significant physical changes in soil, altering the gains and losses of soil organic matter (La Scala et al., 2006; Corradi et al., 2013; Moitinho et al., 2013; Silva-Olaya et al., 2013; Teixeira et al., 2013a; Iamaguti et al., 2015; Epron et al., 2004; Sartori et al., 2006; Lal, 2009). In agricultural areas, such variations occur mainly in the 0- to 30-cm soil layer, and are mostly due to mechanized soil disturbances and induced changes in quantity and quality of organic matter (Jenkinson et al., 1992; Chan, 2001). In tropical soils, the combination of those variations could represent up to 50% of the initial carbon stock in the first 20 cm of soil (Feller and Beare, 1997).

Similarly, soil porosity is also influenced by agricultural activities, directly affecting GHG transport in the soil (Xu and Qi, 2001; Jassal et al., 2004; Epron et al., 2006; Ball, 2013). In this case, gas exchange between soil and the atmosphere is regulated by the oxygen entry into the soil and the escape of GHG, which is directly related to the number and interconnectivity of pores in the soil, which could also limit soil oxygenation and thus microbial activity (Fang et al., 1998; Ball, 2013). A study conducted in Australia in a sugarcane area under burning management and nitrogen fertilization observed elevated rates of soil N₂O emissions for five months, related to increased soil porosity, frequent soil wetting, and high content of soil organic carbon (Denmead et al., 2010).

Sugarcane is produced commercially worldwide and is an important source of biomass used for ethanol production, an alternative to fossil fuels. Brazil has a sugarcane crop area of approximately 8.84 million hectares and it is expected to produce in the 2017 to 2018 cropping season approximately 647.6 million tons (587.37 million Mg) of this crop (Companhia Nacional de Abastecimento, 2017). The large amount of crop residue left

on the soil surface after harvest in mechanically harvested sugarcane areas have tremendous impact on production processes and biogeochemical cycling of carbon and nitrogen, affecting soil organic matter dynamics, and consequently, GHG emissions (Cerri et al., 2013). In addition to influencing carbon and nitrogen cycles, environmental conditions and soil management practices adopted during sugarcane crop cultivation may result in changes in soil physical, chemical, and biological attributes, directly affecting microbial activity and thus the production of CO₂, CH₄, and N₂O and their exchanges between soil and the atmosphere (Blair, 2000; Sartori et al., 2006; Cerri et al., 2007, 2013; Denmead et al., 2010; Allaire et al., 2012; Ball, 2013; Signor and Cerri, 2013; Signor et al., 2014; Tavares et al., 2015).

Sugarcane production could play an important role in soil GHG emissions, because soil management may interfere with the fluxes of carbon and nitrogen between terrestrial ecosystems and the atmosphere. Considering this, we raised the hypothesis that the infield soil GHG emissions could be characterized from laboratory-derived GHG production potentials. Thus, the aim of this study was to investigate the infield soil CO₂ emissions and soil CO₂, CH₄, and N₂O production potentials under laboratory conditions and their relationship to soil attributes in a mechanically harvested sugarcane area.

MATERIALS AND METHODS

Location and Description of the Study Area

The study was conducted in a production area with a 38-yr history of sugarcane (*Saccharum* spp.) crop cultivation located at Santa Cândida farm in Pradópolis, São Paulo State, Brazil (21°20' S lat and 48°08' W long; average altitude: 515 m). Regional climate is classified as B₂rB' ₄a' (Thorntwaite, 1948), indicating a mesothermal region with rainy summers and dry winters. The mean annual precipitation registered was 1517 mm, concentrated from October to March (81.1%), and less frequent precipitations and in lower intensity from April to September (18.9%); the mean annual temperature registered was 22.5°C.

The soil of the experimental area is classified as a high-clay Oxisol (Eutruxox, USDA Soil Taxonomy), and its slope was determined to be 3 to 4%. The sugarcane plantation was established in 2004 and the variety cultivated was CTC 14, which was in the eighth ratoon stage when our experiment was installed in the area. The area had been mechanically harvested for the last 15 yr prior to the study, and after each harvest, approximately 12 t ha⁻¹ yr⁻¹ of crop residues remained on the soil surface. In this area, on 23 and 24 Aug. 2012, a 50- by 50-m radially symmetrical grid was installed containing 133 points spaced at minimum distances of 0.5 m in the center of the sample grid (Fig. 1) to quantify the infield soil CO₂ emissions along with sampled soil for GHG production potentials and soil attributes.

Infield Soil Carbon Dioxide Emissions, Soil Temperature, and Soil Moisture

Infield measurements of soil CO₂ emissions (F_{CO_2}), soil temperature (T_s), and soil moisture (M_s) at all grid points were re-

corded on August 27, 29, and 31, and 3, 5, 7, 11, and 14 Sept. 2012. On all days, measurements were recorded in the morning from 0800 to 0930 h by using two portable LI-8100 automated soil CO₂ flux systems (LI-COR, Inc., Lincoln, NE); the devices were tested and calibrated with each other before the beginning of the experiment. An LI-8100 system uses optical absorption spectroscopy in the infrared spectrum (IRGA, Infrared Gas Analyzer) to monitor changes in CO₂ concentration inside a closed chamber. The chamber was coupled to soil PVC collars that had been installed 24 h prior to the beginning of the measurements at all 133 sample points to reduce the disturbance caused by their insertion in the soil (La Scala et al., 2000a; Panosso et al., 2009; Brito et al., 2010; Bicalho et al., 2014).

A portable sensor from the LI-8100 system was used to measure T_s by using a 20-cm probe (thermistor based) that was inserted 10 cm into the soil near the PVC collars. Measurements of M_s (in % of volume) were performed using a Time Domain Reflectometry (TDR) system (Hydrosense, Campbell Scientific Inc., Logan, UT, United States), which consists of two 12-cm probes that are inserted into the soil, also near the PVC collars.

Soil Sampling and Analysis of Soil Chemical and Physical Attributes

Soil samples from a depth of 0 to 10 cm were obtained from all 133 grid points on 24 and 25 Sept. 2012, after F_{CO_2} , T_s , and M_s measurements had been recorded. These samples were dried and sieved through a 2-mm mesh prior to further analyses that included soil organic matter (SOM) content, estimated from soil organic carbon, which was determined by the wet oxidation method (modified Walkley-Black method) and available P, K, Ca, Mg, and H+Al content (Van Raij et al., 2001), which allowed for the calculation of the sum of bases (Bases) and cation exchange capacity (CEC).

The total soil nitrogen (N) content was obtained by using the dry combustion technique in the presence of oxygen at 1440°C. Soil carbon stock (C_{stock}) was calculated according to the following equation (Veldkamp, 1994):

$$C_{stock} = \frac{OC \times D_s \times E}{10} \quad [1]$$

where C_{stock} is the soil carbon stock (Mg ha⁻¹), OC is the organic carbon content (g kg⁻¹ = SOM/1.724), D_s is the soil bulk density (kg dm⁻³), and E is the soil layer depth (10 cm).

Particle size distribution of sand, silt, and clay were determined by the pipette method after soil dispersion by using one molar solution of sodium hydroxide and sand sieving (Donagema et al., 2011). Soil bulk density (D_s) was determined using the volumetric ring method, which consists of nondeformed samples collected by using a sampler adapted to cylinders with an average internal volume of 50 cm³ (Donagema et al., 2011). The total pore volume (TPV, in % of volume), macropores (Macro), and micropores (Micro) were determined by using the tension table method, in which undisturbed soil samples were saturated and then drained to a potential equal to -0.006 MPa using a porous

plate (Donagema et al., 2011). Air-filled pore space (AFPS, in % of volume) fraction was calculated as the difference between TPV and M_s .

Production Potentials of Soil Greenhouse Gases

Quantification of soil CO₂, CH₄, and N₂O production potentials (P_{CO_2} , P_{CH_4} , and P_{N_2O} , respectively) was performed using the 133 disturbed soil samples collected in the experimental area after being subsampled from soil chemical characterization. Additionally, soil microbial biomass (SMB) was also determined by adapting the method of substrate-induced respiration (glucose addition) by Anderson and Domsch (1978).

The method used for GHG assessment consisted of a 50- to 60-d laboratory incubation with controlled temperature and soil water content adjusted to field capacity (-33 kPa) and determination of rate changes in the headspace gas concentration by gas chromatography (Spokas and Reicosky, 2009; Spokas, 2013). In the process of incubation, triplicates of 5 g of soil were taken from each of the 133 soil samples and placed in 125 mL vials. Then, 1.5 mL of deionized water was added to each vial, which was sealed with butyl rubber septa and preincubated at 25°C for 6 d. Following this period, vials were opened and vented for 20 min and resealed, the first gas sampling performed at 1 or 2 d after this procedure. Laboratory tests were conducted to establish the timing of this preincubation period, which was needed to allow for the development of the equilibrium-steady-state GHG production conditions (Cabrera, 1993; Fierer and Schimel, 2003).

The rates of GHG production and/or consumption were calculated from the linear increase or decrease (slope) in the headspace concentration change with time using the data obtained by sampling during the 50- to 60-d incubation period. For this, incubation headspace was analyzed by taking 5 mL with syringes and injected into vials previously helium-flushed. These gas samples were injected into three different analytical columns contained in a single chromatograph. The first column (1000 ML) is a Porapak Q (0.32 mm × 1.8 m; Restek Corporation) with a minimum helium flow rate of 30 mL min⁻¹, which is connected to an electron capture detector (ECD) for

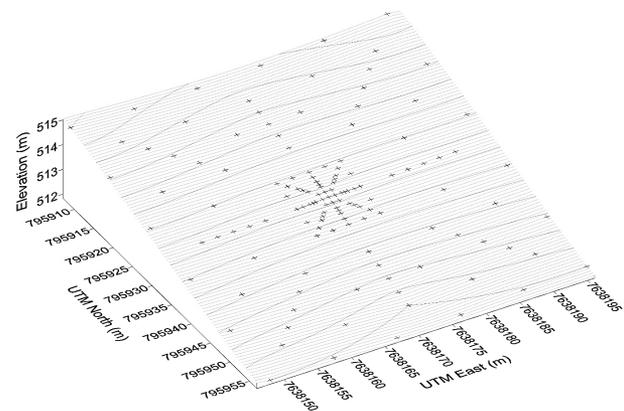


Fig. 1. Sampling grid representation with the 133 points (+) used to quantify the infield soil carbon dioxide (CO₂) emissions, soil CO₂, methane (CH₄), and nitrous oxide (N₂O) production potentials, and soil attributes in the experimental area.

analyzing N₂O. The second column (500 mL) is a Porapak N (0.32 mm × 1.8 m) with the same helium flow rate of the first column and connected to a flame ionization detector (FID) for CH₄ analysis. The third column (1.0 mL) is a CTR-1 column with a 45 mL min⁻¹ helium flow rate and connected to a thermal conductivity detector (TCD) used to measure CO₂, O₂, and N₂. The gas chromatograph was calibrated by injecting 5 mL of known calibration gases into separate vials, which were used as standards.

Analysis of Results

Initially, the data variability was analyzed by using descriptive statistics (mean, standard error of the mean, minimum, maximum, and coefficient of variation) and linear correlation analysis, and then by the multivariate exploratory analyses of principal components and factor analysis. For factor extraction, we used the principal component analysis (PCA), calculated from the correlation matrix between the variables (Jeffers, 1978). Principal component analysis analyzes the interdependence between variables and condenses the information contained in the set of original variables into a set of smaller dimension compound of new latent variables, preserving a relevant amount of original information. The new variables are the eigenvectors (principal components), generated by the linear combinations of original variables and constructed from eigenvalues of the covariance matrix (Hair et al., 2005). The correlation between characteristics (variables) and principal components is obtained by the following expression:

$$r_{x_j}(PC_b) = \frac{a_{jb} \sqrt{\lambda_b}}{s_j} \quad [2]$$

where a_{jb} is the coefficient of j variable in the b -th principal component, λ_b is the b -th characteristic root (eigenvalue) of the covariance matrix, and s_j is the standard deviation of j variable.

From PCA, the data were submitted to the factor analysis, which is another multivariate exploratory technique that allows observing the relationship between a set of variables. The first factor can be considered as the best summary of linear relation shown in the data. The second factor is defined as the second best linear combination of variables and subject to the constraint of being orthogonal to the first factor; to be orthogonal to the first factor, it must be determined from the remaining variance after the first factor has been extracted. Thus, the second factor can be defined as the linear combination of variables that explains most of the residual variance after the effect of the first factor has been removed from the data. To redistribute the variance, we used the Quartimax normalized rotation in the factorial matrix, whose ultimate effect provides a simple factorial pattern theoretically more significant since the rotation is performed exactly to redistribute the variance from the first to the last factor.

We considered the first two factors, whose eigenvalues were higher than the unit and determined from the graph of latent roots in relation to the number of factors in their order of ex-

traction, creating the shape of the resulting curve used to assess the cutoff point (Kaiser, 1958). The coefficients of linear functions, which define the factor loadings, were used in interpreting their meaning considering the signal and relative size of loadings as an indication of weight to be assigned to each variable. Only loadings with high values were considered for interpretation (i.e., usually those higher than or equal to 0.50 in absolute value). After variable standardization (zero mean and unit variance), the analysis was performed using the software Statistica 7.0 (StatSoft Inc., Tulsa, OK).

RESULTS AND DISCUSSION

Descriptive Statistics

Infield F_{CO_2} presented a mean value of 1.19 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, with a minimum of 0.50 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, a maximum of 2.29 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, and a CV of 31.68% (Table 1). These rates are similar to those observed in experiments conducted previously in the same geographic region with sugarcane crops (Brito et al., 2010; Panosso et al., 2011, 2012; Corradi et al., 2013; Bicalho et al., 2014; Tavares et al., 2015). Variations in F_{CO_2} observed in these studies, even performed in areas of the same region, are related to changes in soil attributes for each area, such as soil temperature, soil moisture, soil organic matter, microbial activity, pH, the C/N ratio, phosphorus content, soil bulk density, and soil porosity (Kemmitt et al., 2008; Ngao et al., 2012; Oyonarte et al., 2012; Teixeira et al., 2013a; Karhu et al., 2014; Moitinho et al., 2015). These controlling factors are directly dependent on environmental conditions (such as precipitation and temperature) and agricultural area management (such as soil tillage, liming, harvest system, and machinery traffic), and small variations in each of them may lead to considerable variations in F_{CO_2} .

Soil CO₂ production potentials varied from 0.93 to 4.25 $\mu\text{g C-CO}_2 \text{ g}^{-1} \text{ soil d}^{-1}$, with a mean of 2.34 $\mu\text{g C-CO}_2 \text{ g}^{-1} \text{ soil d}^{-1}$ and a CV of 34.45% (Table 1). Variations in P_{CO_2} observed in this study are mainly due to soil chemical and biological attributes, because the study was conducted under laboratory conditions and used disturbed soil samples. In this case, soil aeration increased due to soil disturbance, and as soil water content was equivalent to field capacity, soil microbial activity increased and thus the production of CO₂ in the soil. The gas transport process, which is related to soil porosity, would not have a greater influence on the production potential process of this GHG since soil samples did not present structure.

Values of P_{N_2O} presented a minimum of -0.19 $\text{ng N-N}_2\text{O g}^{-1} \text{ soil d}^{-1}$, measuring consumption of N₂O during the incubation period, and a maximum of 0.57 $\text{ng N-N}_2\text{O g}^{-1} \text{ soil d}^{-1}$, with a mean of 0.20 $\text{ng N-N}_2\text{O g}^{-1} \text{ soil d}^{-1}$ and a CV of 68.31% (Table 1). These values are relatively low when compared to other studies conducted under infield conditions in sugarcane areas (Signor et al., 2014; Vargas et al., 2014). Three key factors for N₂O emission in the soil can be listed as high contents of water-filled pore space (inversely related to AFPS), temperature, and topsoil mineral N

content (Conen et al., 2000). These three key factors, especially when coupled with non-optimal conditions of anaerobiosis for the denitrification process, could explain the low N₂O production found in our study.

No significant production or oxidation was observed for CH₄, probably due to a lack of optimal conditions for the performance of methanogenic and methanotrophic bacteria. In soils, CH₄ is mainly produced by methanogenic bacteria under anaerobic conditions. The essential soil chemical and mineralogical properties for the occurrence of redox condition involves mainly O, N, Fe, Mn, S, and C (Ponnamperuma, 1972). In this process, Fe and Mn are reduced and methanogenic bacteria, in anaerobic conditions, begin to use C as an electron acceptor, resulting in the CH₄ production (Peters and Conrad, 1996; van Bodegom and Stams, 1999). Methane oxidation, on the other hand, is performed mainly by methanotrophic bacteria under aerobic conditions in dry soils. This is one of the main routes of CH₄ loss from the atmosphere to the soil (King, 1997), in which the bacteria obtain energy and C, and use O₂ for the monooxygenase enzyme, indispensable for the CH₄ oxidation process (Mosier et al., 2004). Under infield conditions, Signor et al. (2014) observed an increase in soil CH₄ emissions as a function of the increasing amount of sugarcane crop residues left on the soil surface. In this case, soil CH₄ production occurs in microsites in anaerobic zones at the center of soil aggregates.

Values of T_s and M_s presented small changes during the 19 d of infield measurements. T_s varied from 19.61 to 21.37°C, with a mean of 20.57°C for the period, and M_s varied from 7.50 to 11.50% (v/v), with a mean of 9.25% (v/v) (Table 1). The main factors that control temporal variations of F_{CO_2} are the available C, T_s , and M_s ; in our study, the small changes in these main factors could be related to the presence of crop residues on the soil surface, reflecting on the infield F_{CO_2} variations over the experimental period (Tedeschi et al., 2006; Kosugi et al., 2007; Ohashi and Gyokusen, 2007; Concilio et al., 2009). Maintaining crop residues on the soil surface creates a physical barrier that preserves M_s , providing thermal insulation (Ussiri and Lal, 2009). It also reduces the daily maximum temperatures and raises the minimum temperatures compared with soils without vegetation cover (Tominaga et al., 2002).

Studies conducted in sugarcane areas showed that F_{CO_2} increases with an increase in the amount of crop residues on the soil surface (Carmo et al., 2013; Signor et al., 2014). This fact can be attributed to the positive relationship between the amount of CO₂ emitted by the soil and SOM, related to the addition of crop residues on the soil surface (de Oliveira et al., 2013; Signor et al., 2014; Vargas et al., 2014). On the other hand, short-term period studies also conducted in sugarcane areas showed that crop residues on the soil surface might contribute to a significant reduction in soil CO₂ emissions (La Scala et al., 2006; Panosso et al., 2011; Corradi et al., 2013; Silva-Olaya et al., 2013).

Linear Correlation Analysis

Linear correlation analysis was significant ($P < 0.05$) for F_{CO_2} and some soil physical attributes related to soil porosity (Table 2). The soil attributes D_s ($r = -0.57$) and Micro ($r = -0.42$) showed negative linear correlations with F_{CO_2} whereas M_s ($r = 0.52$), AFPS ($r = 0.45$), TPV ($r = 0.53$), and Macro ($r = 0.56$) presented positive linear correlations with F_{CO_2} . In a sugarcane-cultivated soil under mechanized harvesting located close to our study site, significant linear correlations were found only for the soil physical attributes D_s ($r = -0.32$), AFPS ($r = 0.18$), Macro ($r = 0.21$), and Micro ($r = -0.18$); the linear correlation coefficients were not significant for the other soil physical and chemical attributes (Bicalho et al., 2014). Correlations between F_{CO_2} and these variables have been cited frequently by several studies, demonstrating the importance of soil physical attributes for microbial activity and gas exchange in the soil-atmosphere system (La Scala et al., 2000a; Xu and Qi, 2001; Epron et al., 2006; Ohashi and Gyokusen, 2007; Panosso et al., 2009, 2011; Herbst et al., 2010; Teixeira et al., 2013b; Bicalho et al., 2014; Moitinho et al., 2015). Although frequent, these correlations are weak.

Table 1. Descriptive statistics of soil carbon dioxide (CO₂) emissions, soil CO₂ and nitrous oxide (N₂O) production potentials, soil microbial biomass, soil temperature, soil moisture, and other soil physical and chemical attributes in the 0- to 0.10-m soil layer.†

| Variable§ | Mean | SE | Min | Max | CV (%) |
|---|--------|-------|--------|--------|--------|
| F_{CO_2} , $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}\ddagger$ | 1.19 | 0.03 | 0.50 | 2.29 | 31.68 |
| P_{CO_2} , $\mu\text{g C-CO}_2 \text{ g}^{-1} \text{ soil d}^{-1}$ | 2.34 | 0.07 | 0.93 | 4.25 | 34.45 |
| P_{N_2O} , $\text{ng N-N}_2\text{O g}^{-1} \text{ soil d}^{-1}$ | 0.20 | 0.01 | -0.19 | 0.57 | 68.31 |
| SMB, $\text{mg microbial C g}^{-1} \text{ soil h}^{-1}$ | 511.20 | 13.90 | 191.30 | 937.10 | 31.17 |
| T_s , °C‡ | 20.57 | 0.03 | 19.61 | 21.37 | 1.86 |
| M_s , %‡ | 9.25 | 0.07 | 7.50 | 11.50 | 9.31 |
| D_s , g cm^{-3} | 1.45 | 0.01 | 1.17 | 1.71 | 7.89 |
| AFPS, % | 40.58 | 0.35 | 31.56 | 51.13 | 9.86 |
| TPV, % | 49.83 | 0.37 | 41.06 | 59.99 | 8.56 |
| Macro, % | 19.61 | 0.58 | 4.04 | 37.06 | 33.80 |
| Micro, % | 30.36 | 0.23 | 23.03 | 35.18 | 8.50 |
| Sand, g kg^{-1} | 424.87 | 0.88 | 401.40 | 449.33 | 2.29 |
| Silt, g kg^{-1} | 99.66 | 1.65 | 55.47 | 144.50 | 19.06 |
| Clay, g kg^{-1} | 475.47 | 1.81 | 424.36 | 524.48 | 4.40 |
| pH | 5.43 | 0.03 | 4.73 | 6.13 | 6.16 |
| SOM, g dm^{-3} | 28.29 | 0.31 | 20.13 | 36.50 | 12.38 |
| C_{stock} , Mg ha^{-1} | 8.26 | 0.10 | 5.59 | 11.19 | 13.69 |
| N, g dm^{-3} | 2.26 | 0.03 | 1.35 | 3.10 | 15.39 |
| C/N | 7.36 | 0.12 | 4.44 | 10.57 | 17.58 |
| P, mg dm^{-3} | 23.21 | 0.61 | 13.07 | 44.72 | 28.79 |
| Bases, $\text{mmol}_c \text{ dm}^{-3}$ | 47.96 | 1.06 | 22.30 | 79.28 | 24.93 |
| CEC, $\text{mmol}_c \text{ dm}^{-3}$ | 82.66 | 0.91 | 56.63 | 107.89 | 12.53 |

† $N = 133$

‡ General mean of all studied days

§ AFPS, air-filled pore space; Bases, sum of bases; C/N, carbon to nitrogen ratio; C_{stock} , carbon stock; CEC, cation exchange capacity; Clay, clay content; D_s , soil bulk density; F_{CO_2} , soil CO₂ emissions; M_s , soil moisture; Macro, macroporosity; Micro, microporosity; N, total soil nitrogen content; P_{CO_2} , soil CO₂ production potentials; P, available phosphorus; P_{N_2O} , soil N₂O production potentials; Sand, sand content; Silt, silt content; SE, standard error of the mean; SMB, soil microbial biomass; SOM, soil organic matter; T_s , soil temperature; TPV, total pore volume.

Soil CO₂ emissions were not linearly correlated to T_s (Table 2), possibly due to low variations throughout the experiment, as measured by CV values (Table 1). Similarly to our results, a study conducted in the same region showed a nonsignificant correlation between F_{CO_2} and T_s (La Scala et al., 2003). However, in a study conducted in a forest area in French Guiana, Epron et al. (2006) observed a positive correlation between F_{CO_2} and T_s , probably due to an increase in soil microbial activity with the increase of T_s because forest soils may have a greater variation and diversity of microorganisms in the soil when compared to soils under a monoculture cultivation, such as the sugarcane crop (Lloyd and Taylor, 1994; Epron et al., 1999; Burton and Pregitzer, 2003; Epron et al., 2006; Ryu et al., 2009). On the other hand, M_s presented a positive linear correlation with F_{CO_2} ($r = 0.52$) (Table 2), demonstrating the importance of this attribute as a controlling factor of F_{CO_2} , mostly its temporal variation. Similarly, Vargas et al. (2014) observed that in soil cultivated with sugarcane, the emissions of CO₂ increased linearly with an increase in M_s , with greater emissions when crop residues were on the soil surface.

Soil CO₂ production potentials showed significant and positive linear correlation coefficients with SOM ($r = 0.22$)

Table 2. Pearson correlation coefficients between soil carbon dioxide (CO₂) emissions, soil CO₂ and nitrous oxide (N₂O) production potentials, and soil microbial biomass with other soil physical and chemical attributes.

| Variable† | F_{CO_2} | P_{CO_2} | P_{N_2O} | SMB |
|-------------|------------|------------|------------|--------|
| F_{CO_2} | – | -0.22* | -0.26* | 0.08 |
| P_{CO_2} | -0.22* | – | 0.35* | 0.38* |
| P_{N_2O} | -0.26* | 0.35* | – | 0.26* |
| SMB | 0.08 | 0.38* | 0.26* | – |
| T_s | -0.10 | 0.12 | -0.08 | -0.03 |
| M_s | 0.52* | -0.23* | -0.36* | -0.01 |
| D_s | -0.57* | 0.14 | 0.11 | -0.15 |
| AFPS | 0.45* | -0.10 | -0.03 | 0.21* |
| TPV | 0.53* | -0.14 | -0.11 | 0.19* |
| Macro | 0.56* | -0.16 | -0.15 | 0.11 |
| Micro | -0.42* | 0.24* | 0.29* | 0.07 |
| Sand | -0.10 | 0.03 | 0.00 | -0.15 |
| Silt | -0.02 | 0.23* | 0.15 | 0.31* |
| Clay | 0.07 | -0.26* | -0.21* | -0.18* |
| pH | -0.08 | 0.41* | 0.21* | 0.62* |
| SOM | 0.05 | 0.22* | 0.07 | 0.19* |
| C_{stock} | -0.28* | 0.22* | 0.08 | 0.04 |
| N | 0.01 | 0.06 | -0.06 | -0.01 |
| C/N | 0.08 | 0.16 | 0.09 | 0.07 |
| P | 0.12 | 0.24* | 0.12 | 0.41* |
| Bases | -0.03 | 0.52* | 0.29* | 0.57* |
| CEC | -0.15 | 0.45* | 0.30* | 0.35* |

*Significant Pearson correlation coefficient values ($P < 0.05$)

† AFPS, air-filled pore space; Bases, sum of bases; C/N, carbon to nitrogen ratio; C_{stock} , carbon stock; CEC, cation exchange capacity; Clay, clay content; D_s , soil bulk density; F_{CO_2} , M_s , soil moisture; Macro, macroporosity; Micro, microporosity; N, total soil nitrogen content; soil CO₂ emissions; P, available phosphorus; P_{CO_2} , soil CO₂ production potentials; P_{N_2O} , soil N₂O production potentials; Sand, sand content; Silt, silt content; SMB, soil microbial biomass; SOM, soil organic matter; T_s , soil temperature; TPV, total pore volume.

and C_{stock} ($r = 0.22$) (Table 2), which are important factors related to the production and emission of CO₂. In fact, SOM is the main source of CO₂ production in the soil promoted by microbial activity (Stotzky and Norman, 1961; Ball et al., 1999; Kemmitt et al., 2008; de Oliveira et al., 2013; Vargas et al., 2014). On the other hand, F_{CO_2} was negatively correlated ($P < 0.05$) with C_{stock} ($r = -0.28$) (Table 2), in contrast to other studies that usually have found a positive relationship between carbon stock and soil CO₂ emission (Costa et al., 2008; Luca et al., 2008; Panosso et al., 2011). This negative correlation may be related to the existing complex relationship between clay minerals and soil microbial activity that directly influences GHG production in the soil and its emission to the atmosphere. In this case, clay could act as a protection to organic carbon against the action of microorganisms, preventing SOM mineralization, as well as reducing the dioxide (O₂) used in the aerobic microbial decomposition processes (La Scala et al., 2000b; Dominy et al., 2002; Fuentes et al., 2006; Graham and Haynes, 2006; Six et al., 2006; Canellas et al., 2010; Tsai et al., 1992; Robertson and Thorburn, 2001; Tominaga et al., 2002). This and the fact that Clay was significantly correlated with P_{CO_2} ($r = -0.26$), P_{N_2O} ($r = -0.21$), and SMB ($r = -0.18$) (Table 2) could explain the negative relationship between F_{CO_2} and C_{stock} found in our study.

Soil CO₂ production potentials, P_{N_2O} , and SMB showed significant correlation coefficients ($P < 0.05$) with most soil chemical attributes and, in general, a moderate correlation with them. It is known that the improvement of soil chemical conditions contributes to the increase of microbial activity and hence for GHG production. In the same way, soil pH not only affects SMB, but also affects the composition of its population in the soil, providing a good environment for the activity of certain classes of microorganisms, increasing SMB and, consequently, the rates of GHG production (Fuentes et al., 2006). In fact, pH showed positive and significant correlation coefficients with P_{CO_2} ($r = 0.41$), P_{N_2O} ($r = 0.21$), and SMB ($r = 0.62$) (Table 2). Similarly, the available phosphorus content is also considered a limiting factor for microbial activity since it is an essential element in its metabolism (Duah-Yentumi et al., 1998). Thus, the high P content found in our study (Table 1) could explain the positive and significant correlation coefficients observed between P and P_{CO_2} ($r = 0.24$) and SMB ($r = 0.41$) (Table 2).

Moreover, the presence of crop residues on the soil surface in sugarcane areas under mechanically harvest management can contribute to the increase of SOM, altering chemical properties and improving soil fertility (Vargas and Scholles, 2000; Canellas et al., 2003; de Oliveira et al., 2013; Vargas et al., 2014); it also contributes to 56% to 82% of CEC in soils under tropical conditions, retaining cations and preventing leaching losses (Van Raij, 1981). In this sense, Bases and CEC presented positive and significant ($P < 0.05$) correlation coefficients with P_{CO_2} ($r = 0.52$ and 0.45 , respectively), P_{N_2O} ($r = 0.29$ and 0.30 , respectively), and SMB ($r = 0.57$ and 0.35 , respectively) (Table 2). Thus, soil pH and nutrient content, combined with the available carbon in the soil under study, may have had an important role

in creating the ideal conditions for microbial activity and GHG production. This fact could be evidenced by the positive and significant linear correlation between SMB and P_{CO_2} ($r = 0.38$) and P_{N_2O} ($r = 0.26$) (Table 2).

This week correlation coefficients between GHG and soil attributes (Table 2) are commonly found in the literature when data are univariately analyzed (La Scala et al., 2000a; Ohashi and Gyokusen, 2007; Panosso et al., 2009, 2011; Herbst et al., 2010; Bicalho et al., 2014). In this case, GHG production and emission have a complex nature and its controlling factors are strongly inter-related, with no single determinant factor (Schwendenmann et al., 2003), i.e., each attribute explains only a small part of the variation of the phenomenon. Therefore, the complexity in studying F_{CO_2} , P_{CO_2} , and P_{N_2O} highlights the need of using more refined techniques to better establish more robust relationships.

Factor Analysis

The relationship of interdependence between soil greenhouse gases and soil attributes is shown in Fig. 2. Two processes (factors) were identified in the soil, which explained almost 72% of the total variance observed in the original data. These results are consistent with the criteria established by Sneath and Sokal (1973), wherein the number of factors used in the interpretation must be such that explain at least 70% of the total variance. Factor 1 represents almost 50% of the total variance observed, and considering the order of relevance of the factor loadings, it retained the attributes Micro (-0.81), Macro (0.74), C/N (-0.70), F_{CO_2} (0.63), M_s (0.63), and D_s (-0.62). Factor loadings represent the correlation of each variable with the factor; the higher their absolute values are, the higher their relevance in interpreting the factor matrix (Hair et al., 2005). In addition, taking into account the values and signs of factor loadings, F_{CO_2} , Macro, and M_s are directly associated and D_s , Micro, and C/N have a contrary association with F_{CO_2} .

The direct association between F_{CO_2} (0.63), Macro (0.74), and M_s (0.63) (Fig. 2) found in our study could be related to the fact that these soil physical attributes control oxygen exchange in the soil, influencing microbial activity and hence F_{CO_2} . In fact, gas exchange between soil and the atmosphere is dependent on soil texture, structure, and water content (Ball and Smith, 1991; Kang et al., 2000). Also, the respiration of macro and microorganisms, as well as roots respiration, are optimized in soils that have a higher amount of medium and large pores (Macro), which allows for a better aeration in the soil (Capeche et al., 2004). On the other hand, the direct association of D_s (-0.62) and Micro (-0.81), which is contrary to Macro (0.74) and M_s (0.63) (Fig. 2), could lead to lower soil CO_2 emissions since high values of D_s could limit the oxygen in the soil due to the decreased number of pores and the corresponding limitation of microbial activity. Such association is a characteristic of mechanically harvested sugarcane areas due to their non-tilled soil structure, which leads to soil compaction in the 0-20-cm layer due to the higher tractor traffic on the area (Tominaga et al., 2002; Souza et al., 2005;

Oliveira et al., 2010), especially when it is performed in clayey soils (Silveira and Stone, 2003), as in the study area (Table 1).

The variables F_{CO_2} (0.63) and C/N (-0.70) were inversely associated in Factor 1 (Fig. 2). Soil C/N ratio is an important soil attribute related to soil carbon quality, influencing soil CO_2 emission (Allaire et al., 2012; Ngao et al., 2012). Thus, the higher the C/N ratio in the soil is, the greater the difficulty for microorganisms to decay soil organic matter, which could lead to lower values of F_{CO_2} . This fact may explain that inverse association between F_{CO_2} and the C/N ratio observed in our study. As a matter of fact, other studies have found a negative relationship between F_{CO_2} and the C/N ratio and also that a low C/N ratio in the soil increases microbial activity (Khomik et al., 2006; Vesterdal et al., 2008; Allaire et al., 2012; Ngao et al., 2012). Therefore, Factor 1 is related to the process associated with the transport of CO_2 in the soil, because some soil physical attributes related to soil structure were retained in this factor, supporting the dependence between F_{CO_2} and soil porosity.

Factor 2 represents almost 22% of the variance of the original data, and considering the order of relevance of the factor loadings, it retained the attributes Bases (0.72), SMB (0.69), pH (0.67), P (0.63), P_{N_2O} (0.57), and P_{CO_2} (0.54) (Fig. 2). These attributes are related to the process associated with GHG production potentials in the soil; in other words, the laboratory derived production rates that were measured in the laboratory and some soil chemical attributes. Furthermore, the factor loadings of these attributes showed the same sign, indicating that they are directly associated in Factor 2, suggesting that the improvement

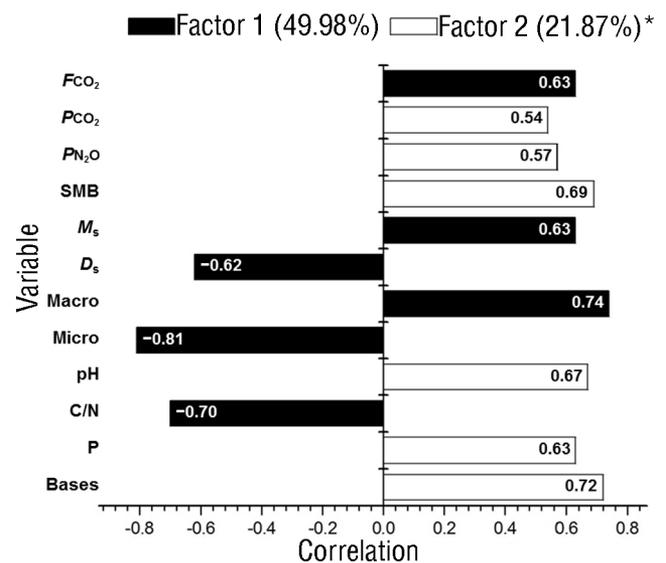


Fig. 2. Factor analysis showing the correlation coefficients between variables and factors. *Value refers to the percentage of variation of the original set of data retained by the factor. Values within the bars are the loadings considered in the factor interpretation (higher than or equal to 0.5). Bases, sum of bases; C/N, carbon to nitrogen ratio; D_s , soil bulk density; F_{CO_2} , soil CO_2 emissions; M_s , soil moisture; Macro, macroporosity; Micro, microporosity; P, available phosphorus; P_{CO_2} , soil CO_2 production potentials; P_{N_2O} , soil N_2O production potentials; SMB, soil microbial biomass

of soil chemical conditions contributes to the increase of microbial activity and hence for GHG production.

It is widely reported that sugarcane crop residues left on the soil surface after harvest increase SOM, which is directly related to the time of adoption of mechanical harvest system in sugarcane areas, being that the increase of soil organic matter generally observed in the upper soil layers (Razafimbelo et al., 2006; Luca et al., 2008; Galdos et al., 2009; Canellas et al., 2010; Thorburn et al., 2012). It also alters soil chemical attributes and improves soil fertility (Vargas and Scholles, 2000; Canellas et al., 2003; de Oliveira et al., 2013; Vargas et al., 2014). Thus, soil pH and nutrient content, combined with the available carbon in the soil under study, may have had an important role in creating the ideal conditions for microbial activity and production of greenhouse gases under laboratory conditions because P_{CO_2} , P_{N_2O} , and SMB are directly associated in Factor 2.

Factors 1 and 2 are orthogonal to each other and thus independent. It means that the attributes related to CO_2 transport (F_{CO_2} , D_s , Macro, Micro, C/N, and M_s) (Factor 1) are not correlated with soil greenhouse gas production potentials process quantified under laboratory conditions (P_{CO_2} , P_{N_2O} , SMB, pH, P, and Bases) (Factor 2). When the characterization of CO_2 in the laboratory is considered with the use of disturbed soil samples, it provided a means of assessing the CO_2 production potentials under ideal conditions, not considering the differences in CO_2 emissions due to gas transport processes, such as those related to soil porosity. However, although considered as independent by the factor analysis, these processes are coupled and occur simultaneously in soils. Therefore, soil greenhouse gas emissions are dependent on gas production processes in the soil and its transport to the atmosphere.

CONCLUSION

Soil CO_2 emissions and soil CO_2 and N_2O production potentials were associated with two processes: their production in the soil and transport to the atmosphere. Under infield conditions, the process related to CO_2 transport was more easily observed, showing a stronger relation between soil CO_2 emission and soil porosity. In contrast, under laboratory conditions, soil chemical attributes have a greater importance for the processes of soil CO_2 and N_2O production potentials. However, although presented as independent, these processes are coupled and occur simultaneously in the soil, in addition to providing information about their variability, showing if infield emissions are due to gas transport processes or soil carbon levels and their quality (i.e., gas production processes). Because these controlling processes have a greater or lower influence depending on the conditions the experiments were performed (under infield or laboratory), the infield soil GHG emissions could not be characterized with precision only from laboratory derived GHG production potentials. Therefore, more studies are needed to establish the best laboratory methodology to capture the complexity of this phenomenon and extrapolate the results to infield conditions.

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