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ORIGINAL ARTICLE

Soil CO_2 emission in sugarcane management systems

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Sugarcane management systems affect soil attributes such as the carbon cycle. This fact has stimulated the sugar and alcohol industry to refine the sugarcane production systems by replacing the pre-harvest burning (PB) and manual harvest with mechanized harvesting followed by residue deposition. The aim of this study was to evaluate different management systems with respect to C cycling carbon dioxide and soil parameters (chemical, physical and biological) which were determined over the season. Three sugarcane cultivation systems were evaluated at the following periods: (a) PB, (b) 5-year green harvest and (c) 10-year green harvest. The results indicated that CO_2 emission was 36% greater in the 10-year sugarcane green harvest system than in the PB system. The bulk density and macroporosity were the factors that were most affected by the different sugarcane management systems and that significantly influenced soil CO_2 emissions. The principal component analysis showed that soil CO_2 emission was 18% influenced by base saturation (V%) and 14% by pH, especially in the PB area. Additionally, 19% was affected by carbon and macroporosity in the 5- and 10-year green harvest areas, respectively. From our results, it can be concluded that the most CO_2 emissions are in the areas of sugarcane green, this is due to the higher carbon concentration when compared with the area of burning sugarcane. The parameters that most influenced the CO_2 emissions were bulk density, porosity, macroporosity, pH and V%.

Keywords: *Saccharum officinarum*; principal component analysis; microbial biomass; chemical attributes; physical attributes

Introduction

Sugarcane cultivation without burning positively influences soil quality due to the increase in residual straw deposited on the soil surface after harvest. Sugarcane crops fix approximately 100 mg CO_2 per dm^2 of leaf area per hour (Paula et al. 2010). Cerri et al. (2007) reported that a sugarcane area that involves both industrial and agricultural processes can sequester 18.5 Mt of atmospheric carbon per year. Based on this value, converting to a sugarcane green harvest system is responsible for the sequestration of 0.48 Mt of carbon per year.

Prior to the sugarcane green harvest system, sugarcane areas were burned pre-harvest to favor manual harvest. This practice is still adopted in some sugarcane production regions of São Paulo State (21°19′8″ S and 48°7′24″ W), Brazil. The practice has been progressively eliminated by law due to several environmental and respiratory health problems (Arbex et al. 2012) caused by particulate matter release into the atmosphere. During sugarcane burning, 0.004 Mg of particulate matter is released (Macedo et al. 2004), with the emission of 4.81 Mg CO_2 ha^{-1} (Marques et al. 2009).

Management practices that change soil organic matter and influence the physical and chemical attributes of soil directly affect the microbial activity and CO_2 emission. Additional studies are therefore necessary to examine the changes in soil attributes after the conversion from pre-harvest burning to the

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green harvest system. Further studies are also needed to investigate how this process affects soil carbon losses via soil CO_2 emission. Here, we evaluate the most influential soil variables affecting CO_2 emission in different sugarcane management systems. Our hypothesis were as follows: (a) when compared with conservation managements systems, the most CO_2 emissions are usually found in the burning sugarcane area and (b) soil management systems influence soil parameters.

Materials and methods

Experiment location

The study was conducted in sugarcane areas belonging to a sugar and alcohol mill located in Northern São Paulo State, Southeast Brazil, close to 21°19′8″ S and 48°7′24″ W. The climate in the region is classified as $B_2rB'4a'$ (humid climate with small hydric deficiency) according to Thornthwaite climate classification. The topography in the area is flat and undulating.

Experimental areas

The studied areas were managed according to sugarcane pre-harvest burning (PB) and green harvest systems. The green harvest systems had a different implementation history. One of the areas has a green harvest history of 5 years (SG-5) with one plant cycle, and the other area has a 10-year history (SG-10) with two plant cycles. Both green harvest areas were converted from the pre-harvest burning system. The soil in the areas was classified as clayey Oxisol. The study was conducted in 2011, in three areas of 1 ha each.

The pre-harvest burning area presented a mean slope of 4% and has been managed with sugarcane burning since the 1980s. During the experimental period, the cultivated sugarcane variety had a cation exchange capacity (CEC) of 4 in its fifth ratoon crop. The mean yield was 67 t ha^{-1}. The 5-year sugarcane green harvest area had a mean slope of 3.7% and has been mechanically harvested since 2006. The cultivated variety was RB85 5453 in its fifth ratoon crop. The mean yield was 80 t ha^{-1}. The 10-year green harvest area had a mean slope of 4.1% and has been mechanically harvested since 2001. The cultivated variety was CEC 20 in its fifth ratoon crop. The mean yield was 75 t ha^{-1}.

At sugarcane crop renovation, which is performed in the pre-harvest burning (each six ratoon crops) and 10-year green harvest (in 2007) areas, mechanical elimination of the previous crop ratoons was performed. Additionally, subsoiling was conducted at 0.45 m depth in the planting furrows. After these operations, the areas were treated with 2 t ha^{-1} of dolomitic limestone. The planting fertilization was conducted with 480 kg ha^{-1} of NPK formulation (10-25-20). Over the years (with the exception of 2011), a mean of 100 m^3 ha^{-1} of vinasse and 300 kg ha^{-1} of urea or 200 kg ha^{-1} of ammonium nitrate was applied.

A grid with 30 sampling points totaling 1 ha was implemented in each area (Figure 1). All points were georeferenced with a total station (Leica® model TC 305) and DGPS (L1/L2 Hiper Lite Plus). The evaluations of CO_2 emission and soil sampling were performed during the 2011 dry period.

Evaluation of soil CO_2 emission

The evaluation of CO_2 was performed at the sampling grid points using three chambers simultaneously in the mornings (7–11 a.m.). The chamber was manufactured by LI-COR® (Nebraska, USA, model LI-8100). The device is a closed system with an internal volume of 991 cm^3 and a contact area with the soil of 71.6 cm^2. The device was placed on PVC collars that were previously inserted (2 days before) into the soil at a 3 cm depth once at each point and site. The soil temperature and moisture were evaluated simultaneously with the measurement of CO_2 concentration using a temperature sensor coupled to the LI-8100 system. The TDR-Campbell® equipment was used to evaluate the soil water content.

Evaluation of soil attributes

The deformed soil samples were collected from the soil surface (0.00–0.20 m depth) for evaluation of chemical (organic carbon, pH and phosphorus) and microbiological (basal respiration and microbial biomass) attributes, particle-size distribution and mean weight diameter (MWD). The undeformed samples were used to analyze soil macroporosity, microporosity and bulk density. A portion of the samples was stored moist for microbiological analysis at up to 30 days. The remaining sample was exposed to air for 24 h and then maintained moist for aggregate preservation. The soil was then placed on sieves of 6.35 and 2 mm. The aggregates were obtained from samples retained by the 2-mm sieve. The sample that passed through the sieve was air dried until reaching a constant weight before evaluating the other soil attributes.

Organic carbon was determined according to the Walkey-Black methodology (Nelson and Sommers 1982), and the chemical analysis was performed as described by Raij et al. (2001). The base saturation was calculated by the formula $V\% = (100 \times S)/T$,

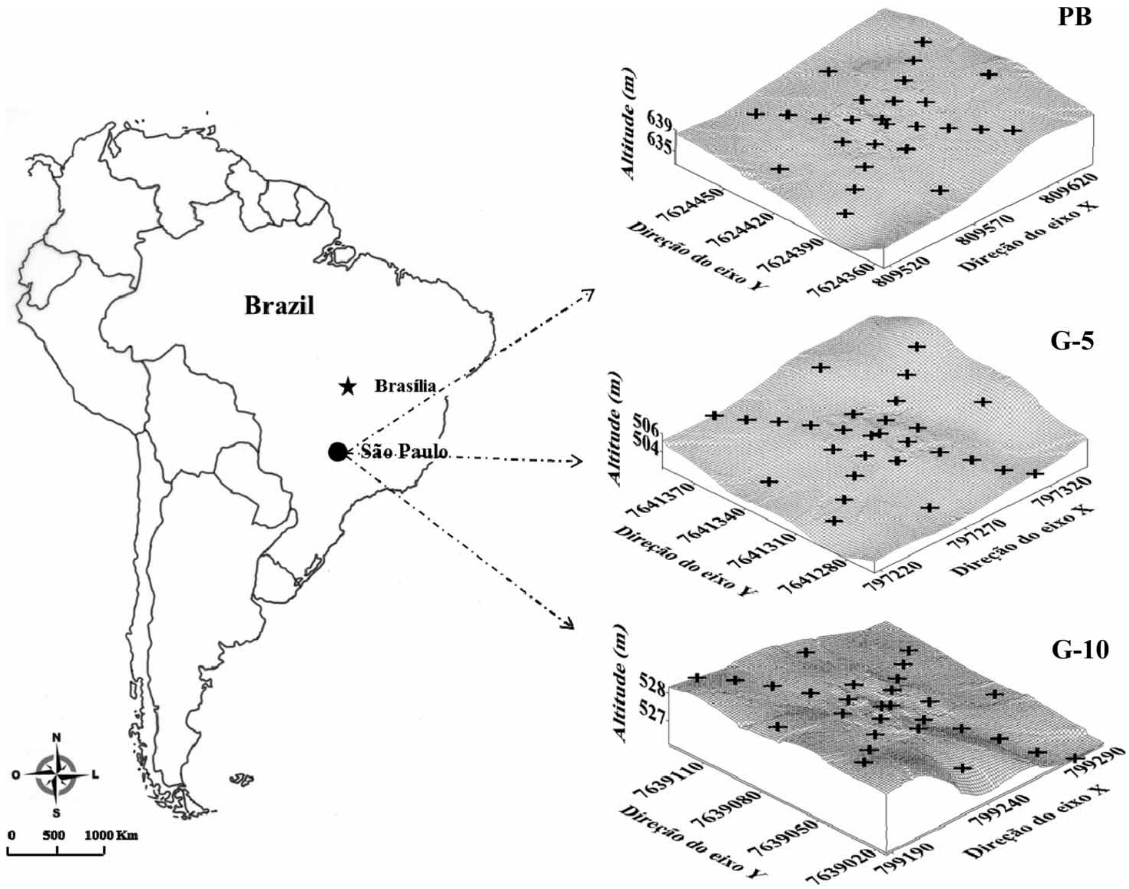

Figure 1. Location of the experimental areas and topography maps. PB, sugarcane pre-harvest burning area; SG-5, 5-year sugarcane green harvest area; SG-10, 10-year sugarcane green harvest area. Details of the sampling grid point.

where S is the sum of bases and T is the CEC at pH 7. The carbon analysis of the soil microbial biomass was performed according to the fumigation–extraction method proposed by Jenkinson and Powlson (1976). The basal respiration was calculated according to the respirometry-titration method described by Alef and NanniPieri (1995). The microbial quotient (qMIC) was calculated according to Anderson and Domsch (1990) using the relationship between microbial biomass and total organic carbon.

The physical analyses were performed according to the Brazilian Agricultural Research Corporation's manual for physical analysis (Embrapa 1997). NaOH was used as a dispersant and clay was obtained with the pipette method to determine the soil particle-size distribution. The bulk density and soil porosity were obtained from the soil samples contained in the rings. The MWD was calculated according to the method described by Kemper and Chepil (1965). We used sieves in water to separate aggregates in sieves of 4.76-, 2.0-, 1.0-, 0.5-, and 0.25-mm diameters. The aggregates were separated into the following classes: C1 (9.52–4.76 mm), C2 (4.76–2.0 mm), C3 (2.0–1.0 mm), C4 (1.0–0.5 mm), C5 (0.5–0.25 mm) and C6 (< 0.25 mm).

Statistical analysis

Descriptive statistics (mean and coefficient of variation) were used for data interpretation and differences among attribute means. The different management systems were tested by the *t*-test ($p < 0.05$) using SAS software (Schlotzhaver and Littell 2013). A multivariate analysis was performed by setting the attribute unit mean and variance to 0 and 1, respectively (Kaiser 1958). A principal component analysis (PCA) was used to explain the structure of soil data variance using linear correlations of the evaluated variables with principal components (PCs) (Johnson and Wichern 2002; Hair et al. 2005). The objective is to use the dataset to identify a variable that explains a significant variance part via linear correlations (Mingoti 2005; Ferreira 2008). For the multivariate analysis, we used data obtained from chemical, physical and microbiological attributes of the soil that presented relationships with soil CO_2 emission in previous studies. The

Table 1. Descriptive statistics of soil microbiological, physical and chemical attributes in sugarcane PB, 5-year green harvest (SG-5) and 10-year green harvest (SG-10) areas.

	PB		SG-5		SG-10	
Attribute	Mean	CV	Mean	CV	Mean	CV
Microbiological						
FCO_2	1.58 b	28.48	1.93 b	30.05	2.71 a	35.05
MB	240.9 b	26.65	319.80 a	39.39	336.00 a	19.43
qMIC	8.32 b	32.21	10.63 a	43.74	13.18 a	16.84
Physical						
Sm	11.53 c	8.67	24.50 a	7.06	20.03 b	7.48
St	24.25 a	1.77	18.89 c	2.43	23.72 b	26.81
MWD	1.60 a	32.50	1.40 a	30.71	1.67 a	28.74
Bd	1.19 b	10.08	1.31 a	10.68	1.35 a	11.11
Clay	561.0 a	8.89	517.50 a	10.31	531.57 a	8.87
Ma	0.19 b	13.15	0.20 b	40	0.24 a	25
Mi	0.37 a	7.56	0.34 b	14.70	0.25 c	32
Chemical						
C	2.94 a	10.88	3.15 a	23.17	2.59 b	17.37
V	75.92 a	4.76	59.04 b	8.01	58.56 b	17.96
pH	5.21 a	3.07	4.80 b	2.29	4.90 b	5.71
P	17.00 b	39.82	36.30 a	54.98	35.04 a	60.81

FCO_2, flow rate of CO_2 (μmol CO_2 m^{-2} s^{-1}); MB, microbial biomass (μg C g^{-1} dia^{-1}); qMIC, microbial quotient (μg C μg C-SMB dia^{-1}); Sm, soil moisture (%); St, soil temperature (°C); MWD, mean weight diameter (mm); Bd, bulk density (kg m^{-3}); clay (g kg^{-1}); Ma, macroporosity (m^3 m^{-3}); Mi, microporosity (m^3 m^{-3}); C, organic carbon (g kg^{-1}); V, base saturation (%); P, phosphorus (mg dm^{-3}); CV, coefficient of variation. Means followed by the same letter within a line do not differ from each other by Student's *t*-test at the 5% probability level.

results of the analyzed variables were used to explain the studied management systems and were compared with mean values of CO_2 flow and basal respiration.

Results and discussion

The highest CO_2 flux (FCO_2) values were observed in the sugarcane green harvest areas. The mean values were 1.93 and 2.71 μmol CO_2 m^{-2} s^{-1} for SG-5 and SG-10, respectively. For PB, we found a mean emission of 1.58 μmol CO_2 m^{-2} s^{-1}. This result indicates a significant FCO_2 increase ($p < 0.05$) according to the management system evolution. However, a significant difference ($p < 0.05$) was found only for SG-10 compared to the other areas. These data indicate that the SG-five-transition stage has a more recent history of burning elimination (Table 1).

The highest FCO_2 values in SG-10 may be associated with greater microbial activity in areas with major plant residue deposition on the soil surface (Table 1). According to Carbonell-Bojollo et al. (2012), the microbial activity emits more CO_2 in ideal soil moisture and temperature conditions. This result is confirmed by greater microbial biomass amounts of 240.9, 319.8 and 336.6 μg C g^{-1} dia^{-1} for PB, SG-5 and SG-10, respectively. Greater microbial activity was found in the areas with major sugarcane straw deposition over time. Furthermore, the qMIC, which evaluates organic carbon availability for microbial activity, was higher in SG-10 ($p < 0.05$). These data indicate that there is active and less recalcitrant organic matter (Hart et al. 1989), which results in greater CO_2 emission in SG-10 than other areas. These findings suggest high microbial activity and efficiency in organic matter decomposition.

The bulk density was greater ($p < 0.05$) in the green harvest areas (Table 1) due to longer periods of machinery traffic, which is a known characteristic of this system (Flowers and Lal 1998). The macroporosity was greater ($p < 0.05$) in the 10-year green harvest area. This finding was also observed for soil CO_2 emissions and supports the possibility that macroporosity influences CO_2 emissions. According to Fick's law, this result is related to the linearity of the gas path in the soil because macroporosity provides a less tortuous path for the CO_2 molecules (Alvenäs and Jansson 1997; Brito et al. 2009). Conversely, microporosity promotes minor linearity in the porous space and is associated with more tortuous paths that hamper CO_2 gas transportation from the soil to the atmosphere. Thus, lower soil microporosity values resulted in greater CO_2 emissions due to the different management systems. The microporosity significantly decreased ($p < 0.05$) emissions of the evaluated management systems (Table 1). There is greater soil compaction in sugarcane green harvest areas due to the higher frequency of machinery and implement use. The use of machines deforms the physical structure and promotes other particle arrangement (Carvalho et al. 1991).

There were higher organic carbon values observed in SG-5 ($p < .05$) than in the other management systems (Table 1). The high microbial activity in SG-10 could reduce the organic carbon content because the increase in organic matter decomposition cycles by microorganisms results in a low organic carbon content, which is more protected and stabilized in microaggregates (Lenka and Lal 2013). Other studies also described a higher organic matter content in Oxisol and Alfisol submitted to sugarcane pre-harvest burning in the green harvest systems of São Paulo/Brazil (Panosso et al. 2008) and Australia (Blair 2000), respectively.

The base saturation was higher in PB than in other areas (Table 1). This result may be caused by the ash deposited on the soil surface from the previous sugarcane crop burning. The ash contributes to soil fertilization with prompt addition of mineral nutrients such as K, Ca and Mg, and increases soil base saturation (Scheuner et al. 2004; Niemeyer et al. 2005). However, the phosphorus content was greater in the sugarcane green harvest areas due to plant biomass accumulation because organic compounds are responsible for phosphorus release. A similar result was obtained by Canellas et al. (2003) in Inceptisol soil with sugarcane pre-harvest burning and green harvest areas in Rio de Janeiro State/Brazil.

To study the multivariate structure contained in the initial dataset of soil attributes, previous authors have worked with PCA that condenses the original measured variables (soil attributes) into new non-measured variables in an attempt to evaluate the discriminatory power of the original variables (Carvalho Junior et al. 2008). We considered the PCs with eigenvalues higher than the unit, since they are ideal for this analysis (Kaiser 1958). Thus, the first four PCs were used (PC1, PC2, PC3 and PC4) to explain 65.71% of the attributed variance (Figure 2). The first two PCs, PC1 and PC2, explained 46.53% of the data total variance. PC1 could explain 30.43% of the variance, and PC2 explained 10.10% of the variance. Panosso et al. (2011) studied soil FCO_2 in both sugarcane green harvest and pre-harvest burning systems and reported that PC1 and PC2 explained 52.1% and 18.5% of the variance, respectively.

In PC1, the soil attributes that presented higher correlation coefficients were the following: *V*% (−0.83), Sm (0.82), pH (−0.75), Bd (0.58) and Clay (−0.56). Panosso et al. (2011) examined CO_2 emission from soil cultivated with sugarcane and found the influence of the physical and chemical attributes on PC1 discriminatory power. In PC2, the attributes were the following: C (−0.62), Ma (0.61), WMD (0.54), Mi (−0.54) and FCO_2 (0.48). In PC3 and PC4, the attributes were Bd (−0.56) and St (0.54), respectively (Table 2).

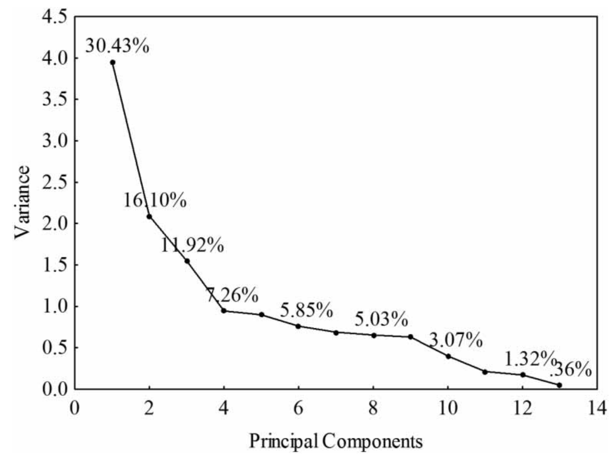

Figure 2. Explained variance graph of the variable set for each PC, with emphasis on the first 5 PCs, which totaled 75%.

Each pair of PCs generated a two-dimensional representation of the original sampling space termed a biplot (Figure 3). The biplots explain the variable structure by directing variable bundles in the regions of maximum variability. The biplot graph indicates the formation of at least two very distinct groups. The first group is located at the left side of the graph and was formed by samples from the pre-harvest burning area. The second group of points is positioned at the right of the first PC and was composed of samples from the sugarcane green harvest areas. However, further analysis showed a subdivision of group 2. This suggests that there is an attribute position in three different groups (PB, SG-5 and SG-10). The PB group presented lower point dispersion and was composed of samples from the sugarcane pre-harvest burning area. Conversely, the SG-5 and SG-10 groups represent samples from the 5- and 10-year green harvest areas and demonstrate a higher point dispersion or greater variability of the evaluated attributes. Panosso et al. (2011) reported that PCA indicated higher point dispersion from a sugarcane pre-harvest burning area, while the green harvest areas presented lower dispersion and less variability.

The correlations shown in Figure 3 are represented by arrows of each attribute. The projection in the graph, when PC1 is evaluated for PB group, is a group of soil physical and chemical attributes such as *V*% and pH. The attributes that better correlated with PC1 are highlighted (Figure 3) because they also had a higher discriminatory power. Therefore, the results indicate that FCO_2 in the PB area was mainly influenced by the attributes *V*% and pH,

Table 2. Correlation coefficients among analyzed variables and PCs (PC1–PC4), and importance ranking of soil microbiological, physical and chemical variables.

	PC1 (%)		PC2 (%)		PC3 (%)		PC4 (%)	
Total	30.42		16.09		11.91		7.26	
Cumulative	30.42		46.52		58.43		65.70	
Variable	*R*	Ranking	*R*	Ranking	*R*	Ranking	*R*	Ranking
Microbiological								
FCO_2	0.45	10° (5.12%)	0.48	5° (11.27%)	0.03	13° (0.074%)	−0.31	4° (10.43%)
MB	0.52	7° (6.89%)	−0.001	13° (0.001%)	0.40	3° (10.68%)	0.12	9° (1.54%)
Physical								
Sm	0.82	2° (17.26%)	−0.26	9° (3.46%)	0.19	10° (2.55%)	−0.14	8° (2.22%)
St	−0.51	8° (6.71%)	0.34	7° (5.72%)	−0.15	11° (1.55%)	0.54	1° (31.33%)
MWD	−0.06	12° (0.10%)	0.54	3° (14.20%)	0.41	2° (11.26%)	0.35	3° (13.70%)
Bd	0.58	4° (8.58%)	0.09	12° (0.46%)	−0.56	1° (20.79%)	0.002	13° (0.0001%)
Clay	−0.56	5° (8.21%)	−0.30	8° (4.55%)	−0.30	4° (6.01%)	−0.37	2° (15.03%)
Ma	0.31	11° (2.45%)	0.61	2° (18.33%)	0.08	12° (0.43%)	−0.30	5° (9.66%)
Mi	−0.54	6° (7.47%)	−0.54	4° (13.82%)	0.27	7° (4.96%)	0.03	12° (0.14%)
C	0.003	13° (0.001%)	−0.62	1° (18.86%)	0.25	8° (4.27%)	0.04	11° (0.19%)
Chemical								
V	−0.83	1° (17.76%)	0.18	10° (1.71%)	0.29	5° (5.56%)	−0.23	7° (5.84%)
pH	−0.75	3° (14.25%)	0.38	6° (6.90%)	0.27	6° (4.99%)	−0.30	6° (9.60%)
P	0.45	9° (5.16%)	−0.11	11° (0.67%)	0.64	9° (2.68%)	−0.05	10° (0.27%)

R, correlation; MB, microbial biomass; Sm, soil moisture; St, soil temperature; MWD, mean weight diameter; Bd, bulk density; Ma, macroporosity; Mi, microporosity; C, organic carbon; *V*%, base saturation; P, phosphorus.

which are related to soil microbial activity. The correlations among *V*% and pH with PC1 were negative. However, FCO_2 showed a positive correlation with this component. Therefore, the group formed by points from the pre-harvest burning area presented lower FCO_2 values than the points from the green harvest areas. The data from Panosso et al. (2011) corroborate our results and show that the sum of bases was the attribute that presented the highest correlation with PC1 (0.93). This attribute has great discriminatory power in the sample group from the pre-harvest burning area.

The group of points formed mostly by samples from SG-5 was mainly influenced by Sm, which

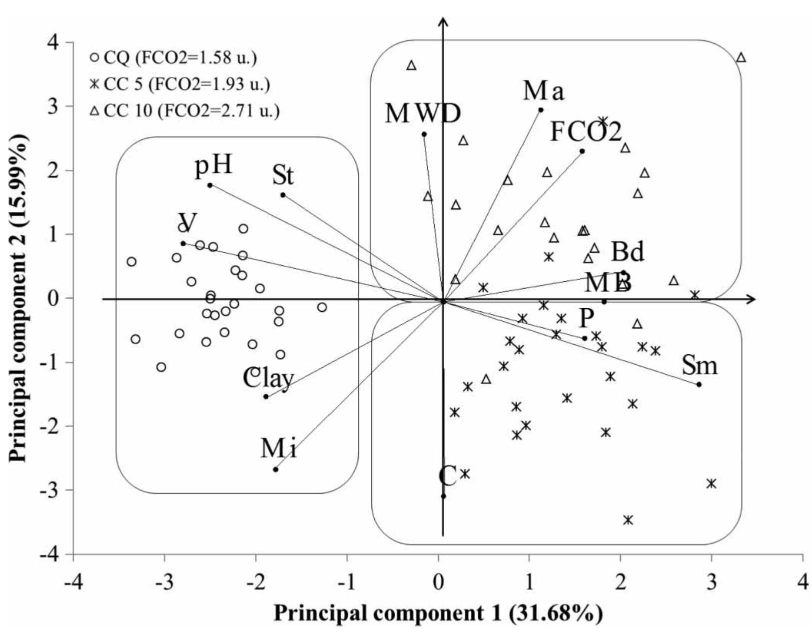

Figure 3. Two-dimensional representation of PC1 and 2 (biplot) of the PCA. PB, sugarcane pre-harvest burning; SG-5, 5-year sugarcane green harvest; SG-10, 10-year sugarcane green harvest; MB, microbial biomass; Sm, soil moisture; St, soil temperature; MWD, mean weight diameter; Bd, bulk density; Ma, macroporosity; Mi, microporosity; C, organic carbon; *V*%, base saturation; P, phosphorus.

was the second attribute in PC1 with the greatest discriminatory power (SG-5 group – Figure 3). According to several studies (La Scala et al. 2000; Epron et al. 2004; Kosugi et al. 2007; Song et al. 2013), soil moisture is directly related to soil CO_2 emission. In SG-10 (SG-10 group), bulk density was the most influential factor and had a positive correlation with PC1 (Table 2).

In PC2, FCO_2 and Ma were the most important attributes for variance explanation and had a positive correlation. Furthermore, both were positioned in the SG-10 group and presented correlation bundles in the same direction (Figure 3). This result demonstrates a direct relationship between both attributes because the main soil macroporosity function is to promote the flow of matter, water and gases in the soil and directly affects soil FCO_2 (Brito et al. 2009; Fang et al. 1998).

Organic carbon is responsible for differentiating the group of samples from SG-5 and was able to explain 18.68% of the data variance in PC2 (Table 2) and had a negative correlation. In the biplot graph, it presented bundles in the opposite direction of FCO_2. These data indicate an indirect relationship between carbon and FCO_2. Thus, greater carbon loss via CO_2 may lead to smaller carbon amounts in the soil (Cerri et al. 2007). Soil microporosity, which is also responsible for differentiating the PB group, was the most important attribute in the first two PCs and showed negative correlations. This finding is possibly due to the microporosity antagonistic behavior to macroporosity. A comparison with FCO_2 via the biplot graph showed opposite directions, which indicates an indirect relationship between both attributes.

The CO_2 emission was greater in the sugarcane green harvest than in the pre-harvest burning area. Furthermore, bulk density and soil porosity were the factors most affected by the different sugarcane management systems, influencing significantly soil CO_2 emissions. The *V*% affected the variability of CO_2 emission by 18% and the pH by 14%, especially in the sugarcane pre-harvest burning area. Carbon also affected the variability by 19% and macroporosity by 18% in the 5- and 10-year sugarcane green harvest areas, respectively.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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