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# Soil management of sugarcane fields affecting $CO_2$ fluxes

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ABSTRACT: The harvesting system of green sugarcane, characterized by mechanized harvesting and no crop burning, affects soil quality by increasing the remaining straw left on the soil surface after harvesting, thus, contributing to the improvement of physical, chemical, and microbiological soil attributes, influencing $CO_2$ fluxes. This study aimed to evaluate $CO_2$ fluxes and their relation to soil properties in sugarcane crops under different harvesting managements: burned (B), Green harvesting for 5 years (G-5) and Green harvesting for ten years (G-10). For this, a 1 ha sampling grid with 30 points was installed in each area, all located in the Northeast of São Paulo State, Brazil. In each point, $CO_2$ fluxes were measured and the soil was sampled to analyze the microbial biomass, physical (soil moisture and temperature, mean weight diameter, bulk density, clay, macroporosity and microporosity) and chemical characterization (pH, organic C, base saturation and P). The $CO_2$ fluxes were divided into four quantitative criteria: *high*, *moderate*, *low* and *very low* from the Statistical Division (mean, first quartile, median and third quartile) and the other data were classified according this criterion. The Principal Component Analysis (PCA) was used to identify the main soil attributes that influence $CO_2$ fluxes. The results showed that G-10 $CO_2$ fluxes were 28 and 41 % higher than those in the G-5 and B treatments, respectively. The PCA analysis showed that macroporosity was the main soil attribute that influenced the *high* $CO_2$ fluxes.

Keywords: *Sacharum officinarum*, principal component analysis, porosity, biomass

## Introduction

The practice of burning sugarcane residues prior to harvesting aims to facilitate manual cutting, but the temperature during sugarcane burning is around 160-200 °C on the soil surface, causing nutrients loss by volatilization such as phosphorus, sulfur and nitrogen (Ball et al., 1993) and may lead to a great decline in soil C stocks (Song et al., 2013). The "harvesting of green sugarcane" is a system without burning that leaves biomass waste in the field after harvesting, positively influencing soil quality by increasing the deposited residual straw (mean 10 to 30 Mg ha$^{-1}$) allowing carbon accumulation in the soil, which implies in a positive $CO_2$ balance as described by Razafimbelo et al. (2006).

Soil $CO_2$ fluxes from areas of sugarcane cultivation were studied by Brito et al. (2009) that found greater fluxes in areas with greater soil macroporosity. Panosso et al. (2009) compared the soil $CO_2$ in pre-harvesting burned crop with a green harvesting system and found that soil cations were the main soil attribute to explain the $CO_2$ fluxes mainly in the burned area.

Soil $CO_2$ fluxes result from physical and biological processes that affect $CO_2$ production and transport from the soil to the atmosphere. In addition, production is related to root respiration and the action of microorganisms during OM decomposition (Jenkinson and Ladd, 1981; Brito et al., 2009). Transport of soil gases is influenced by the physical structure parameters, such as porosity, which drive the gas flow. Saturation of soil pores also determines $CO_2$ fluxes. According to the literature, the main soil attributes that influence $CO_2$ fluxes include temperature and content of soil water (Xu and Qi, 2001; Epron et al., 2004, 2006; Kosugi et al., 2007; La Scala et al., 2010; Leon et al., 2014), attributes with great influence on microbial activities that promote soil respiration.

The principal component analysis (PCA) of $CO_2$ fluxes (Panosso et al., 2012) showed that water filled pore space, and total porosity and macroporosity were the main components to explain the variance of $CO_2$ fluxes. Another study, about soil $CO_2$ efflux in a water limited ecosystem (Leon et al., 2014), showed that the most important attributes were root biomass, soil volumetric water content and total porosity.

Mitigating $CO_2$ fluxes in sugarcane cultivation still requires further studies aiming to assess their viability and enhancing their applicability for environmental purposes. More specifically, there is a need to study the main factors responsible for high soil $CO_2$ fluxes, which can assist in the challenge of achieving stability of soil carbon through improved decision-making managements. This study aimed to evaluate $CO_2$ fluxes and their relation to soil properties in sugarcane areas under different harvesting managements.

## Materials and Methods

### Experimental site

This study was conducted on a farm with more than 30 years of sugarcane (*Saccharum* spp.) cultivation history. The land belongs to a sugar and ethanol mill located in the Pradópolis, São Paulo State, Brazil (21°19′8″ S, 48°7′24″ W), approximately 500 m above sea level

(Figure 1). The soil was classified as Haplustox (USDA Soil Taxonomy) (Latossolo Vermelho Eutroférrico, according to Brazilian Soil Classification System) with a clayey texture (561 g kg$^{-1}$ to B, 517 g kg$^{-1}$ to G-5 and 531 g kg$^{-1}$ to G-10), and the topography of the area is flat and undulating. The regional climate is classified as $B_2rB'4a'$ by the Thornthwaite system (Rolim et al., 2007), indicating a mesothermal region with rainy summers and dry winters. The average precipitation is 1425 mm yr$^{-1}$ and is concentrated between Oct and Mar. The average annual temperature over the last 30 years was 22.2 °C.

In 2011, three plots were chosen in areas with different systems and management times (Figure 1): the burned sugarcane (B) area has been managed under residue burning since the 1980s and the other areas were harvested under the green sugarcane system (G) with different starting times of green sugarcane adoption [5 years (G-5) that started in 2006 and another area with ten years (G-10) that started in 2001]. At the time of renewing the plantations, which occurred in every six ratoons in B and in G-10 in 2007) with mechanical removal of the ratoon of the previous crop and subsoiling to 0.45 m deep in the planting furrows. Afterward, 2 t ha$^{-1}$ of dolomitic limestone and 480 kg ha$^{-1}$ of NPK fertilizer at 10-25-20 formulation were also applied. On average, 100 m$^3$ ha$^{-1}$ of vinasse (by-product of biomass distillation of the sugarcane fuel industry) and 300 kg ha$^{-1}$ of urea or 200 kg ha$^{-1}$ of ammonium nitrate were applied to the areas after 5-7 months of the first fertilization.

In 2011-2012 (experimental evaluation period), treatment B with the sugarcane variety CTC4 (average maturity and high agricultural productivity) was in in its 5th ratoon with average yield of 67 t ha$^{-1}$. Treatment G-5 with the planted variety RB85 5453 (early maturity, erect growth, high productivity with no limitation of soil water) was in its 4th ratoon with average yield of 80 t ha$^{-1}$. Treatment G-10 with the sugarcane variety CTC 20 (early maturity, high tillering and high productivity along the cuts) was in its 5th ratoon with an average yield of 75 t ha$^{-1}$. In this experiment, no manure or fertilizers were applied between the years 2010 and 2011 (before and during the field experiment) to control interferences of these factors on the $CO_2$ fluxes. In each area, a sampling irregular grid of 1 ha was installed with 30 sampling points spaced at intervals with minimum of 2 m and maximum of 100 m. All points were georeferenced with the aid of a total station and a DGPS (Model L1/L2 Hiper Lite Plus).

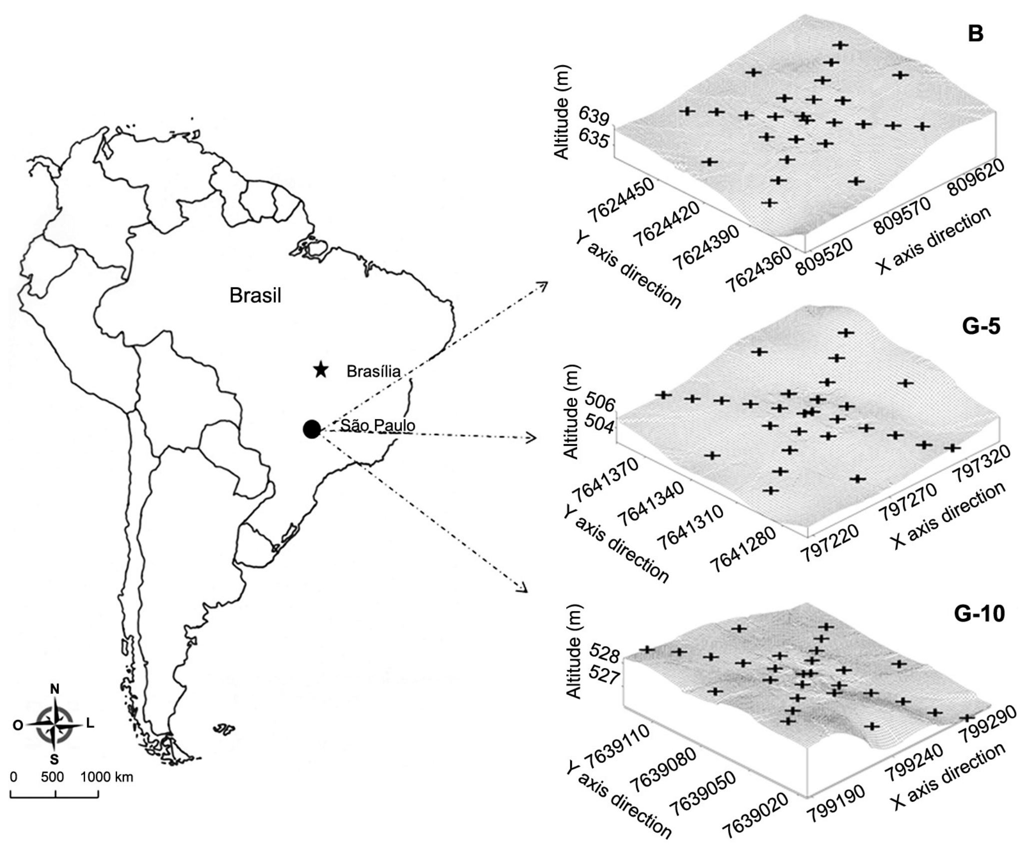


Figure 1 – Description of experimental locations and relief maps with sampling grid details. B = burned sugarcane; G-5 = green sugarcane with 5 years of implementation; G-10 = green sugarcane with 10 years of implementation.

### Measurement of $CO_2$ fluxes

Measurements of soil $CO_2$ fluxes were simultaneously performed in the three sugarcane areas in the same period (10 d in Aug-Sept 2011) and on the same day time (7:00-11:00 a.m.) after harvesting, for standardization. For that, three portable systems (1 system/area) were used to monitor the changes in $CO_2$ concentration inside the chamber using an infrared gas analyzer. The soil chamber has an internal volume of 854.2 $cm^3$ with a circular soil contact area at the base of 83.7 $cm^2$, which was placed on PVC collars previously inserted at each sampling point to 3 cm deep keeping is distant from the ratoon plant (approximately 30 cm) to decrease its influence on the $CO_2$ fluxes. Once the chamber is set to the measurement mode, it takes around 1.5 min to run the time-change interpolation of $CO_2$ concentration inside the chamber. The chambers were previously calibrated for this work.

Soil temperature (Ts) and soil water content (Ms) were measured simultaneously with $CO_2$ concentration through a temperature sensor coupled with the system, and Ms was registered with a portable Hydrosense system.

### Soil sampling and evaluation

For the microbial biomass (Biom) analysis, soil samples were collected at each point in the grid on the same day and time of $CO_2$ measurement, but only for 2 d of each collection period (the first and last day of $CO_2$ measurement) due to the large number of samples to be analyzed in 30 d (recommendation for the microbiological analysis). In the field, samples were kept in plastic bags inside Styrofoam boxes and transferred immediately to a refrigerator at 4 °C. The biomass analysis was performed according to the fumigation-extraction method proposed by Jenkinson and Powlson (1976).

For the other soil analysis, the samples were collected once at each point before the $CO_2$ analysis. Disturbed soil samples were collected from the first 20 cm of soil to evaluate organic carbon (C) (Nelson and Sommers, 1982), pH in $CaCl_2$ and phosphorus (P) by resin procedure (Raij et al., 2001), clay and mean weight diameter of soil aggregates (MWD).

Samples were exposed to air for 24 h, kept moist for aggregate preservation and then placed on a sieve set of 6.35 and 2 mm mesh diameter. Aggregates were obtained from samples retained by the 2 mm mesh, whereas those that passed through were again exposed to air until constant weight was achieved. Undisturbed soil samples were collected with aluminum rings and used to analyze macroporosity (Ma), microporosity (Mi) and bulk density (Bd). These physical analyses were carried out according to Brazilian Agricultural Research Corporation methodologies – Embrapa (1997).

### Statistical analyses

Mean daily $CO_2$ fluxes were evaluated by the *t* test for comparison between management areas ($p < 0.05$), using the program Minitab 14. These values were integrated to calculate the $CO_2$ accumulated during 10 d.

Quantitative criteria of $CO_2$ fluxes were defined by the distribution of $CO_2$ data in each area (Table 1), defined as: *very low* (VL) fluxes, which included values lower than the first quartile (Q1); *low* fluxes (L), between Q1 and median values; *moderate* (M) fluxes, between median and third quartile (Q3); and *high* (H) fluxes, values greater than Q3.

This criterion was used to identify the influence of soil attributes on different $CO_2$ concentrations, mainly by high fluxes and if the amount of soil attributes followed the same trend of $CO_2$ criterion. When the values were different for the three sugarcane systems, discussion was made separately for each area.

The multivariate structure in the original data set was evaluated by the PCA that condensed the relevant information into a smaller set of orthogonal latent variables called principal components (PC-eigenvectors). Each pair of principal components (PCs) generates a two-dimensional representation of the original sample space, known as a biplot. The biplot explains the structure of variables directing beams of variable regions of maximum variability. In this work, we considered the principal components whose eigenvalues were greater than a unity (Kaiser, 1958). The sign and relative size of the linear function coefficients, which define the PC scores were used as an indication of the weight to be assigned to each variable in the different experimental plots (Johnson and Wichern, 2002). The correlation between soil attributes with PCs to explain the management types were compared with the mean values of soil $CO_2$ fluxes.

## Results and Discussion

### $CO_2$ total fluxes

Considering the $CO_2$ total fluxes, G-10 showed higher values (mean 2.71 μmol $CO_2$ $m^{-2}$ $s^{-1}$), representing a significant difference ($p < 0.05$) of 28 % compared

Table 1 – Summary of soil $CO_2$ flux (μmol $m^{-2}$ $s^{-1}$) distribution statistics of burned and green cane areas.

| Area | Mean | Variance | Minimum | Q1 | Median | Q3 | Maximum | K-S |
|---|---|---|---|---|---|---|---|---|
| B | 1.58 b | 0.21 | 0.54 | 1.37 | 1.62 | 1.85 | 2.47 | 0.10 |
| G-5 | 1.93 b | 0.34 | 1.06 | 1.56 | 1.78 | 2.34 | 3.32 | 0.12 |
| G-10 | 2.71 a | 0.91 | 1.12 | 2.12 | 2.39 | 3.21 | 4.76 | 0.14 |

B = Burned cane; G-5 = Green harvest sugarcane for 5 years; G-10 = Green harvesting sugarcane for 10 years; Q1 = first quartile; Q3 = third quartile; K-S: Kolmogorov-Smirnov test. Means followed by the same letter in column do not differ from each other by the *t* test at 5 % probability level.

with G-5 (1.93 µmol $CO_2$ $m^{-2}$ $s^{-1}$) and 41 % compared with B (1.58 µmol $CO_2$ $m^{-2}$ $s^{-1}$) (Table 1). The G-5 and B did show statistical difference, the G-5 area is in a transition stage, considering the recent conversion to the green sugarcane system. This effect can be seen in Figure 2 that shows the $CO_2$ total emission accumulation in the three management systems.

Most $CO_2$ fluxes in G-10 may be associated with greater microbial activity in areas with major plant residue deposition on soil surface. Minimum soil tillage, like the green sugarcane management, provides favorable conditions for the development of microorganisms in the soil surface layer, which increases microbial biomass and $CO_2$ production (Matias et al., 2009).

Biom results showed similar trends of fluxes in the three experimental areas (Table 2), with higher values of Biom falling in the *high* and *moderate* $CO_2$ flux groups and lower values in the *low* and *very low* $CO_2$ flux groups. This indicates a direct participation of the microbial biomass in $CO_2$ production during soil organic matter (SOM) decomposition (Jenkinson and Ladd, 1981). However, this process is not always favorable for storing soil carbon, and for some authors, the reduction in SOM can be a result of $CO_2$ fluxes (Cerri et al., 2007).

The physical and chemical soil attributes showed no clear relation with the different groups of $CO_2$ fluxes, with the exception of macro- and microporosity, where macroporosity was the soil attribute of high frequency in all three areas, mainly to explain the *high* $CO_2$ fluxes group (Figures 3A, B, C). This can be attributed to gas transport in the soil, because according to Fick's gas diffusion Law, macroporosity provides better conductivity for the $CO_2$ molecule in the soil, facilitating gas fluxes (Alvenäs and Jansson, 1997; Brito et al., 2009). In turn, microporosity provides a more irregular path hindering $CO_2$ fluxes in the soil. Thus, G-10 presented greater macroporosity than B and G-5 (Table 2), meaning that despite greater bulk density in G-10 due the mechanized traffic, soil porosity did not impair the fluxes compared to B and this aspect can be attributed to the straw left on the soil that promotes more soil aggregation and porosity.

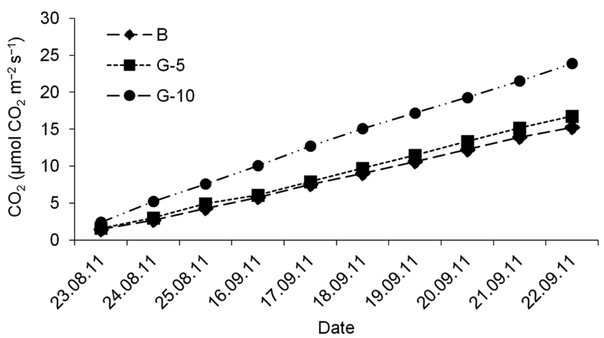


Figure 2 – Accumulated soil $CO_2$ emission on soil during Aug-Sept 2011 in burned sugarcane (B), green harvest sugarcane for 5 years (G-5) and 10 years (G-10).

Table 2 – Descriptive statistics of soil microbiological, physical and chemical attributes across experimental areas in accordance to CO2 flux criterion (high, moderate, low and very low).

| | $FCO_2$ | SD | Biom | SD | Ms | SD | Ts | SD | MWD | SD | Bd | SD | Clay | SD | Ma | SD | Mi | SD | C | SD | V% | SD | pH | SD | P | SD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Burned cane (B) | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *High* | 2.11 | 0.25 | 226.44 | 21.91 | 11.87 | 0.92 | 24.78 | 0.3 | 1.48 | 0.52 | 1.17 | 0.1 | 557.94 | 18.34 | 0.2 | 0.02 | 0.37 | 0.02 | 2.82 | 0.41 | 77.32 | 3.51 | 5.26 | 0.16 | 14.38 | 2.92 |
| Moderate | 1.72 | 0.07 | 224.34 | 35.93 | 11.58 | 0.66 | 24.38 | 0.37 | 1.68 | 0.58 | 1.19 | 0.09 | 568.08 | 17.12 | 0.19 | 0.03 | 0.38 | 0.04 | 2.98 | 0.29 | 74.8 | 2.16 | 5.17 | 0.12 | 18.00 | 5.73 |
| Low | 1.48 | 0.08 | 215.00 | 34.83 | 11.66 | 1.10 | 24.31 | 0.60 | 1.78 | 0.58 | 1.26 | 0.19 | 531.50 | 16.22 | 0.19 | 0.03 | 0.35 | 0.03 | 2.90 | 0.32 | 77.1 | 4.22 | 5.29 | 0.19 | 19.63 | 11.24 |
| Very low | 0.96 | 0.27 | 63.61 | 12.68 | 11.00 | 0.9 | 25.00 | 0.30 | 1.00 | 0.45 | 1.00 | 0.12 | 536.00 | 19.11 | 0.19 | 0.02 | 0.38 | 0.02 | 3.01 | 0.22 | 73.95 | 3.47 | 5.13 | 0.14 | 16.14 | 3.02 |
| Green cane with 5 years (G-5) | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *High* | 2.78 | 0.27 | 345.92 | 29.87 | 24.44 | 1.79 | 18.84 | 0.66 | 1.69 | 0.57 | 1.35 | 0.18 | 527.57 | 13.09 | 0.26 | 0.06 | 0.32 | 0.03 | 2.59 | 0.37 | 60.29 | 4.02 | 4.86 | 0.10 | 28.29 | 7.06 |
| Moderate | 2.03 | 0.17 | 346.57 | 27.06 | 25.05 | 1.82 | 18.88 | 0.67 | 1.17 | 0.36 | 1.31 | 0.11 | 524.31 | 19.42 | 0.19 | 0.04 | 0.33 | 0.02 | 3.5 | 0.81 | 57.71 | 4.60 | 4.81 | 0.16 | 29.50 | 11.95 |
| Low | 1.66 | 0.06 | 291.57 | 17.26 | 24.29 | 1.79 | 18.92 | 0.23 | 1.42 | 0.32 | 1.35 | 0.16 | 505.25 | 14.66 | 0.2 | 0.02 | 0.33 | 0.04 | 3.18 | 0.74 | 58.72 | 5.42 | 4.76 | 0.09 | 36.63 | 17.74 |
| Very low | 1.27 | 0.17 | 301.79 | 16.24 | 23.88 | 1.65 | 18.93 | 0.10 | 1.30 | 0.36 | 1.26 | 0.14 | 501.79 | 11.78 | 0.18 | 0.04 | 0.39 | 0.09 | 3.30 | 0.72 | 59.71 | 5.33 | 4.79 | 0.12 | 51.71 | 13.07 |
| Green cane with 10 years (G-10) | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *High* | 4.02 | 0.24 | 342.58 | 31.24 | 20.66 | 1.87 | 21.58 | 0.84 | 1.85 | 0.57 | 1.33 | 0.18 | 541.60 | 13.6 | 0.27 | 0.11 | 0.26 | 0.14 | 2.66 | 0.23 | 62.4 | 11.58 | 5.00 | 0.4 | 39.29 | 12.76 |
| Moderate | 2.84 | 0.27 | 355.80 | 23.44 | 20.21 | 1.37 | 26.03 | 0.85 | 1.62 | 0.46 | 1.35 | 0.18 | 410.63 | 19.06 | 0.23 | 0.03 | 0.26 | 0.04 | 2.65 | 0.82 | 57.42 | 11.68 | 4.87 | 0.23 | 30.71 | 17.23 |
| Low | 2.18 | 0.06 | 332.61 | 12.76 | 19.39 | 1.42 | 24.47 | 0.93 | 1.61 | 0.49 | 1.36 | 0.13 | 434.75 | 19.89 | 0.25 | 0.03 | 0.24 | 0.08 | 2.55 | 0.26 | 56.66 | 7.84 | 4.85 | 0.19 | 31.38 | 19.09 |
| Very low | 1.56 | 0.26 | 314.94 | 14.55 | 20.08 | 0.77 | 21.65 | 0.52 | 1.75 | 0.55 | 1.37 | 0.14 | 464.20 | 13.85 | 0.22 | 0.03 | 0.27 | 0.02 | 2.46 | 0.35 | 58.91 | 11.94 | 4.95 | 0.32 | 42.50 | 17.88 |

$FCO_2$ = fluxes of $CO_2$ (µmol $CO_2$ $m^{-2}$ $s^{-1}$); Biom = microbial biomass (µg C $g^{-1}$ $d^{-1}$); Ms = soil moisture (%); Ts = 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 $dm^{-3}$); SD = Standard deviation.

The PCA results showed that the first two principal components, PC1 and PC2, explained respectively 50 and 30 % of the variance for all areas and jointly was responsible for more than 80 % of the variance. A similar result was found in a study by Panosso et al. (2011) on $CO_2$ fluxes, where the PCs together explained 70 % of the variability of soil attributes (physical and chemical), with PC1 explaining 52 % and PC2, 18 %. This means that the soil attributes included in the two principal components are sufficient to explain the $CO_2$ flux variations in the soil. This is because the soil attributes used in this study promote the $CO_2$ flux, such as porosity that makes gas transportation in the soil viable (Xu and Qi, 2001; Kosugi et al., 2007; Brito et al., 2009) and the microbiological attribute that produces $CO_2$ by microbial respiration during OM decomposition increasing the $CO_2$ flux (Fang et al., 1998).

**Burned sugarcane**

In the burned area, the attributes contributing most to PC1 by order of influence represented by the correlation coefficient were Bd (-0.99), Biom (-0.97) and Mi (0.94) (Table 3). Bd and Biom influenced the *low* $CO_2$ fluxes (mean 1.48 µmol $CO_2$ $m^{-2}$ $s^{-1}$) (Figure 3A), Bd described 15 % of the variability and Biom in 14 %. The positive and negative correlation could indicate that in places with low bulk density and microbial biomass, there was a greater incidence of *low* $CO_2$ fluxes (Figure 3A), reinforcing the relation between biomass and $CO_2$, in areas where biomass was low, there were more *low* $CO_2$ fluxes. This is because the microorganisms promote the $CO_2$ flux, as cited previously.

Bulk density influences soil porosity in general, increasing Mi, and the prevalence of more Mi than Ma can hinder gas transportation in the soil and the emission to the surface, resulting in more *low* category of $CO_2$ fluxes. This effect can be confirmed by the Mi analysis that described 13 % of the variability in *very low* $CO_2$ fluxes (mean 0.96 µmol $CO_2$ $m^{-2}$ $s^{-1}$) (Figure 3A), because Mi hinders the soil gas circulation through the less rectilinear and more irregular paths, diminishing *high* $CO_2$ fluxes and promoting *very low* $CO_2$ fluxes.

The PC2 showed that the attributes explaining most of the variance were Ma (-0.91), C (0.84) and Ms (-0.78). Ms explained 14 % of the *high* $CO_2$ flux class (2.11 µmol $CO_2$ $m^{-2}$ $s^{-1}$) (Figure 3A). Similar results were found by Ryu et al. (2009) in soils in California (U.S.A.), where Ms explained 14 % of the $CO_2$ flux variability and showed a negative correlation with $CO_2$. Epron et al. (2006) also found a negative correlation between $CO_2$ and Ms in a study on $CO_2$ fluxes from forest soils in French Guiana.

Still, the negative relationship between soil respiration and soil water content contrasted with results that highlighted soil moisture controlling temporal soil respiration (Panosso et al., 2008; Maier et al., 2010; Goutal et al., 2012), but not spatial variation and, in our study, only the spatial variability of $CO_2$ was analyzed, which explained the non-direct effect of soil moisture on the $CO_2$ flux.

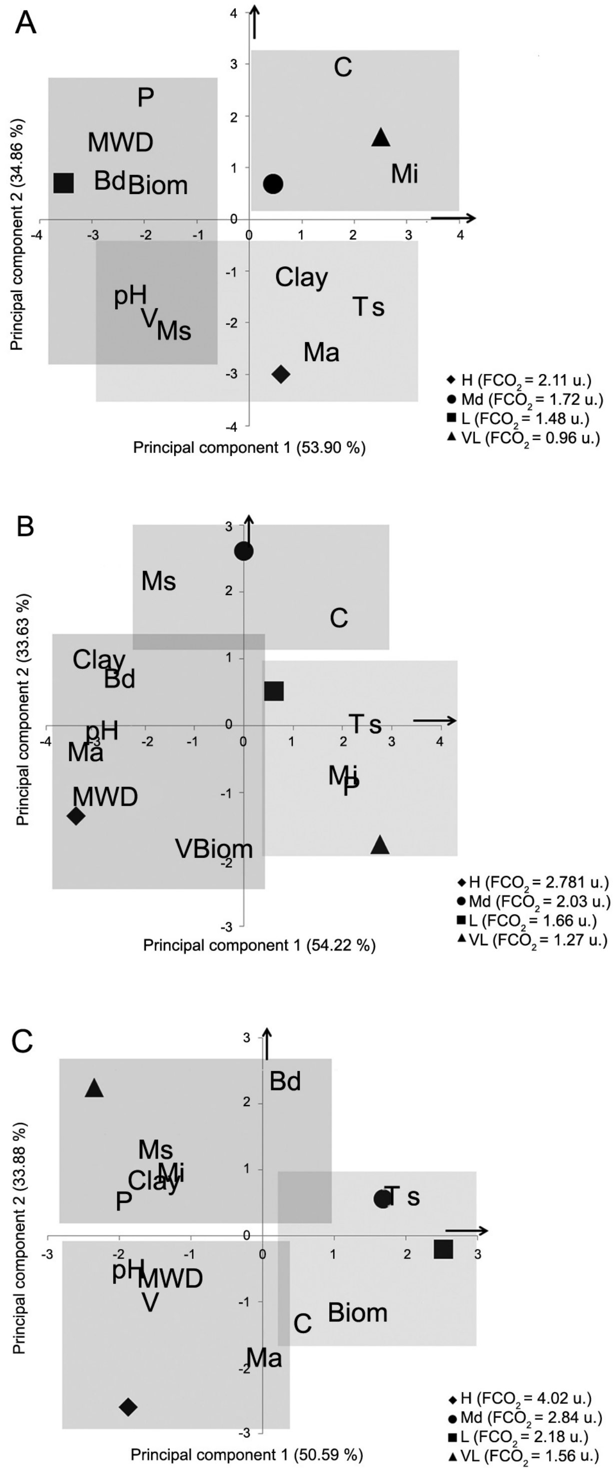


Figure 3 – Two-dimensional representation of the principal components 1 and 2 (biplot) in areas of B (A), G-5 (B) and G-10 (C), with the description of *high* (H), *moderate* (Md), *low* (L) and *very low* (VL) $CO_2$ fluxes. Biom = microbial biomass; Ms = Soil water content; Ts = soil temperature; MWD = mean weight diameter; Bd = bulk density; Ma = macroporosity; Mi = microporosity; C = organic carbon content; V% = base saturation; P = phosphorus.

Table 3 – Variance data of the principal components PC1 and PC2 with correlation and ranking of importance of the microbiological, physical and chemical soil attributes.

| | | PC1 | | PC2 | | |
|---|---|---|---|---|---|---|
| Burned cane (B) | | | | | | |
| Variance | Total | 53 | | 34 | | |
| | Accumulative | 53 | | 88 | | |
| Variable | | Correlation | Ranking | Correlation | Ranking | VTE |
| Microbiology | Biom | -0.97 | 2nd (14 %) | 0.12 | 12th (0.3 %) | 7 % |
| Physical | Ms | -0.54 | 9th (4 %) | -0.78 | 3rd (14 %) | 58 % |
| | Ts | 0.67w | 8th (6 %) | -0.63 | 6th (9 %) | |
| | MWD | -0.85 | 4th (11 %) | 0.37 | 9th (3 %) | |
| | Bd | -0.99 | 1st (15 %) | 0.14 | 11th (0 %) | |
| | Clay | 0.32 | 12th (1 %) | -0.44 | 8th (4 %) | |
| | Ma | 0.41 | 11th (2 %) | -0.91 | 1st (19 %) | |
| | Mi | 0.94 | 3rd (13 %) | 0.19 | 10th (0 %) | |
| Chemical | C | 0.53 | 10th (4 %) | 0.84 | 2nd (16 %) | 33 % |
| | V | -0.69 | 7th (7 %) | -0.71 | 4th (12 %) | |
| | pH | -0.81 | 5th (10 %) | -0.57 | 7th (7 %) | |
| | P | -0.73 | 6th (8 %) | 0.65 | 5th (10 %) | |
| Green cane with 5 years (G-5) | | | | | | |
| Variance | Total | 54 | | 33 | | |
| | Accumulative | 54 | | 87 | | |
| Variable | | Correlation | Ranking | Correlation | Ranking | VTE |
| Microbiology | Biom | -0.11 | 12th (0.2 %) | -0.95 | 2nd (22 %) | 8 % |
| Physical | Ms | -0.45 | 10th (3 %) | 0.86 | 3rd (18 %) | 58 % |
| | Ts | 0.93 | 2nd (13 %) | -0.12 | 12th (0.3 %) | |
| | MWD | -0.74 | 8th (8 %) | -0.6 | 5th (8 %) | |
| | Bd | -0.71 | 9th (7 %) | 0.21 | 10th (1 %) | |
| | Clay | -0.85 | 3rd (11 %) | 0.33 | 8th (2 %) | |
| | Ma | -0.95 | 1st (13 %) | -0.3 | 9th (2 %) | |
| | Mi | 0.81 | 6th (10 %) | -0.45 | 7th (4 %) | |
| Chemical | C | 0.78 | 7th (9 %) | 0.6 | 4th (9 %) | 33 % |
| | V | -0.3 | 11th (1 %) | -0.95 | 1st (22 %) | |
| | pH | -0.82 | 5th (10 %) | -0.16 | 11th (0.6 %) | |
| | P | 0.85 | 4th (11 %) | -0.52 | 6th (6 %) | |
| Green cane with 10 years (G-10) | | | | | | |
| Variance | Total | 50 | | 33 | | |
| | Accumulative | 50 | | 84 | | |
| Variable | | Correlation | Ranking | Correlation | Ranking | VTE |
| Microbiology | Biom | 0.64 | 8th (6 %) | -0.68 | 4th (11 %) | 8 % |
| Physical | Ms | -0.74 | 7th (9 %) | 0.48 | 6th (5 %) | 58 % |
| | Ts | 0.9 | 4th (13 %) | 0.15 | 11th (0.5 %) | |
| | MWD | -0.91 | 3rd (13 %) | -0.42 | 7th (4 %) | |
| | Bd | 0.15 | 11th (0.3 %) | 0.97 | 2nd (22 %) | |
| | Clay | -0.75 | 6th (9 %) | 0.26 | 10th (1 %) | |
| | Ma | 0 | 12th (0.0004 %) | -0.99 | 1st (23 %) | |
| | Mi | -0.64 | 9th (6 %) | 0.32 | 9th (2 %) | |
| Chemical | C | 0.24 | 10th (0.9 %) | -0.76 | 3rd (14 %) | 33 % |
| | V | -0.78 | 5th (10 %) | -0.61 | 5th (9 %) | |
| | pH | -0.93 | 2nd (14 %) | -0.36 | 8th (3 %) | |
| | P | -0.97 | 1st (15 %) | 0.12 | 12th (0.3 %) | |

Biom = microbial biomass; Ms = soil moisture; Ts = temperature of the soil; MWD = mean weight diameter; Bd = bulk density; Ma = macroporosity; Mi = microporosity; C = organic carbon content; V% = base saturation; P = phosphorus content; VTE = total variance explained.

Soil C content showed a positive correlation with PC2 and an opposite trend with Ma for the group *high* $CO_2$ fluxes (Figure 3A), which suggests that in places with high $CO_2$ fluxes, the C trend is decreased, that is, more fluxes and less C storage (Cerri et al., 2007). A similar result was found by Panosso et al. (2012) where the $CO_2$ results showed a positive correlation with PC2 (0.77) and negative with carbon stock (-0.31). Intense OM decomposition tends to consume the C available in the soil with increasing $CO_2$ released by microorganisms. On the other hand, low organic carbon content can be understood as protected and stabilized inside microaggregates (Lenka and Lal, 2013). Moreover, corroborating the results of our study, Fang et al. (1998) detected more $CO_2$ associated with the low C content in pine soils.

**Green sugarcane with 5 years**

For the G-5 treatment, the attributes with greater correlation to PC1 were Ma (-0.95), Ts (0.93), and clay (-0.85) (Table 3). Ma and clay were grouped in the *high* $CO_2$ class (2.78 µmol $CO_2$ $m^{-2}$ $s^{-1}$) (Figure 3B), where the Ma explained 13 % and clay 11 % of variance. Panosso et al. (2011) showed correlation of -0.73 between clay and PC1 in a study of $CO_2$ fluxes, with greater clay in the green than in the burned cane, however, the $CO_2$ showed more significance in PC2, indicating little interaction of clay with $CO_2$.

A possible explanation of negative correlation of clay with PC1 to explain the *high* $CO_2$ flux is that clay promotes a type of carbon protection in the soil, that is, the adsorption of OM with mineral particles (mainly clay minerals and oxides) protects OM from microbial decomposition and prevents C loss as $CO_2$, however, if the clay content is low, as shown in our study, protection is smaller, promoting more *high* $CO_2$ flux situations.

Soil temperature Ts explained 13 % of the variance in *low* $CO_2$ fluxes (mean of 1.66 µmol $CO_2$ $m^{-2}$ $s^{-1}$) for the G-5 treatment. It is justifiable because soil temperature in G-5 was lower than B and G-10 and low temperature can promote low $CO_2$ fluxes due the slow microorganism activity. The great performance of soil microorganisms occurred around 30 °C (Kononova, 1975) and in G-5, soil temperature was 18 °C (Table 2). The correlation between $CO_2$ and Ts was also found in studies of Carbonell-Bojollo et al. (2012), Lenka and Lal (2013), Shrestha et al. (2013) and Song et al. (2013).

In PC2, the attributes that showed higher correlation were V (-0.95), Biom (-0.95) and Ms (0.86). The V and Biom were grouped in the *very low* $CO_2$ flux class (mean 1.27 µmol $CO_2$ $m^{-2}$ $s^{-1}$) (Figure 3B), indicated by the negative correlation coefficient, with places of low V and Biom with more incidences of *very low* $CO_2$ fluxes. This is because low base saturation and soil acidity affected the soil microbial activity resulting in lower $CO_2$ fluxes.

**Green sugarcane with 10 years**

The attributes that mostly contributed to the explanation of PC1 on the G-10 were, in order of influence, P (-0.97), pH (-0.93) and MWD (-0.91) (Table 3). In addition, we observed that pH and MWD influenced the *high* $CO_2$ fluxes group (mean 4.02 µmol $CO_2$ $m^{-2}$ $s^{-1}$) in 14 % and 13 % respectively, with negative correlations with PC1. This indicates that the greater incidence of *high* $CO_2$ fluxes can be explained by the low values of pH and MWD.

The pH values ranged from 4-5 (Table 2), probably due to the more intense OM decomposition than in the other areas due the greater amount of straw that stimulates microbial decomposition and this process may decrease the pH during the nitrification stage. Xu and Qi (2001) showed negative correlation of $CO_2$ emission with the pH in a study on spatial variation of soil $CO_2$ fluxes.

MWD is associated with the physical protection of OM, and soil aggregates play this role by preventing the release of occluded carbon that serves as a source of energy for the microbial biomass. Thus, the negative correlation between MWD with PC1, mainly to explain the *high* $CO_2$ fluxes, helps to understand that lower MWD can promote less C protection and, thus, *high* $CO_2$ fluxes.

Some variation (15 %) of $CO_2$ fluxes within *very low* $CO_2$ (1.56 µmol $CO_2$ $m^{-2}$ $s^{-1}$) was explained by the P content, with a negative correlation with PC1. This indicates that the increased amount of P in the G-10 area influenced the smaller incidence of *very low* fluxes. The P content stimulates the production of the phosphatase enzyme produced by specific phosphate solubilizing microorganisms (Barroso and Nahas, 2006), resulting in greater $CO_2$ by microorganisms during decomposition, thus, explaining the smaller incidence of *very low* $CO_2$ fluxes.

PC2 presented a greater explanation by the attributes Ma (-0.99), Bd (0.97) and C (-0.76). The Ma trend was the same in B and G-5 areas in which *high* $CO_2$ fluxes were explained by Ma (Table 3). Panosso et al. (2012) studied $CO_2$ soil fluxes in sugarcane management and also found significant correlation of PC1 with $CO_2$ (0.77) and with Ma (0.75).

In a study by Leon et al. (2014), the PCA showed that the principal soil attribute responsible for *High* $CO_2$ fluxes season was root biomass. In our study, Ma was always present and explained the significant variance of *high* $CO_2$ flux, despite the negative correlation with PC1 (Figure 3B) and PC2 (Figures 3A, C). Ma explained 19 % in B, 13 % in G-5 and 23 % in G-10 of *high* $CO_2$ fluxes.

Ma has an important relationship with soil $CO_2$ fluxes, as the greater number of macropores enables soil gas circulation (Brito et al., 2009), furthermore, an increased number of Ma enables greater concentrations of soil $O_2$, which stimulates the activity of microbial decomposition and consequent soil $CO_2$ fluxes. In a study by Goutal et al. (2012), changes in soil macroporosity percentages affected plant roots and associated microbial activities. Thus, soil Ma and Mi influenced possible flux trajectories of soil gases, which affected $O_2$ and $CO_2$ fluxes (Brito et al., 2009). According to the Fick's law (Alvenäs and Jansson, 1997), the relations between Ma and $CO_2$ are controlled by several factors including total porosity, soil water content and tortuosity coefficient.

Other soil attributes interpreted in isolation can cause double interpretation, for example, Bd and C were attributes that presented both positive and negative correlations with the principal components (Table 3). A study of Panosso et al. (2011) concluded that the bulk density associated with the humification index relates better than other properties with soil $CO_2$ emission, as this property is the most important to understand the emission variability in the area of burned cane.

In some studies, $CO_2$ and C showed positive correlations (La Scala et al., 2000; Lenka and Lal, 2013; Medeiros et al., 2011) mainly related to the supply of the substrate to microbial activity. Negative correlations (Fang et al., 1998) associated with the limitation of decomposition due to adverse soil and climate conditions have also been observed, although their influence was not always significant (Epron et al., 2004). According to Song et al. (2013), the increase in $CO_2$ fluxes associated with soil carbon is complex and may involve both positive and negative feedbacks. This requires further studies of the $CO_2$ flow and soil carbon dynamics.

## Conclusions

The harvesting of green sugarcane presented higher $CO_2$ total fluxes than the burned sugarcane did. This effect is associated with greater microbial activity in areas with greater plant waste deposition on the soil surface. On the other hand, the $CO_2$ fluxes based on *high-low* criteria showed that macroporosity explained the "*high*" $CO_2$ fluxes, this is because the greater number of macropores improved soil gas circulation and enabled greater concentrations of soil $O_2$, which stimulate the activity of microbial decomposition and consequent soil $CO_2$ fluxes.

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