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RESEARCH ARTICLE

Short-Term Soil CO_2 Emission and Soil Attributes Under Contrasting Sugarcane Cultivars

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Abstract Agriculture is a great emission source of CO_2 into the atmosphere, contributing significantly to the greenhouse effect. Considering the hypothesis that there are differences in soil carbon dynamics due to the distinct physiological and morphological characteristics of sugarcane cultivars, the aim of this study was to characterize the short-term soil CO_2 emission associated with soil attributes in agricultural areas under cultivation of five sugarcane cultivars. The experiment was conducted in an area of high-clay Oxisol (Hapludox, USDA Soil Taxonomy) located at the Cerrado biome, Midwestern region of Brazil. Over the course of 20 days, ten measurements of soil CO_2 emission (FCO_2), soil temperature (Ts), and soil moisture (Ms) were carried out. Subsequently, soil samples were collected at a depth of 0–0.20 m to determine soil physical and chemical attributes. In timescale, FCO_2, Ts, and Ms varied depending on the amount of straw produced by each cultivar. The cultivars RB935608, RB935744, and SP832847 induced a higher soil CO_2 emission since they are associated with controlling factors of the primary CO_2 production process (higher organic matter content and lower C/N ratio in the soil). Thus, strategies to reduce greenhouse gas emissions in agriculture, such as the choice of sugarcane cultivars that provide lower soil CO_2 emissions, are essential to mitigate important environmental issues such as the global warming.

Keywords Soil respiration · Soil attributes · *Saccharum* spp. · Multivariate analysis

Introduction

Human activities have been identified as the main responsible for the emission of greenhouse gases (GHG) such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) into the atmosphere, contributing to increasing the overall average temperature (Lu et al. 2015). Among these gases, CO_2 has contributed the most to the additional greenhouse effect in the last 200 years (IPCC 2007). In this sense, agriculture and its management options have been identified as important emission sources of soil CO_2 into the atmosphere (IPCC 2014).

Brazil is globally important for food security as it is one of the largest producers and exporters of important crops such as sugar and soybean, among many others. This global agricultural prominent position, as well as the fact that 75% of CO_2 emissions come from agricultural activities (Cerri et al. 2013), has contributed to positioning Brazil as the fourth largest GHG emitter (IPCC 2014). Among the agricultural potentials, Brazil is the world's largest producer of sugarcane crop (*Saccharum* spp.), with 646 million tons in 2017 in a cropped area close to 9 million ha (FAOSTAT 2014; CONAB 2017).

The accelerated demand of the sugar-energy industry has driven the development of specific sugarcane cultivars to regional conditions of temperature and soil, which influence crop development and consequently the potential of each cultivar (higher sugar content or higher biomass

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production) (Santiago and Rossetto 2008). Along with this development is the concern about the impacts of CO_2 emissions due to cultural practices and soil management in sugarcane production systems (La Scala et al. 2006; Figueiredo et al. 2010; Panosso et al. 2011).

Agricultural management interferes with the gains and losses of soil organic matter and therefore affects soil CO_2 emissions to the atmosphere (Lal 2009). Moreover, the emitted CO_2 from agricultural soils is the result of interactions between climate and soil physical, chemical, and biological attributes (Carvalho et al. 2010; Panosso et al. 2011; Teixeira et al. 2011, 2013; Silva-Olaya et al. 2013; Bicalho et al. 2014; Zhang et al. 2015). Furthermore, in sugarcane areas, the deposition of crop residues on the soil surface contributes positively with some soil attributes (Razafimbelo et al. 2006; Galdos et al. 2009; Canellas et al. 2010). However, to our knowledge, no studies can be found in the literature comparing soil CO_2 emission under the cultivation of different sugarcane cultivars. In fact, the existing studies are limited to assess soil CO_2 emissions in areas with a single cultivar (Luca et al. 2008; Panosso et al. 2009; Figueiredo et al. 2010; Teixeira et al. 2011; Bicalho et al. 2014; Bahia et al. 2015).

Differences in soil carbon dynamics are the result of distinct physiological and morphological characteristics of each sugarcane cultivar. In this study, we intend to demonstrate that sugarcane cultivars may contribute to the reduction in soil CO_2 emission and to the mitigation of greenhouse gases. Thus, the aim of this study was to characterize the short-term soil CO_2 emission associated with soil attributes in agricultural areas under cultivation of five sugarcane cultivars.

Materials and Methods

Characterization of the Study Area

This study was conducted in Dourados, MS, Brazil, in an area located at the geographical coordinates 22°14′S and 54°49′W and 452 m above sea level, in a high-clay Oxisol (Hapludox, USDA Soil Taxonomy) (152, 104, and 744 g kg^{-1} of sand, silt, and clay, respectively). The area presents a slope of approximately 3%. According to Thornthwaite system, the regional climate is defined as $B_1rB'_4a'$, indicating a mesothermal humid region with a low or no water deficit and a summer evapotranspiration lower than 48% of the annual evapotranspiration. The mean annual temperature ranged from 20 to 22 °C, with the means of the coldest and warmest months ranging from 15 to 19 °C and 23 to 26 °C, respectively. The mean annual precipitation was 1550 mm, concentrated between November and January (Amaral et al. 2000).

Experimental Design

The sugarcane cultivars RB935744, RB72454, RB935608, RB855113, and SP832847 were planted for the first time in the study area on November 28, 2009, in plots next to each other; their characteristics are shown in Table 1 and are recommended for cultivation in the region. The experimental design was a completely randomized design with five treatments (cultivars), with each experimental unit consisting of four sugarcane rows (5 × 4) spaced 1.2 m between rows, totaling 3000 m^2 of planted area. Fertilization was performed by applying 2 t ha^{-1} of an organic compost in the planting furrow, just below the sugarcane stem. Prior to sugarcane planting, the area was cultivated with different green manures, especially black oat (*Avena stringosa*).

Harvesting was performed manually and without burning the sugarcane field in 4 m of the two central rows of each plot, totaling 9.6 m^2, in order to assess the yield of stems and pointers and dry matter (straw). A portable precision balance was used for weighing in the field. Subsequently, the material was dried in a forced ventilation oven at 65 °C until constant weight to determine the dry mass (Table 2).

Soil CO_2 Emission, Soil Temperature, and Soil Moisture Assessments

A grid containing 60 points, represented by PVC collars, was installed in the inter-row of the sugarcane crop and spaced 5 m from each other. Ten measurements were taken over a period of 20 days (September 15, 16, 19, 21, 22, 26, 27, and 30, and October 3 and 4, 2011, which correspond to the Julian days 258, 259, 262, 264, 265, 269, 270, 273, 276, and 277, respectively) from 8:00 to 10:00 h.

Soil CO_2 emission (FCO_2) was recorded using a portable LI-8100 automated soil CO_2 flux system (LI-COR, Lincoln, NE, USA). This system consists of a closed chamber, which is coupled to the PVC collars previously installed at all 60 sampling points. In its measurement mode, this system monitors changes in the CO_2 concentration inside the chamber by means of optical absorption spectroscopy in the infrared spectrum (IRGA, infrared gas analyzer). Simultaneously to the soil CO_2 emission measurements, assessments of soil temperature (Ts) were conducted in the layer of 0–0.20 m using a thermometer (portable thermistor), which is part of the LI-8100 system. Soil moisture (Ms) was assessed at all sampling points by using a TDR system (Hydrosense TM, Campbell Scientific Inc., Logan, UT, USA), which measured the available moisture in the soil (% of volume) at a depth of 0–0.20 m.

Table 1 Agronomic characteristics of the cultivars under study

Cultivar	General characteristics
RB935744	High productivity, fast development, erect growth habit, easy straw removal, medium inter-row closing, late maturing, and medium-thick stem diameter
RB72454	High productivity, fast development, easy straw removal, regular inter-row closing, good stem diameter, good height, and heavy weight
RB935608	High productivity, fast development, medium straw removal, stem with a striated appearance, internodes of medium length and diameter, and leaves with a medium width
RB855113	High productivity, high clump, regular growth rate, medium-late maturing, medium straw removal, erect growth habit, good inter-row closing, and erect, stuffed, and medium diameter of stems
SP832847	High productivity, medium clump, late maturing, medium straw removal, semi-erect growth habit, and the presence of stem lodging

RIDESA (2010); CTC (2013)

Table 2 Yield and straw accumulation on the soil surface for each sugarcane cultivar

Cultivar	Stem[a] (t ha^{-1})	Pointer[a,b]	Straw[c]
RB935744	134.12	41.48	13.37
RB72454	118.67	35.11	12.26
RB935608	137.70	44.15	14.40
RB855113	126.98	39.46	11.30
SP832847	128.97	37.11	12.90

[a] Fresh mass

[b] Green leaves and stem portion not used for sugar production

[c] Dry mass

Analysis of Soil Physical and Chemical Attributes

At the end of field measurements, soil samples were taken at each of the 60 sampling points from a depth of 0–0.20 m in order to determine base saturation (BS), sum of bases (Bases), potential of hydrogen (pH), calcium (Ca), magnesium (Mg), potassium (K), phosphorus (P), cation exchange capacity (CEC), and potential acidity (H + Al), following the methodology proposed by Embrapa (1997). Total organic carbon (TOC) was determined using a total organic carbon analyzer coupled to a Solid Sample Module (Shimadzu Corp., Kyoto, Japan). Soil organic matter (SOM) was obtained by multiplying TOC by 1.724. In addition, the total soil nitrogen analysis was performed by the Kjeldahl method (Embrapa 1997).

Soil physical attributes were determined by collecting undisturbed soil samples using cylinders with an internal volume of 50 cm^3. These samples were taken near the sampled points in the middle of the layer of 0–0.20 m (Embrapa 1997). Soil bulk density (Ds), macroporosity (Macro), microporosity (Micro), and total pore volume (TPV) were determined from these samples. Air-filled pore space (AFPS) was calculated considering the difference between the fraction of porosity filled with water (Ms) and TPV.

Data Processing and Statistical Analysis

The analysis of variance was performed using the completely randomized design and repeated measures in time. Mean comparison was made using Tukey's test at a significance level of 5% probability by using the software SAS (SAS version 9.1, SAS Institute, Cary, NC, USA). The data were also submitted to the multivariate exploratory analyses of principal components and factor analysis. After variable standardization (zero mean and unit variance), the analysis was performed using the software Statistica 7.0 (StatSoft Inc., Tulsa, OK, USA).

Among the different techniques available to extract factors, we used the principal component analysis (PCA), calculated from the correlation matrix between variables (Jeffers 1978). Considering the 21 physical and chemical attributes assessed in this study, only 11 were selected by the factor analysis (factor loadings > 0.50 in absolute value). The Hotelling's T^2 test was performed in order to test the differences among cultivars.

PCA condenses information from a set of original variables into a smaller set composed of new latent variables, preserving the relevant amount of original information. The new variables are the eigenvectors (principal components), generated by linear combinations of the 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 Eq. (1):

$$r_{xj}(pc_h) = \frac{a_{jh}\sqrt{\lambda_h}}{s_j} \tag{1}$$

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

Factor analysis is also a multivariate exploratory technique that allows observing relations among a set of variables. However, when compared to PCA, factor analysis presents more restrictive assumptions and uses only latent dimensions (shared variance), being a theoretically based analysis (Hair et al. 2005).

Among the different available techniques for factor extraction, we used the principal components, calculated from the correlation matrix between variables. The first factor extracted from the matrix is a linear combination of original variables, which represents the maximum of variation contained in the samples. Thus, the first factor is the best summary of linear relationships shown in the data. The second factor is defined as the second best linear combination of variables, 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 a 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 variances, we used the varimax rotation in the factorial matrix, whose ultimate effect provides a simple factorial pattern theoretically more significant since the rotation is carried out exactly to redistribute the variance from the first to the last factors.

The multivariate analysis was performed with scores of the first three 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 extraction, 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 its meaning considering the signal and relative size of loadings as an indication of weight to be assigned to each variable.

Results

Temporal Variability of FCO_2, Ts, and Ms in Soils under Cultivation of Sugarcane Cultivars

The analysis of variance of repeated measures in time is shown in Table 3. FCO_2 did not present significance ($F = 0.41$, $p = 0.9993$) for the interaction between treatments (cultivars) and time (days of measurement). Thus, FCO_2 showed a similar pattern of temporal variability when the cultivars were compared. A similar behavior was observed for the factor days of measurement ($F = 1.74$; $p = 0.0765$). However, a significant difference was observed between the emissions of the cultivars ($F = 32.72$, $p < 0.0001$). The highest average of FCO_2 over the experimental period was observed in the cultivar RB935608 (2.79 µmol m^{-2} s^{-1}), which was 69% higher than the emission observed in the cultivar RB72454, which presented the lowest emission (1.64 µmol m^{-2} s^{-1}).

For Ts and Ms, significant differences were observed for treatment (cultivars), time, and the interaction between both factors (Table 3). Therefore, Ms and Ts did not present the same pattern of temporal variability when the cultivars were compared. However, Ts showed a low variability (CV = 6.27) throughout the period of study. The treatments with the cultivars RB72454 and RB855113 presented lower FCO_2 values (1.65 and 1.92 µmol m^{-2} - s^{-1}, respectively) (Table 3) and lower amounts of straw (12.26 and 11.30 t ha^{-1}, respectively) (Table 2).

The lowest daily average values of Ts were observed in the cultivar RB935744, except for the day 259, and the highest values were observed in the cultivar SP832847, except for the days 259 and 264. Significant effects were observed for the factors cultivar ($F = 75.16$, $p < 0.0001$), time of measurement ($F = 149.34$, $p < 0.0001$), and the interaction between both factors ($F = 10.69$, $p < 0.0001$), indicating that the behavior of Ts varied as a function of time and cultivars, as well as a function of the interaction between them. To verify the existence of a possible relationship between FCO_2 and Ts, a linear correlation analysis was conducted, showing a positive relationship in the cultivar RB935744 ($r = 0.68$, $p < 0.05$). The other cultivars showed no significant effect for this analysis ($p > 0.05$).

On the Julian day 270, all treatments showed higher values of Ms, which may be due to the precipitation that occurred during the experiment. In fact, at the day before (269), a precipitation of 27.8 mm was observed in the afternoon, and between the days 274 and 275, an accumulated precipitation of 8 mm was observed. In the cultivar RB935608, an increase of 68% in Ms was observed after precipitation when comparing the averages of the days 269 (21.08%) and 270 (35.50%). Considering the correlation analysis, a significant effect was observed between FCO_2 and Ms for the cultivars RB935608 ($r = 0.79$, $p < 0.05$) and RB855113 ($r = 0.71$, $p < 0.05$), which showed the largest and smallest amount of straw (Table 2), respectively.

Multivariate Analysis of Variance of Soil Attributes in the Cultivation of Sugarcane Cultivars

Soil attributes selected by principal component analysis (PCA) are shown in Table 4. This selection indicates the existence of a relationship between attributes and groups of soil attributes. It is noteworthy that none of the assessed

Table 3 Slicing of interaction between sugarcane cultivars and days of measurement for soil CO_2 emission (FCO_2), soil temperature (Ts), and soil moisture (Us)

Julian day	FCO_2 (μmol m^{-2} s^{-1})					
	RB935744	RB72454	RB935608	RB855113	SP832847	Mean
258	1.76	1.31	2.34	1.65	1.72	1.90 a
259	2.00	1.42	2.43	1.74	1.99	1.95 a
262	2.06	1.67	2.41	1.69	2.11	2.01 a
264	1.81	1.65	2.66	1.94	1.89	2.07 a
265	1.84	1.66	2.71	1.71	2.12	2.04 a
269	1.72	1.56	2.74	1.79	2.19	1.96 a
270	1.96	1.76	2.83	1.92	2.43	2.17 a
273	2.16	1.72	2.86	1.97	2.64	2.26 a
276	2.44	1.81	3.11	1.92	2.42	2.34 a
277	2.06	1.80	2.89	1.91	2.28	2.12 a
Mean	1.97 B	1.65 C	2.79 A	1.92 BC	2.04 B	

	F	*p*
Cultivar	32.72	<0.0001
Time	1.74	0.0765
Cultivar*time	0.41	0.9993
CV (%)	40.38	

Julian day	Ts (°C)					
	RB935744	RB72454	RB935608	RB855113	SP832847	Mean
258	17.53 Bde	17.83 Bc	18.37 Be	20.39 Aab	21.38 Aab	19.10
259	20.18 Aa	19.66 Bb	19.49 BCd	19.27 BCcd	19.04 Cd	19.53
262	19.93 Bab	19.88 Bb	20.13 ABbc	20.26 ABab	20.48 Abc	20.14
264	19.13 Babcd	19.43 ABb	19.90 Acd	19.70 Abc	19.61 ABcd	19.55
265	18.10 Bcde	18.13 Bc	18.57 ABe	18.68 ABd	18.76 Ad	18.45
269	17.23 Ce	17.94 Bc	18.49 ABe	18.45 Bd	19.05 Ad	18.23
270	17.65 Cde	18.13 BCc	18.57 Be	18.68 ABd	19.22 Ad	18.45
273	20.34 Ca	20.83 BCa	21.13 Ba	21.15 Ba	21.87 Aa	21.06
276	19.57 Babc	19.92 Bb	20.64 Aab	20.52 Aab	20.83 Ab	20.30
277	19.31 Cabc	19.85 BCb	20.33 ABbc	20.11 ABbc	20.58 Abc	20.03
Mean	18.90	19.16	19.53	19.72	20.08	

	F	*p*
Cultivar	75.16	<0.0001
Time	149.34	<0.0001
Cultivar*time	10.69	<0.0001
CV (%)	6.27	

Julian day	Ms (%)					
	RB935744	RB72454	RB935608	RB855113	SP832847	Mean
258	11.17 Aefg	13.00 Aef	7.67 Be	5.67 Be	6.08 Be	8.72
259	8.50 ABg	9.25 Af	7.33 ABe	7.67 ABe	7.25 Be	8.00
262	9.42 Bfg	10.67 Bef	9.83 Bde	9.75 Bde	13.42 Ad	10.62
264	14.08 Bdef	15.08 Bde	12.83 Bcd	14.42 Bcd	20.42 Abc	15.37
265	15.25 Acde	14.42 Ae	18.83 Ac	13.25 Acd	13.42 Ad	14.23
269	24.17 Aab	23.33 Abc	21.08 Ab	17.50 Bbc	22.58 Ab	21.73

Table 3 continued

Julian day	Ms (%)					
	RB935744	RB72454	RB935608	RB855113	SP832847	Mean
270	27.08 Ca	39.75 Aa	35.50 ABa	29.58 BCa	27.92 BCa	31.97
273	18.33 ABcd	19.58 Acd	21.08 BCc	15.00 Cc	16.42 ABCcd	17.08
276	28.08 Aa	25.33 ABb	24.33 ABCb	22.33 BCb	20.25 Cbc	24.07
277	19.58 Abc	20.17 Ac	21.00 Ab	20.75 Ab	19.33 Abc	20.17
Mean	17.07	19.06	17.57	15.59	16.71	
			F			*p*
Cultivar			14.21			<0.0001
Time			248.45			<0.0001
Cultivar*time			5.54			<0.0001
CV (%)			48.33			

Cultivar*time = interaction between treatments and days of measurement

Means followed by the same uppercase letters in the row and lowercase letters in the column do not differ from each other by Tukey's test at 5% probability

physical attributes was selected by PCA. However, FCO_2, Ts, and Ms, cited in the temporal analysis, were selected by this multivariate analysis.

Soil attributes showed significant differences ($p < 0.05$) among cultivars, except for available P content. The cultivars that showed the highest average values for the assessed attributes were RB72454 and RB935608 for Ms (19.06 and 17.57%, respectively), RB935608 for FCO_2 (2.79 μmol m^{-2} s^{-1}) and SOM (29.70 g dm^{-3}), and SP832847 and RB855113 for Ts (20.08 and 19.72 °C, respectively). For Ca and Mg contents, the cultivar RB935608 differed significantly ($p < 0.05$) from RB935744, presenting the highest values for both attributes (Table 4). For H + Al, only the cultivars RB72454 and RB855113 differed significantly from each other.

The highest value of FCO_2 (2.79 μmol m^{-2} s^{-1}) was observed in the cultivar RB935608, which differed significantly from the others ($p < 0.05$). This same behavior was observed for SOM (29.70 g dm^{-3}). In contrast, this cultivar presented one of the lowest values of soil C/N ratio (11.62). Moreover, by means of the Hotelling's T^2 test ($p < 0.0001$), the cultivar RB935608 differed from the others when all the attributes selected by PCA are analyzed together. Under the same conditions, the cultivars SP832847 and RB72454 also differed from each other (Table 5).

Table 6 shows the factors and their variances (factor loadings). Three isolated factors (processes) were identified occurring in the soil. The first factor (Factor 1), which represents 33.1% of total variance, indicates a process associated with soil chemical attributes. The attributes retained in this factor, by order of relevance, are BS (0.96), H + Al (− 0.88), Mg (0.87), Ca (0.85), pH (0.62), and P (0.52) (Table 6). The higher the absolute value of the load factor is, the more important its value in interpreting the factorial matrix (Hair et al. 2005).

The second factor (Factor 2), which represents 25% of the original variance of data, retained, by order of relevance, the attributes FCO_2 (0.93), C/N (− 0.86), and SOM (0.75), which are related to the soil CO_2 production process. FCO_2 and SOM demonstrated a relationship of dependence, being directly associated with their respective factor loadings and showing the same sign (positive). However, these attributes are inversely correlated with soil C/N ratio, which presents a negative sign. The third factor (Factor 3), which represents 13% of the original variance of data, retained the attributes Ms (− 0.79) and Ts (0.77). The variability of these attributes is related to the local climate conditions. Thus, Factor 3 was interpreted as attributes associated with climate.

The analysis of variance of scores retained in Factor 2 (Table 7) indicates that the cultivar RB935608 was the most representative for the variables FCO_2, SOM, and C/N ratio, i.e., the processes related to the emission of CO_2 from soil to the atmosphere are significantly higher in this cultivar when compared to the cultivars RB72454 and RB855113. However, it does not differ significantly from the cultivars SP832847 and RB935744 (Table 7).

Discussion

Effect of Cultivars on the Temporal Variability of FCO_2, Ts, and Ms

In this study, FCO_2 and Ms varied as a function of the assessed cultivars and their values were higher in the

Table 4 Analysis of variance (ANOVA) of soil attributes in the cultivation of sugarcane cultivars selected by PCA

Cultivar	FCO$_2$ (μmol m^{-2} s^{-1})	Ts (°C)	Ms (%)	pH	Ca (mmol$_c$ dm^{-3})	Mg
RB935744	1.97 b	18.90 d	17.07 bc	6.02 b	49.50 c	17.13 c
RB72454	1.65 b	19.16 cd	19.06 a	6.01 b	52.63 bc	18.83 abc
RB935608	2.79 a	19.53 bc	17.57 ab	6.13 ab	60.75 a	21.29 a
RB855113	1.92 b	19.72 ab	15.59 c	6.13 ab	58.29 ab	20.08 ab
SP832847	2.04 b	20.08 a	16.71 bc	6.22 a	56.54 ab	18.00 bc

Cultivar	P mg dm^{-3}	BS %	SOM g dm^{-3}	C/N	H + Al mmol$_c$ dm^{-3}
RB935744	18.47 a	59.62 b	25.74 b	14.28 a	46.93 ab
RB72454	17.69 a	62.07 ab	26.87 b	12.98 ab	47.82 a
RB935608	23.04 a	67.34 a	29.70 a	11.62 b	41.70 ab
RB855113	21.43 a	67.92 a	27.33 b	12.48 ab	39.55 b
SP832847	20.05 a	63.53 ab	27.87 b	12.58 ab	44.69 ab

	Test	Value	*F*	*P*
Cultivar	Hotelling's	0.04590	4.378747	0.000000

N = 60; FCO$_2$ = soil CO$_2$ emission; Ts = soil temperature; Ms = soil moisture; pH = potential of hydrogen; Ca = exchangeable calcium; Mg = exchangeable magnesium; P = available phosphorus; BS = base saturation; SOM = soil organic matter; C/N = carbon to nitrogen ratio; H + Al = potential acidity

Means followed by the same letter do not differ from each other by Tukey's test at 5% probability

Table 5 Multivariate analysis of variance (MANOVA) of sugarcane cultivars as a function of the selected attributes by PCA

Cultivar	RB935744	RB72454	RB935608	RB855113	SP832847
RB935744	–				
RB72454	0.577186^{NS}	–			
RB935608	0.015907*	0.000025*	–		
RB855113	0.736007^{NS}	0.110382^{NS}	0.014285*	–	
SP832847	0.479163^{NS}	0.048299*	0.013246*	0.598640^{NS}	–

	Test	Value	*F*	*p*
Cultivar	Hotelling's	0.460899	2.876768	0.000373

*Significant and ^{NS}not significant by the Hotelling's T^2 test ($p < 0.0001$)

cultivars with higher straw amounts. An opposite behavior was observed for Ts (Tables 2, 3). FCO$_2$ was correlated linearly to Ms in the treatments with lower and higher straw content. For Ts, on the other hand, this correlation was observed only in the treatment with the second highest residual contribution. Different studies estimated that maintaining around 15 t ha^{-1} y^{-1} of sugarcane residues on the soil surface after harvest favor a decrease in temperature and the maintenance of water content in the soil since crop residues provide its thermal insulation (Ussiri and Lal 2009; Resende et al. 2006; Galdos et al. 2009; Vargas et al. 2014).

Ms content has an important role when assessing FCO$_2$ since it controls the processes of production (Epron et al. 2006; Lal 2009; Carbonell-Bojollo et al. 2012), transport (Ball and Smith 1991; Kang et al. 2003), and emission of CO$_2$ from soil to the atmosphere (Linn and Doran 1984; La Scala et al. 2006; Schwartz et al. 2010). In addition, depending on the content of Ms in the soil, these processes may be favored or inhibited because moisture affects microbial activity and gas diffusion (Lal 2001). These effects are mainly due to the interaction of Ms and soil porous space (Ordóñez-Fernández et al. 2008).

Table 6 Correlation coefficient between soil attributes and each factor

Attribute	Factor 1 (33.1%)*	Factor 2 (25%)*	Factor 3 (13%)*
pH	**0.62**	0.05	0.38
Ca	**0.85**	0.14	0.22
Mg	**0.87**	0.11	−0.06
P	**0.52**	0.17	0.07
BS	**0.96**	0.11	0.08
H + Al	**−0.88**	−0.09	−0.04
SOM	0.16	**0.75**	0.24
C/N	−0.08	**−0.86**	−0.12
FCO_2	0.12	**0.93**	0.04
Ts	0.26	0.14	**0.77**
Ms	0.02	−0.26	**−0.79**
Interpretation	Nutritional status of soil	Soil CO_2 production	Attributes associated with climate

Values in bold are the loadings (> 0.5 in absolute value) considered in the factor interpretation

pH = potential of hydrogen; Ca = exchangeable calcium; Mg = exchangeable magnesium; P = available phosphorus; BS = base saturation; H + Al = potential acidity; SOM = soil organic matter; C/N = carbon to nitrogen ratio; FCO_2 = soil CO_2 emission; Ts = soil temperature; Ms = soil moisture

*Value refers to the percentage of variation of the original set of data retained by the factor

Table 7 Analysis of variance of sugarcane cultivars as a function of the attributes retained in Factor 2 (FCO_2, SOM, and C/N ratio)

Cultivar	Means of Factor 2 (FCO_2, SOM and C/N ratio)
RB935744	0.05 ab*
RB72454	−0.63 b
RB935608	0.86 a
RB855113	−0.25 b
SP832847	−0.03 ab

*Means obtained from the scores of Factor 2 followed by the same letter do not differ from each other by Tukey's test at 5% probability

In a study on the temporal and spatial variability of FCO_2 in forest areas, Schwendenmann et al. (2003) observed that soil water content explained the variations of FCO_2 over time. However, these authors found that FCO_2 decreased after a precipitation, whereas, in our study, FCO_2 increased. In this case, soil CO_2 flux was affected by high humidity periods due to the formation of an anaerobic environment in the soil created by the oxygen expulsion related to the heavy precipitation. The positive correlation between FCO_2 and Ms observed in our study indicates that soil water content varied during the experiment within a range in which its increase raised microbial activity, but without limiting soil oxygenation.

Ts and Ms are also variables dependent on climate and that directly affect FCO_2 (Davidson et al. 2000; Teixeira et al. 2010; Silva-Olaya et al. 2013). The effect provided by soil covering in reducing Ts is a controlling factor of FCO_2 since microbial activity is accelerated as soil temperature increases and, consequently, carbon mineralization rate is higher (Ussiri and Lal 2009). Another important factor is that, in addition to quantity, the distribution of crop residues on the soil surface also induces variations in soil surface temperature and moisture (Lou et al. 2011). In this sense, in our study, Ts presented the lowest value under the cultivars with higher straw production (e.g., RB935744). According to Tominaga et al. (2002), a more homogeneous distribution of crop residues on the soil surface may be more important than their amount when measuring variations in soil temperature.

Moreover, Ts undergoes daily and seasonal variations, with marked influence in the surface horizons, i.e., in the layers of greater microbial activity, which makes this variable one of the most important factors in the soil CO_2 emission process. An increase in air and soil temperatures accelerates organic matter decomposition and the activity of microorganisms and roots (Six et al. 2006; Silva-Olaya et al. 2013). In its turn, this acceleration influences FCO_2, which responds linearly to increases in soil temperature (Acreche et al. 2013). Thus, assessing this attribute when characterizing the temporal variability of soil CO_2 flux to the atmosphere is very important.

Interdependent Relationship Between Soil Attributes and Cultivars

The multivariate analysis of factors selected three factors that explained 71.1% of the original variance of data. These results are in accordance with the classification criteria proposed by Sneath and Sokal (1973), wherein the number of factors used in the interpretation should explain at least 70% of the total variance of data. Factor 1, which represented 33.1% of the total variance of data, was correlated with the group of chemical variables (BS, H + Al, Mg, Ca, pH, and P), which are related to soil nutritional status (Table 6). In fact, soil fertility may influence plant nutritional status, affecting its growth and development (Malavolta 2006) and hence the production of crop residues, which ultimately will affect soil respiration. Thus, this phenomenon may be occurred due to the different nutritional requirements of each cultivar.

In addition, although the conducted soil tillage and fertilization were the same for the assessed cultivars, significant differences were observed regarding the soil chemical attributes associated with them. This result may be due to the differentiated nutrient extraction of each cultivar, which may also explain the difference in straw production since the cultivars have distinct physiological and morphological characteristics (Table 1).

The factors are independent and thus orthogonal to each other, i.e., the relationships found in Factor 2 (FCO_2, SOM, and C/N) occur independently of the observed relationships in Factor 1 and Factor 3. The relationship observed in Factor 2 represents the balance between the input and output carbon in the soil and therefore the dynamics of microbial activity, which is regulated by the C/N ratio of straw (Six et al. 2006). The cultivar RB935608, which favored the highest FCO_2, presented the lowest C/N ratio and the highest SOM (Table 4), confirming a direct relationship between FCO_2 and SOM and an inverse relationship with the C/N ratio found in Factor 2 (Table 6). Therefore, when the environment favors SOM decomposition by microorganisms (increased microbial activity due to a high N content in the soil), an increased soil respiration may occur. In addition, the high C/N ratio is an indicator of the lack of soil nitrogen, which is limiting to microbial activity (Dorodnikov et al. 2011).

In order to reduce the emissions by means of soil carbon sequestration in agricultural and forest areas, the decomposition and mineralization of SOM should be minimized. Soil and sugarcane management practices related to high additions of organic material and non-soil disturbance, as observed in the studied areas, provide a greater soil carbon stability (Razafimbelo et al. 2006; Galdos et al. 2009). Management provides an increase in aggregate stability (Roscoe and Buurman 2003), protecting the organic matter inside them against microbial decomposition (Dominy et al. 2002; Fuentes et al. 2006; Graham and Haynes 2006; Six et al. 2006; Canellas et al. 2010), in addition to reducing O_2 availability to oxidative decomposition processes (Robertson and Thorburn 2001; Tominaga et al. 2002).

Ts and Ms were retained in Factor 3, and this result indicates that, under the conditions of this study, these attributes, which are usually associated with climate conditions, represent a phenomenon isolated from the processes of soil CO_2 production (Factor 2) and soil nutritional status (Factor 1). The interaction of attributes retained in Factors 2 and 3 is usually observed between seasons (Ohashi and Gyokusen 2007; Brito et al. 2009), months (Stoyan et al. 2000), and more often after precipitations (La Scala et al., 2000; Panosso et al., 2011; Teixeira et al. 2012; Bicalho et al. 2014), the latter confirming the results observed in our study when FCO_2, Ts, and Us were analyzed in timescale (Table 3).

The cultivars RB935608, RB935744, and SP832847 induced higher values of FCO_2, being representative when Factor 2 was analyzed separately (Table 7). Thus, the cultivars RB72454 and RB855113 are the most indicated for cultivation from an environmental point of view since they have an equivalent yield when compared to the other cultivars (Table 2), but are associated with lower soil CO_2 emissions (Table 7).

The biofuel ethanol, produced by the Brazilian sugarcane industry, has conquered the international market, making Brazil its world's largest exporter, accounting for more than half of the ethanol commercialized in the world (CONAB 2017). For this reason, the demand for ethanol has stimulated the expansion of sugarcane areas. Considering this scenario of rapid expansion of the agricultural sector and a constant concern about environmental impacts responsible for significant GHG emissions (Bayer et al. 2006), governments have discussed ways to reduce them without harming the economic growth of this sector. In this context, strategies that contribute to reducing soil CO_2 emission, such as planting cultivars that induce lower GHG emissions, may assist in mitigating these gases and hence reducing the global warming.

Conclusions

The cultivars RB935608, RB935744, and SP832847 are related to higher soil CO_2 emissions, since they are associated with controlling factors of the primary CO_2 production process (higher organic matter content and lower C/N ratio). In the timescale, soil CO_2 emission varied depending on the contribution of straw of each cultivar.

Other studies are needed aiming at isolating the root effect of the studied cultivars in order to determine the effective plant contribution as an active living organism in the emission process of CO_2 from soil to the atmosphere. Therefore, strategies to reduce GHG emissions in agriculture, such as the choice of sugarcane cultivars that provide lower soil CO_2 emissions, are essential to mitigate the effects of the global warming.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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