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Fractal dimension and anisotropy of soil CO_2 emission in a mechanically harvested sugarcane production area

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ABSTRACT

Soil CO_2 emissions (FCO_2) are spatially dependent, and their spatial structure varies in different directions along the soil surface (anisotropy). This anisotropy, which can result from several pedological factors that are directly related to soil carbon dynamics, is affected by soil management. In this study, the anisotropies of the spatial variability of soil CO_2 emissions and of other soil properties were determined for a sugarcane production area under mechanical harvest, when crop residues are left on soil surface, located in the northeastern part of the state of São Paulo, Brazil. The anisotropic characterization of variables was performed by deriving the fractal dimension (D_F) from experimental semivariograms calculated at angles of 0°, 45°, 90° and 135° from the between crop line direction (0°). The mean FCO_2 was 2.19 μmol m^{-2} s^{-1}, and values were significantly lower in the 0° direction. A principal component analysis was applied to study soil properties and the first principal component was mainly related to soil physical properties and FCO_2. A multiple regression analysis indicated that air-filled pore space (AFPS) was the main factor affecting the spatial variability of FCO_2 in all directions. The AFPS D_F values were significantly lower in the direction in which sugarcane crops were planted, indicating anisotropy of this property and greater homogeneity in this direction. Even after rainfall, there was no change in the structure of spatial variability as expressed by the values of D_F. The results indicate that in sugarcane areas, several factors inherent to soil forming processes and management practices during harvest and seeding were responsible for the observed anisotropy, which affected soil CO_2 emissions.

1. Introduction

According to the IPCC (2007), 60% of the greenhouse effect can be attributed to the increase of atmospheric carbon dioxide (CO_2). Soil CO_2 emissions (FCO_2), which are influenced by soil carbon dynamics, are one of the main components of the planet's carbon cycle. In Brazil, approximately 33.4 ± 3.4 Pg C is stored in the first 30 cm of soil (Bernoux et al., 2002). With an output of 630 million tons and a cropped area of approximately 8 million hectares in 2009, Brazil is the main sugarcane producer in the world (CONAB, 2009). Sugarcane production is mostly concentrated in the central-south region, and with 4.87 million hectares under cultivation, the state of São Paulo is responsible for 60% of production (UNICA, 2010; Rudorff et al., 2010). Approximately 50% of the total production is mechanically harvested and not burned, and it has been estimated that this number will reach 80% in the next 10 years (Galdos et al., 2009). In the state of São Paulo, approximately 90% of sugarcane areas will be mechanically harvested (green management) by 2014. In the green management the mechanical harvesting provides the return of crop residues to the soil surface favoring soil organic matter accumulation and gas emission reduction, when compared to the burned system (Razafimbelo et al., 2006; Cerri et al., 2007). Thus, to understand the ability of green areas to mitigate the greenhouse effect, the spatial and temporal variability of soil CO_2 emissions must be understood.

Soil CO_2 emissions are caused by several processes related to the production, which is related to the soil microbial activity since this determines the consumption of O_2 and liberation of CO_2 into the soil, and transport of CO_2 inside the soil and to atmospheric exchange at the soil surface. Therefore, FCO_2 is dependent on soil characteristics such as soil temperature and moisture (Ryu et al., 2009; Epron et al., 2006), soil organic carbon content (Kemmitt et al., 2008), phosphorus content (Duah-Yentumi et al., 1998) and soil density and porosity, which are related to the oxygen content of the soil and to atmospheric gas exchange (Fang and Moncrief, 1999; Xu and Qi, 2001; Jassal et al., 2004).

Geostatistic tools, which have been used to analyze the spatial variability of chemical and physical soil properties, are useful for

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characterizing the interactions between soil and the environment (Isaaks and Srivastava, 1989). Therefore, it is important to better understand the spatial variability of FCO_2 in agricultural areas and to determine an optimal grid arrangement of sampling points in the field (Martin and Bolstad, 2009).

Characterization of the spatial variability of FCO_2 is partially subjective because the range, which is derived from experimental semivariogram adjustments, must be selected. Previous studies have used different range values for different locations, soil types and vegetation covers (Stoyan et al., 2000; La Scala et al., 2000; Rayment and Jarvis, 2000; Ohashi and Gyokusen, 2007; Kosugi et al., 2007; Konda et al., 2008). This subjectivity can be attributed to the dependence of the experimental semivariogram on grid characteristics, such as the direction and sampling distance used at the experimental site (Burrough, 1981; Palmer, 1988).

In addition to the spatial dependence, soil properties can be anisotropic and spatially variable. Anisotropy occurs because soil properties, including FCO_2, are spatially distributed in a complex network that acts in several directions and at various scales (Trangmar et al., 1985; Martin and Bolstad, 2009). According to La Scala et al. (2009), agricultural soil management causes additional anisotropy and affects soil properties, such as soil carbon, porosity and water content that are directly related to the production of CO_2 and its transport from the soil to the atmosphere.

The fractal geometry of the distribution of soil properties presents challenges for the description of heterogeneity. According to Burrough (1981), the fractal dimension can be used as a tool to characterize the complex autocorrelations in several scales of natural phenomena. Fractal theory enables the quantification and integration of new information on soil physical, chemical and biological phenomena measured at different spatial scales (Perfect and Kay, 1995; Eghball et al., 1999; Pérez et al., 2010).

The fractal dimension (D_F) is capable of detecting the impacts of relief, rain precipitation, vegetation cover and soil management on, for instance, the induced anisotropy of soil properties (Eltz and Norton, 1997; Eghball et al., 1999; Vidal-Vázquez et al., 2005; Usowicz and Lipiec, 2009; Pérez et al., 2010). Vidal-Vázquez et al. (2010) characterized the microrelief fractal dimension of a Latosol subjected to different tillage systems and confirmed a relationship between D_F and certain semivariogram parameters, such as the range value and nugget effect. La Scala et al. (2009) observed a complex anisotropic structure in soil CO_2 emissions and found that the majority of this structure occurred perpendicular to the direction of tillage (the crop line direction). A more thorough understanding of FCO_2 anisotropy in agricultural areas is needed for better estimations, especially in large areas.

This research hypothesized that the soil management and orientation of sugarcane crops caused a spatial anisotropy in soil properties that controlled the spatial variability of FCO_2. The objective of this study was to characterize, by means of a fractal dimension, the anisotropy of FCO_2 and other soil properties in a mechanically harvested sugarcane area.

2. Materials and methods

This study was conducted in a production area with a 38-year history of sugarcane (*Saccharum* spp.) cultivation. The experimental plot was located at São Bento farm in the city of Guariba, São Paulo, Brazil. The geographical coordinates of the site are 21°24′S and 48°09′W, and the elevation is 550 m above sea level. The soil is classified as a Eutroferric Red Latosol (Haplustox, USDA Soil Taxonomy), and the slope was determined to be 3%. The regional climate is classified as $B_2rB'4a'$ by Thornthwaite system (Rolim et al., 2007), indicating a mesothermal region with rainy summers and dry winters. The mean precipitation is approximately 1425 mm and is concentrated between October and March. The mean annual temperature over the last 30 years was 22.2 °C.

The study area was mechanically harvested for 8 years prior to the study, and approximately 12 t ha^{-1} of crop residues remained on the soil surface each year. Crops were harvested on September 1st, 2008 (day 245). The sugarcane variety used was CTC-6. To characterize spatial variability in different directions, an 89-point 50 m × 50 m grid with a minimum separation distance of 0.5 m was installed (Fig. 1). The points of the grid were oriented in different directions, which were: 0° with points lined up between two crop lines, 90° was perpendicular to the crop line; and 45° and 135° were the directions of tillage used for 6 years to eliminate ratoon crops.

To measure FCO_2, two portable LiCor (LI-8100) systems were used at the beginning of crop growth and at 54 days after planting. The LI-8100 system monitors changes in the CO_2 concentration inside a closed chamber using optical absorption spectroscopy in

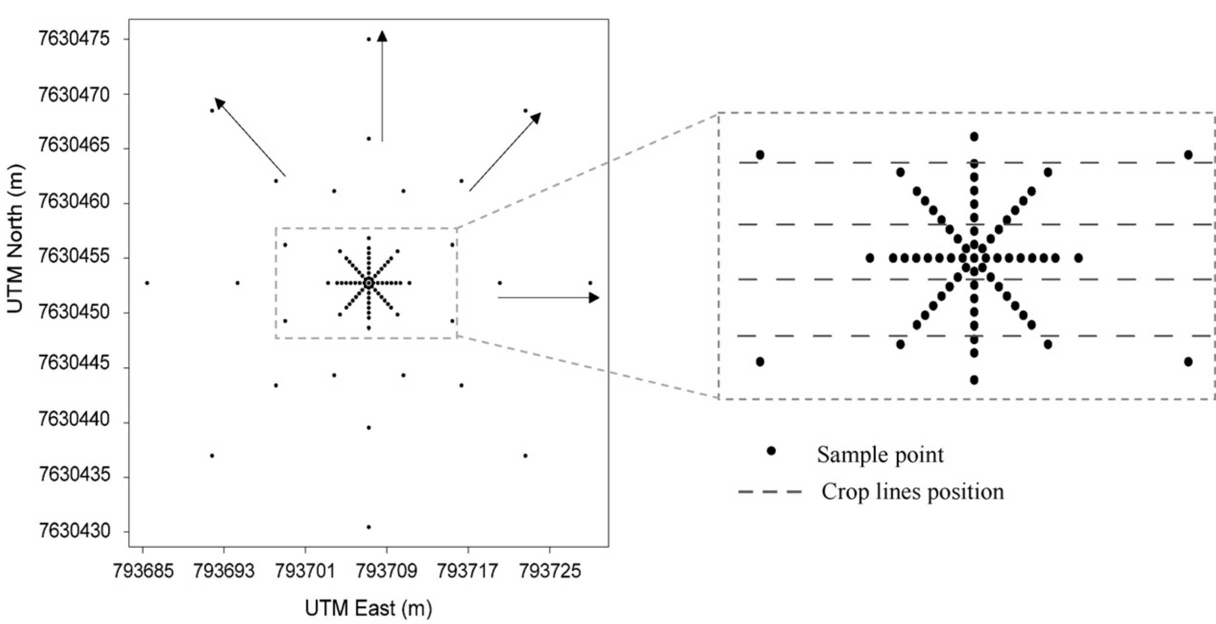

Fig. 1. The study area (50 m × 50 m) with 89 points and all directions with crop lines position on the field.

the infrared spectrum. The chamber is a closed system with an internal volume of 854.2 cm^3 and a circular soil contact area of 83.7 cm^2. The chamber was coupled to a soil PVC collar that had been installed previously at all 89 sample points. Once the chamber was closed, approximately 1.5 min were required for FCO_2 measurements at each point.

To measure soil temperature (T_s), a portable sensor from the LI-8100 system was used. The 20-cm probe (thermistor based) was inserted 5 cm into the soil near the PVC soil collars. Soil moisture in % of volume (M_s) was measured by a time domain reflectometry (TDR) system (Hydrosense TM, Campbell Scientific, Australia). In the TDR system, two 12-cm probes are inserted into the soil. A high frequency electromagnetic energy is generated by the probe body to polarize soil water molecules to the extent needed to measure the dielectric permittivity. The travel time of electromagnetic energy along a waveguide (probes) is dependent on the dielectric permittivity. The high frequency signals are transformed to a square wave output with a frequency proportional to the soil moisture, therefore, the measurement reflects the average water content over the length of the probes. Moisture measurements were also recorded near the soil collars. Measurements of FCO_2, T_s and U_s at all grid points were recorded on Julian days 299, 301, 302, 308, 313 and 322 in 2008. On days 301, 302, 308 and 322, measurements were taken in the mornings, and on days 299, 301, 302 and 313, measurements were taken in the afternoons.

After all FCO_2 measurements had been recorded, soil samples from a depth of 0–10 cm were taken from all 89 grid points. Samples were dried and sieved through a 2-mm mesh prior to further analyses. These analyses included soil organic matter content (SOM), available phosphorus (P), K, Ca, Mg, and H + Al content (Raij et al., 1987), which enabled the calculation of the sum of bases (Bases) and cation exchange capacity (CEC).

After sieving for sand and adjusting the pH to 10–11 with 1 M NaOH, the particle size distribution (sand, silt, and clay) was determined by the pipette method. The soil carbon stock (Cstock, 0–25 cm) was calculated with the following equation (Bayer et al., 2000): Cstock = (OC × D_s × E)/10; where Cstock is the soil carbon stock (Mg ha^{-1}); OC is the organic carbon content (g kg^{-1} = SOM/1.724); D_s is the bulk soil density (kg dm^{-3}); and E is the depth of the soil layer (10 cm).

The soil bulk density (D_s) was determined for non-deformed samples collected in cylinders with an average internal diameter of 5.0 cm and a height of 4.0 cm (EMBRAPA, 1997). To determine the total pore volume (TPV, macropores and micropores), the undisturbed soil samples were saturated for 48 h in the pan with water up to two thirds the height of the ring. After the saturation period, the samples were drained in the potential equal to −0.006 MPa using a tension table (EMBRAPA, 1997). The air-filled pore space (AFPS in % of volume) fraction was calculated as the difference between the total pore volume (TPV in % of volume) and the soil moisture (M_s) defined previously.The spatial dependence analysis was conducted with an experimental semivariogram (Webster and Oliver, 1990). For a given separation distance h, the semivariance estimation was determined by the following expression:

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \quad (1)$$

where $\hat{\gamma}(h)$ is the semivariance at a separation distance of h; N is the number of pairs separated by h; $Z(x_i)$ is the value of variable Z at point x_i; and $Z(x_i + h)$ is the value of variable Z at point $x_i + h$. The semivariograms of all properties were calculated for four directions: 0°, the direction of the between crop lines; 90° perpendicular to the crop lines; and 45° and 135°, the directions of soil tillage. The semivariograms were calculated with an angle tolerance of ±45°. Prior to the semivariogram analysis, trends, or non-stationarity, were removed from the data by a surface adjustment in the x and y coordinates of the function.

The fractal surface structure can be described by the following power law relation:

$$|z(x) - z(x+h)| \propto h^H \quad (2)$$

where z is the property value; x is the spatial location; h is the separation distance; and H is the fractal codimension or Hölder exponent. If $0 < H \leq 1$, the fractal codimension is defined as:

$$H = d - D_F \quad (3)$$

where D_F is the fractal dimension, and d is the Euclidian dimension of the system in which the fractal dimension is described, with values of 1, 2 and 3 for lines, areas and volumes, respectively. Hence, for properties distributed in the soil, the fractal dimension is represented by D_F = 3 − H. Comparing Eqs. (1) and (2), a property with a fractal dimension in a certain scale follows the expression:

$$\hat{\gamma}(h) \propto h^{2H} \quad (4a)$$

or,

$$\log[\hat{\gamma}(h)] \propto 2H \log[h] \quad (4b)$$

Eq. (4b) indicates that the slope of the logarithm of the experimental variogram is 2H. Therefore, H is obtained by a regression analysis equation (Perfect and Kay, 1995):

$$H = \lim_{h \to 0} \frac{\log[\hat{\gamma}(h)]}{2 \log[h]} \quad (5)$$

If H = 0, D_F = 3, and there is no spatial variability structure (nugget effect) and no relation between the spatial variation of the property of interest and h, the distance between points. When $0 < H < 3$, the fractal dimension assumes values that characterize the presence of a spatial variability structure, and a well-defined dependence of the property varies in space or with h (Palmer, 1988).

Initial data analysis was conducted in order to assess the influence of sugarcane root respiration on soil CO_2 emission by analyzing the difference or similarity of FCO_2 from points located between crop line and points located near to crop line (Fig. 1). The one-way analysis of variance (ANOVA) was performed to verify differences in the mean values of the physical and chemical soil properties and the soil CO_2 emissions at each grid point. The normality of errors and the homogeneity of variance were also tested.

The multivariate structure of the initial dataset was analyzed by a principal components analysis (PCA). PCA condenses relevant information into a smaller set of orthogonal variables, referred to as eigenvectors, that are generated by a linear combination of the original variables. The first principal component extracted from the covariance matrix is a linear combination of the original variables, and it accounts for as much of the variation in the samples as possible. The second component is the second linear function of the original variables, and it accounts for the majority of the remaining variability. The remaining components are similarly defined. The factors are independent of one another, have no units and are standardized variables (i.e., they have a normal distribution, a mean of 0, and a variance of 1). The coefficients of the linear functions defining the factors are used to interpret their meaning. The sign and relative size of the coefficients are indications of the weights to be used for each variable. The effect of direction on the principal components was tested with an analysis of variance and the scores of each principal component. Differences between the levels of the different directions were tested with the Tukey multicomparison test of means. A bidimensional representation, known as a biplot, was created for the principle components. This enabled visualization of the structure of the soil properties and explained the maximum variability of the entire set of soil properties studied. The first three principal components, PC1, PC2 and PC3, were considered, and their eigenvalues were greater than unity (Kaiser, 1958).

A multiple regression analysis was conducted for the dataset and for each direction (0°, 45°, 90° and 135°) with a stepwise variable selection method to better understand the spatial dependence of FCO_2. The stepwise method was applied in each sugarcane management system in different variable subsets. The level of significance for the *F*-test, which is used to judge a variable's applicability in an existing model, was $P = 0.10$. Statistical analyses, including descriptive statistics, and linear and multiple regressions, were performed using SAS (SAS version 9, SAS Institute, Cary, NC, USA). Principal component analysis was conducted using version 7.0 of STATISTICA (StatSoft. Inc., Tulsa, OK, USA). Spatial variability and the fractal dimension were determined using a program developed by one of the authors (Vivas-Miranda, 2000).

3. Results and discussion

3.1. Spatial–temporal characterization of soil CO_2 emission

No significant differences (Student's *t* test; $P > 0.05$) were observed on the means of FCO_2 for all studied days in points between and near to crop lines. Under green management, usually, root mass of sugarcane plant is redistributed towards the 0–10 cm layer between crop lines, resulting in greater rhizodeposition of C in this zone that could contribute to microbial activity and other properties such like organic matter content and aggregate stability (Graham and Haynes, 2006). Additionally, Otto et al. (2011) characterizing the distribution of the sugarcane root system after three consecutive years of mechanically harvest in a Typic Kandiudox in Jaboticabal, SP, Brazil (21°19′S and 48°19′W), at the same region of our experimental site, conclude that sugarcane root density decreases exponentially with depth and distance from plants, on the inter-row. Our results could be related to those facts resulting in no significant differences observed on means when between and near to crop line emissions are compared. Table 1 presents the mean FCO_2, T_s and M_s values from the study. The FCO_2 values were similar to those found in previous studies of soils cultivated in sugarcane (Panosso et al., 2009; Brito et al., 2009). The highest mean values of 2.68 μmol m^{-2} s^{-1} (day 313) and 2.33 μmol m^{-2} s^{-1} (day 322) were registered after precipitation events of 34 mm and 32 mm, respectively. These values represented an increase of 26% compared with the mean FCO_2 values before the precipitation events. Several authors have reported a relationship between FCO_2 and soil moisture and, consequently, between FCO_2 and precipitation events (Schwendenmann et al., 2003; Epron et al., 2004; Kosugi et al., 2007). La Scala et al. (2000) observed an increase of 63% in the mean FCO_2 values after a 14 mm precipitation event on a bare Oxisol. Panosso et al. (2009) observed smaller FCO_2 increases following precipitation events for mechanically harvested sugarcane areas than for areas harvested with burning. These smaller increases were likely due to the large amount of crop residues on the soil surface in the mechanically harvested area.

The diurnal FCO_2 variability was analyzed for days 301 and 302 by comparing the mean morning and afternoon values. For day 301, no significant differences were observed between the mean morning and afternoon values of FCO_2, T_s and U_s (Student's *t* test, $P < 0.05$, Table 1). In contrast, for day 302, the mean morning and afternoon FCO_2 values were 1.90 μmol m^{-2} s^{-1} and 2.15 μmol m^{-2} s^{-1}, respectively. This difference between days 301 and 302 could be explained by the increased microbial activity on day 302, as a result of higher temperatures than day 301. Despite the presence of crop residues on the soil surface, the significant increase in T_s increased the evapotranspiration rate of the crop and significantly reduced M_s. As the moisture in the soil decreased, an increasing volume of pore space was occupied by air, which increased the oxygen level in the soil, the microbial activity, and the atmospheric CO_2 exchange rate (Fang and Moncrief, 1999; Jassal et al., 2004).

Table 1
Descriptive statistics of soil CO_2 emissions (μmol m^{-2} s^{-1}), soil temperature (°C) and soil moisture (% volume). M and A indicate the morning and afternoon periods, respectively.

Days	Soil CO_2 emission		Soil temperature		Soil moisture	
	Mean	CV	Mean	CV	Mean	CV
299A	2.27	38.8	25.95	4.1	30.85	35.09
301M	2.08	36.3	24.78	5.0	23.93	17.58
301A	2.01	37.9	26.76	4.2	26.36	20.78
302M	1.90	32.9	24.77	4.5	24.49	25.76
302A	2.15	37.6	27.12	2.8	21.34	19.58
308M	2.12	42.2	24.38	4.0	33.93	36.45
313A	2.68	48.9	26.66	2.6	32.60	11.26
322M	2.33	44.5	27.46	14.1	28.61	23.47

$N = 89$. CV, coefficient of variation (%).

The coefficient of variation (CV) of FCO_2 was between 32.9% and 48.9% on the morning of day 302 and the afternoon of day 313, respectively (Table 1). The results are consistent with other published (Dasselaar et al., 1998; La Scala et al., 2000; Epron et al., 2004; Tedeschi et al., 2006; Konda et al., 2008; Panosso et al., 2009). Herbst et al. (2009) studied the spatio-temporal variability of bare soil respiration in agricultural areas and recorded CV values of approximately 33% and a relatively heterogeneous soil respiration structure at smaller scales. The CV values of FCO_2 are a first indicator of spatial variability; however, according to Fang et al. (1998), these values are insufficient for the comparison of CO_2 emissions from different studies because knowledge on specific sampling methods is lacking. This inadequacy justifies the use of geostatistics.

3.2. Anisotropy of soil CO_2 emission and soil properties

For the initial anisotropy characterization of FCO_2 and the other soil properties a variance analysis with unique factor for the grid direction was performed. Mean value differences were significant for some properties based on the Tukey test at a 5% probability level (Table 2). Smaller FCO_2 values were observed in the 0° direction, except on the afternoons of days 301 and 302 when no significant differences were observed between mean FCO_2 values in different grid directions. The mean value of emissions in the 0° direction was 1.72 μmol m^{-2} s^{-1}, which was 29% smaller than the mean values in the 45° and 135° directions (2.42 μmol m^{-2} s^{-1}). Even after precipitation events, emissions in the 0° direction were low. The mean values of other soil properties, including M_s, D_s, TPV, AFPS, Clay, Silt, pH, Cstock and CEC, were also significantly different in different directions. However, no significant differences were observed for T_s, Sand, SOM and Bases. The similar mean T_s values in different directions could be attributed to the presence of crop residues on the soil surface, which blocked direct solar incidence. Several studies have reported increases in soil organic matter in sugarcane production areas following conversion from burning to green or mechanical harvests (Razafimbelo et al., 2006; Galdos et al., 2009). These increases could be attributed to the presence of large amounts of crop residues on the soil surface. The lower FCO_2 values in the direction of the crop line were attributed to the lower AFPS values in this direction compared with the

Table 2
Means of the soil CO_2 emissions and other soil properties and the respective coefficient of variation (CV) values for the different directions.

Properties	0°		45°		90°		135°	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV
FCO_2 299A ($\mu mol\,m^{-2}\,s^{-1}$)	1.85 b	24.8	2.43 ab	40.1	2.31 ab	26.5	2.64 a	47.0
FCO_2 301M ($\mu mol\,m^{-2}\,s^{-1}$)	1.67 b	37.2	2.18 ab	34.4	2.23 ab	35.4	2.31 a	34.0
F CO2 301A ($\mu mol\,m^{-2}\,s^{-1}$)	1.70 a	35.0	2.00 a	49.0	2.15 a	27.0	2.32 a	35.4
FCO_2 302M ($\mu mol\,m^{-2}\,s^{-1}$)	1.55 b	29.2	2.09 a	37.2	1.96 ab	26.3	2.04 ab	32.6
FCO_2 302A ($\mu mol\,m^{-2}\,s^{-1}$)	1.87 a	26.4	2.34 a	42.9	2.35 a	41.5	2.16 a	32.3
FCO_2 308M ($\mu mol\,m^{-2}\,s^{-1}$)	1.44 b	42.6	2.47 a	44.9	2.19 a	29.9	2.39 a	36.6
FCO_2 313A ($\mu mol\,m^{-2}\,s^{-1}$)	2.01 b	44.9	3.34 a	57.8	2.66 ab	34.6	2.84 ab	39.9
FCO_2 322M ($\mu mol\,m^{-2}\,s^{-1}$)	1.63 b	43.3	2.53 a	50.9	2.50 a	32.1	2.68 a	40.4
FCO_2 ($\mu mol\,m^{-2}\,s^{-1}$)	1.72 b	32.1	2.42 a	41.1	2.29 ab	24.4	2.42 a	35.2
T_s (°C)	26.24 a	1.6	25.78 a	1.6	25.96 a	2.8	25.96 a	2.4
M_s (%)	31.07 a	21.7	26.68 b	11.1	27.07 b	9.6	26.74 b	14.4
AFPS (%)	9.34 b	68.5	16.75 a	27.2	16.84 a	21.5	17.03 a	29.2
D_s ($g\,cm^{-3}$)	1.22 a	2.7	1.15 b	6.4	1.15 b	4.9	1.15 b	5.8
TPV (%)	40.40 b	2.4	43.43 a	5.2	43.91 a	4.8	43.77 a	4.4
Macro	4.49 b	41.2	6.76 ab	38.3	8.38 a	42.2	6.85 ab	38.4
Sand ($g\,kg^{-1}$)	141.81 a	2.4	142.00 a	3.2	141.55 a	1.9	142.60 a	2.2
Silt ($g\,kg^{-1}$)	244.69 bc	3.3	256.10 ab	7.5	267.60 a	4.3	239.33 c	6.8
Clay ($g\,kg^{-1}$)	613.50 ab	1.2	601.90 bc	3.0	590.85 c	2.2	618.08 a	2.8
pH	4.5 b	6.6	4.6 ab	3.9	4.6 ab	4.1	4.7 a	5.3
SOM ($g\,dm^{-3}$)	24.90 a	8.6	23.50 a	10.0	23.85 a	8.8	23.65 a	8.4
Cstock ($Mg\,ha^{-1}$)	860.16 a	7.7	769.95 b	9.1	774.57 b	7.3	770.86 b	8.3
P ($mg\,dm^{-3}$)	17.76 a	9.8	17.25 a	39.6	20.05 a	61.4	16.20 a	27.2
Bases ($mmol_c\,dm^{-3}$)	43.34 a	25.2	44.47 a	16.1	44.77 a	17.0	45.15 a	27.9
CEC ($mmol_c\,dm^{-3}$)	106.34 a	7.9	102.37 a	5.3	106.87 a	11.2	97.95 a	7.6
V (%)	40.83 a	23.4	43.47 a	15.5	42.09 a	16.6	46.04 a	27.1

Means followed by the same letters in rows are equal (Tukey; $P < 0.05$). $N = 89$; FCO_2, soil CO_2 emission; T_s, soil temperature; M_s, soil moisture; AFPS, air-filled pore space; D_s, soil bulk density; TPV, total pore volume; Macro, macroporosity; Sand, sand content; Silt, silt content; Clay, clay content; SOM, soil organic matter; Cstock, carbon stock; P, available phosphorous; Bases, sum of bases; CEC, cation exchange capacity; and V, base saturation.

others. These lower values coincided with the higher soil moisture values in this direction, which decreased gas diffusion.

Table 3 presents the results of the principal component and variance analyses and the multicomparison tests. In this study, PC1, PC2, and PC3 explained 36.6%, 17.7%, and 12.5% of the total variability, respectively, for a total of 66.8%. PC1 was positively correlated with the group of soil physical properties (Macro, TPV and AFPS) and with CO_2 transport within the soil (Jassal et al., 2004; Fang and Moncrief, 1999). The analysis of variance of the PC1 scores showed that direction was a significant factor ($F = 15.39$; $P < 0.0001$), indicating that the relationships between the variables with larger differences in PC1 were not the same in all grid directions. The multiple comparison analysis supported the significant differences ($P < 0.05$) of the variable relationships in the 0° direction compared with the other directions. Similar results were observed for principal components PC2 and PC3. The soil carbon stock (Cstock) and the CEC, both chemical soil properties, were negatively correlated with PC2, while the clay content was positively correlated this component. The analysis of variance of the PC2 scores indicated that the relationships between soil properties (variables) were different in different directions ($F = 3.22$; $P = 0.0273$) and significantly different in the 0° (direction of the crop line) and 135° (tillage direction) directions. Soil pH was negatively correlated with PC3, and significant differences were observed between scores from the 0° and 135° directions ($F = 4.61$; $P = 0.0051$). These results suggest that management practices could significantly change the spatial distribution of soil physical properties, including FCO_2, in mechanically harvested sugarcane production areas.

As shown in Fig. 2, the bidimensional representation of the first two principal components, which explained 54.3% of the total variability in the soil properties, shows a clear difference between samples taken from the 0° direction and samples taken from the other directions. The variables FCO_2, AFPS, TPV and Macro, located on the right side of PC1 (positive correlation), were relatively insignificant in the 0° direction. The soil properties CEC, Cstock and Clay were the most discriminatory in PC2, while soil pH (0.83) was the only discriminatory property in PC3. Scott-Denton et al. (2003) studied the spatial variability of soil respiration in conifer forests in Colorado, USA, and they used principal component analysis to identify 6 independent components that explained 74% of the total variance; the first principal component was mainly associated

Table 3
Correlation coefficients between soil properties and each of the principal components (PC1–PC3), analysis of variance and the multicomparison test applied to the scores of the principal components.

Principal components	PC1	PC2	PC3
Eigenvalues	3.3	1.6	1.1
Explained variance (%)	36.6	17.7	12.5
Correlations			
Macro	**0.75**	−0.16	0.28
TPV	**0.84**	−0.01	0.35
Clay	−0.42	**0.62**	0.37
pH	0.37	0.05	**−0.83**
CEC	−0.15	**−0.79**	0.24
Cstock	−0.31	**−0.72**	−0.10
FCO_2	**0.77**	−0.10	0.09
T_s	**−0.50**	−0.12	0.12
AFPS	**0.88**	0.08	−0.05
Interpretation	$FCO_2 + T_s$ + soil physical properties	Soil chemical properties and Clay	Soil pH
ANOVA			
F	15.39	3.22	4.61
P	<0.0001	0.0273	0.0051
Means comparison			
0°	a	a	b
45°	b	ab	ab
90°	b	ab	ab
135°	b	b	a

Correlations in bold were used for interpretation (>0.50). Values followed by the same letters in columns are not significant at the 0.05 level. $N = 89$; FCO_2, soil CO_2 emission; T_s, soil temperature; AFPS, air-filled pore space; TPV, total pore volume; Macro, macroporosity; Clay, clay content; SOM, soil organic matter; Cstock, carbon stock; and CEC, cation exchange capacity.

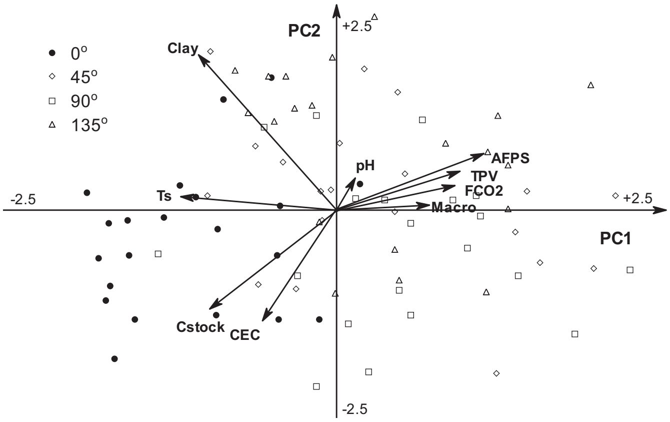

Fig. 2. Biplot of the first two principal components, PC1 and PC2, from the principal component analysis for all soil samples. The variables were soil CO_2 emissions (FCO_2), soil temperature (T_s), macroporosity (Macro), total pore volume (TPV), air-filled pore space (AFPS), carbon stock (Cstock), cation exchange capacity (CEC), and clay content (Clay).

with variables related to soil carbon. In our study, the first principal component was mainly related to soil physical properties, especially the AFPS, a measure of the pore volume not filled with water.

Table 4 presents FCO_2 fractal dimension values derived from the slope of the experimental semivariograms ($\log(\gamma) \times \log(h)$) at a scale (range/separation distance) of 5/0.5 m. At this scale, D_F values were significant ($D_F < 3$, $P < 0.05$) for most directions. Exceptions included the 135° direction in the morning of day 302 and the 90° direction in the morning of day 308. The D_F values observed (Tukey text, $P < 0.01$) in the 0° and 45° directions ($D_F = 2.73$) were significantly smaller than the values recorded in the 90° and 135° directions (2.83 and 2.89, respectively). These D_F values are similar to those observed by La Scala et al. (2009), who studied FCO_2 in agricultural areas and reported D_F values that were less than 3.0 in the direction perpendicular to the soybean crop line. The variability structure, expressed by the D_F values, was steady when precipitation events did not cause different D_F values. This finding is different from that of La Scala et al. (2000), who used semivariograms to show changes in the spatial variability of FCO_2 after precipitation. Temporal changes in the FCO_2 D_F values could have been related to changes in the pattern of spatial variability for this property. These pattern changes have been associated with changes in soil temperature and moisture (Epron et al., 2006). The estimated D_F values of many natural phenomena are unsteady in relation to the scale, location and orientation of sampling points (Abedini and Shaghaghian, 2009). In a recent study conducted on a bare soil, Herbst et al. (2009) observed a range of soil respiration values of approximately 2.7 m, indicating a relatively homogeneous variability structure at this scale and the superiority of a denser sampling arrangement for field characterization of soil respiration. Hence, compared with the results of La Scala et al. (2009), the different D_F values in different grid directions could be attributed to the larger number of points and the smaller separation distances.

Table 4
Fractal dimension (D_F) values of soil CO_2 emissions derived from empirical semivariograms in different directions at a scale (h/a) of 0.5/5 m for all study days.

Direction (°)	Days							
	299T	301M	301T	302M	302T	308M	313T	322M
0	2.70	2.85	2.75	2.60	2.76	2.74	2.76	2.69
45	2.66	2.87	2.78	2.81	2.75	2.75	2.50	2.72
90	2.77	2.95	2.82	2.81	2.77	<u>2.96</u>	2.75	2.80
135	2.87	2.91	2.91	<u>3.00</u>	2.89	2.83	2.89	2.78

Underlined fractal dimension values were not significant ($D_F > 3$).

Graphs of the FCO_2 fractal dimension (±standard error) derived for different scales (Fig. 3a) indicate the scales at which this property can be considered homogeneous (Palmer, 1988). The D_F values of FCO_2 (Fig. 3) varied from 2.5 in the 0° direction (at a scale of 0.5/5 m) to 3.1 in the 135° direction (at a larger scale of 5/50 m). Despite the tendency of D_F to increase with scale, distinct behaviors were observed for the different directions. At scales smaller than 10 m, all directions had D_F values that were significantly smaller than 3.0; as the scale approached 10 m, the D_F values were closer to 3.0. Fractal dimension values greater than 3.0 are associated with smaller angles of the logarithm of semivariance as a function of the logarithm of distance or with a non-existent spatial dependence. The same trends were not observed in the 0° direction for which increases of D_F with scale were not as pronounced and a D_F value near 3.0 was observed at 20 m. This observation indicated strong anisotropy in the spatial variability structure of FCO_2, which could not be characterized by a unique fractal dimension value for different scales or directions. Vidal-Vázquez et al. (2005) used fractals to characterize the anisotropy and heterogeneity of the microtopology of agricultural soils and reported that the anisotropy was due to processes related to the formation and management of soils, such as the type of tillage and the direction and slope of the soil. Fig. 3b and c shows D_F, AFPS and Clay values for different directions and scales. Certain soil properties, including AFPS (Fig. 3b), for which the same rates of change of D_F with distance in the 0° direction were identified behaved similarly to FCO_2. The D_F values of other soil properties, such as Clay (Fig. 3c), behaved differently at different scales. At distances of approximately 20 m in the 0° direction, the D_F values of properties such as FCO_2 and AFPS were not significantly smaller than 3.0. Souza et al. (2003) studied the influence of relief on the spatial distribution of chemical soil properties (pH, P, K, Ca, Mg, Bases, CEC and SOM) and texture (sand, silt and clay) in a Latosol and reported anisotropy, mainly related to the landscape form and management practices, for all studied properties. Usowicz and Lipiec (2009) studied the fractal dimension of soil resistance to penetration in areas compacted by intense tractor use and concluded that the fractal dimension was an indicator of the mechanized traffic in an area. Hence, the anisotropy in the spatial variability structure of FCO_2, especially in the 0° direction, was likely related to the observed anisotropy of the soil physical properties, especially AFPS (Fig. 3), and exacerbated by vehicle traffic, which would be more intense in the mechanized harvested areas. Pérez et al. (2010) using the fractal theory to analysis the spatial complexity of penetrometer resistance in a sugarcane harvesting area in Bayamo, Cuba, did also observe anisotropic prefractal pattern induced by harvester and other vehicles in a sugarcane production area. In addition, our results are in accordance with those of Martin and Bolstad (2009), who reported that spatial changes in soil respiration at smaller scales were the result of different effects related to soil temperature and moisture and to physical, chemical and biological properties.

3.3. Multiple linear regression analysis

To better understand the relationships between FCO_2 and soil properties, a multiple linear regression analysis was performed for all grid points (general model) and for specific grid directions (Table 5). In the general model, AFPS, which explained 48% of FCO_2 variability, was the first property selected. Sand was the next variable selected, increasing the FCO_2 determination coefficient to 52%. Finally, Cstock was selected, further increasing R^2 to 54%. The estimated parameters for AFPS and Cstock were positive, while the parameter for Sand was negative. The positive parameter estimated for AFPS could be related to gas diffusivity, which is improved at higher AFPS values (Davidson et al., 2000;

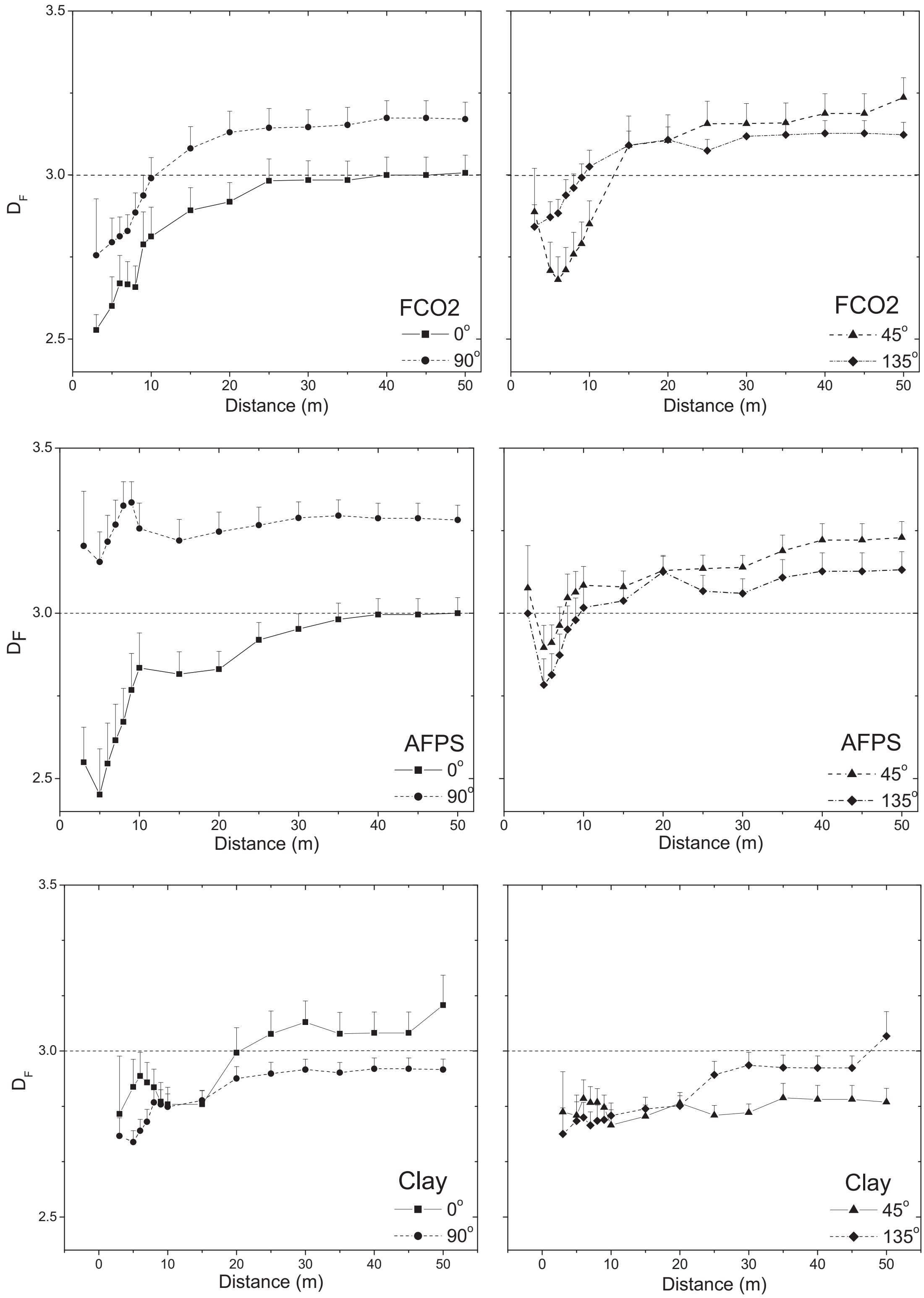

Fig. 3. Fractograms of soil CO_2 emissions (FCO_2), the air-filled pore space (AFPS) and clay content (Clay) calculated from semivariograms at different scales (distances) and directions.

Schwendenmann et al., 2003; Kosugi et al., 2007). The positive Cstock parameter could be explained by the use of carbon by microorganisms during the decay of soil organic matter (Singh and Gupta, 1977; Brito et al., 2009). In a previous study conducted in a mechanically harvested sugarcane production area, Panosso et al. (2011) observed that 46% of the spatial variability of FCO_2 was explained by AFPS, Sand and the degree of humification of the soil organic matter, with positive parameters estimated for all three.

In the 0° direction, AFPS, which explained 34% of FCO_2 variability, was the only variable used in the multiple linear regression models. In the 45° direction, AFPS and Sand, which together explained 74% of FCO_2 variability, were used in the model.

Table 5
Multiple linear regression models of soil CO_2 (FCO_2) for all samples points (general model) and for different directions.

Variable	Parameter	SE	*P*	R^2
General model (*N* = 89)				
Intercept	6.68833	2.54548	0.0104	
AFPS	0.10141	0.01103	<.0001	0.49
Sand	−0.05073	0.01793	0.0059	0.52
Cstock	0.00152	0.00088	0.0881	0.54
Directions				
0°				
Intercept	1.24495	0.18013	<.0001	
AFPS	0.05042	0.01603	0.0053	0.34
45°				
Intercept	12.09932	3.99780	0.0076	
AFPS	0.15099	0.02759	<.0001	0.58
Sand	−0.08596	0.02737	0.0060	0.74
90°				
Intercept	−1.89127	3.99971	0.6436	
AFPS	0.06461	0.02693	0.0309	0.34
Cstock	0.00472	0.00135	0.0036	0.53
pH	1.02807	0.38060	0.0172	0.63
CEC	0.01413	0.00602	0.0341	0.71
T_s	−0.26134	0.13368	0.0708	0.77
135°				
Intercept	13.91188	6.70965	0.0536	
AFPS	0.08317	0.03206	0.0189	0.47
T_s	−0.49707	0.24660	0.0599	0.57

SE: standard error of the estimated parameter; R^2: coefficient of determination.

In the 90° direction, AFPS and Cstock, which explained 53% of FCO_2 variability, were used first, followed by pH, CEC and T_s, which increased the coefficient of determination to 77%. In the 135° direction, AFPS and T_s were used. In the 90° and 135° directions, soil temperature (T_s) estimates were negative because this property is typically positively correlated with microbial activity and FCO_2 (Scott-Denton et al., 2003; Ryu et al., 2009). CEC and pH were positive parameters in the model for the 90° direction, and previous studies have documented complex relationships between FCO_2 and soil chemical properties, pH, soil carbon and soil nutrients (Ekblad and Nordgren, 2002; Savin et al., 2001). According to Stotzky and Rem (1966), CEC, which buffers soil pH and promotes microbial activity, is an important property related to CO_2 production in soil. Differences in the multiple linear regression models for the different grid directions indicated anisotropy and the complex relationship between FCO_2 and soil physical and chemical properties (Ryu et al., 2009). AFPS, which was significant in all models, including the general model, explained the majority of the spatial variability of FCO_2. Thus, the results suggest that in mechanically harvested sugarcane production areas, open pore spaces could be one of the main factors associated with the spatial variability of soil respiration. This finding is in agreement with the hypothesis that FCO_2 and AFPS have similar variability structures, which are characterized by the fractal dimension in different grid directions and at different scales (Fig. 3). In addition, attributes such like Sand, Cstock and T_s, selected in others directions, contributed not only to the capacity of the models to explain the anisotropic variations of soil CO_2 emission, but also they provided additional information to understand the FCO_2 phenomenon in agricultural area.

Regardless of the number and the frequency of tillage operations, it is accepted that tillage practices do alter most of the soil physical properties. The excessive pressure exert by machines during sugarcane mechanized harvest could compact soil, decreasing the water infiltration rate and increasing bulk density (D_s) (Cassel and Edwards, 2003; Otto et al., 2011). Neves et al. (2003) observed sugarcane areas a TPV of 49% in compacted fraction and 60% in non-compacted Oxisols. Otto et al. (2011) observed TPV around 41%, also in green sugarcane areas, similar to those values of our work. Hence, the results we found for TPV values (Table 2), when compared to others in literature, suggest we have a compaction condition especially in between crop lines. Our results indicate smaller TPV and AFPS, with greater D_s values, at 0° direction, which is the between lines. Pérez et al. (2010) reports that harvesting machinery can change, in many cases, the spatial organization and orientation of soil compaction zones, furthermore, soil dynamics, in terms of soil mechanical properties, can change their spatial scaling in response to harvesting machinery.

4. Conclusions

In the experimental mechanically harvested sugarcane areas, the spatial variability of soil CO_2 emissions was predominantly explained by changes in the oxygen level of the soil, expressed by the water-free soil porosity. The fractal dimension values of soil properties in different directions indicated spatial anisotropy of FCO_2 and other soil properties. The soil CO_2 emissions were spatially dependent at a scale of 0.5 m in all grid directions and at a medium scale of up to 2 m, especially in the direction between the crop lines (0°). Several factors inherent to soil forming processes, especially physical properties of the soil, and management practices during harvest and seeding were responsible for the observed anisotropy, which affected soil CO_2 emissions. Hence, the anisotropy feature of mechanized sugarcane areas must be taken into account when a more accurate estimate of FCO_2 and its relation to soil properties is considered.

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