Revista Brasileira de Ciência do Solo

Division - Soil Use and Management | Commission - Soil and Water Management and Conservation

Spatial and Temporal Variability of Soil CO_2 Flux in Sugarcane Green Harvest Systems

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ABSTRACT: The sugarcane green harvest system, characterized by mechanized harvesting and the absence of crop burning, affects soil quality by increasing crop residue on the soil surface after harvest; thus, it contributes to improving the physical, chemical, and microbiological properties and influences the soil carbon content and CO_2 flux (FCO_2). This study aimed to evaluate the spatial and temporal variability of soil FCO_2 in sugarcane green harvest systems. The experiment was conducted in two areas of sugarcane in São Paulo, Brazil: the first had a 5-year history of sugarcane green harvest (SG-5) and the second had a longer history of 10 years (SG-10). The temporal FCO_2 were evaluated in the dry and rainy periods, and spatial variability in the dry period, and related to soil chemical and physical properties, including organic C porosity, bulk density, soil penetration resistance, mean weight diameter of soil aggregates, clay, P, S, Ca, Mg and Fe. The temporal variability indicated no differences between the dry and rainy periods in SG-10, while in SG-5 soil moisture was increased by 33 % in the rainy period. The spatial variability indicated a different pattern from the temporal one, where FCO_2 in SG-10 was correlated with soil temperature, air-filled pore space, total porosity, soil moisture, and the Ca and Mg contents; in the SG-5 area, FCO_2 was correlated with soil mean weight diameter of soil aggregates and the sulfur content.

Keywords: CO_2 emission, soil respiration, straw, mechanized harvest, physical properties.

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Received: August 10, 2015
Approved: November 12, 2015

How to cite: Tavares RLM, Souza ZM, La Scala Jr N, Castioni GAF, Souza GS, Torres JLT. Spatial and Temporal Variability of Soil CO_2 Flux in Sugarcane Green Harvest Systems. Rev Bras Cienc Solo. 2016;40:e0150252.

INTRODUCTION

The sugarcane green harvest system (characterized by the absence of crop burning, with mechanized harvest and residue deposition on the soil surface, especially leaves and culms), which has replaced the pre-harvest burning method, has increased in use in Brazil since the 1990s due to increased awareness of environmental impacts, such as the increase in gas emissions that cause the greenhouse effect and emissions of particulate matter that have a harmful impact on human health (Arbex et al., 2012; Sisenando et al., 2012). The sugarcane green harvest system promotes soil protection by the deposition of larger quantities of straw (average 10 to 30 Mg ha^{-1}) which provides higher C accumulation in the soil, leading to a positive CO_2 balance (Razafimbelo et al., 2006) as the C that would be emitted directly by burning remains in the system, it can be incorporated into the soil, favoring microbiota (Panosso et al., 2011).

In order to better quantify soil CO_2 emission in agricultural areas, it is imperative to characterize its spatial and temporal variability and how these parameters are affected by management practices (Panosso et al., 2009). Kosugi et al. (2007) demonstrated the complexity of soil respiration patterns, since spatial variability indicates CO_2 emissions are lower where the soil water content is higher; however, in terms of temporal variability, the opposite effect was found, as soil respiration was higher with increasing soil moisture. The mechanisms controlling the spatio-temporal variability of soil CO_2 efflux in water-limited ecosystems is highly complex (Leon et al., 2014).

Soil CO_2 emissions from areas under sugarcane cultivation have been studied recently. Brito et al. (2009) observed that low areas with a convex structure are likely to collect surface run-off and thereby increase the amount of moisture infiltrating the soil microbial population, resulting in higher rates of C mineralization and CO_2 emissions. Panosso et al. (2009) compared the spatial and temporal variability of soil CO_2 emissions in pre-harvest burning with a seven-year green harvest system and found that the CO_2 emissions were 39 % higher in the burned plot when compared to the green one. Additionally, they showed that, with green management, CO_2 was more homogeneous when spatial and temporal variability were considered.

Soil CO_2 emissions in a sugarcane area affected by tillage events were investigated by Silva-Olaya et al. (2013), and they showed that conventional operations (consisting of two heavy offset disk harrowing operations and a subsoiling operation) cause more emissions of CO_2 to the atmosphere when compared with minimum tillage (chemically eliminating sugarcane ratoon followed by a subsoiling operation with row planting) and reduced tillage (involving two phases of mechanical elimination of the ratoon and two subsoiling operations). They suggested that the impact of minimum and reduced tillage on organic C loss was lower than that observed for conventional operation. A study by Corradi et al. (2013) on green cane harvest showed higher CO_2 emissions with no crop residues on the soil surface (bare soil) compared to soil covered with straw. The authors concluded that the conservation of sugarcane crop residues on the soil after harvest could have an impact on soil C conservation.

Overall, studies on soil CO_2 fluxes in sugarcane areas have involved the comparison of green and burned cane, or different soil tillage practices, but few studies have analyzed the effect of green harvest, taking into account the time after conversion. Our hypothesis is that there exists a dynamic change in the spatial and temporal patterns of soil CO_2 emissions once the sugarcane harvest system is converted from burned to green, and that this depends on crop residue input and the compaction of the soil due to mechanized operations over time after conversion. Following this, the objective of this work was to evaluate the spatial and temporal variability of CO_2 emissions in sugarcane green harvest systems five and 10 years after conversion from pre-harvest burning.

MATERIALS AND METHODS

The study was conducted in two sugarcane areas belonging to a sugar-alcohol mill, located in the northeast of São Paulo State, southeastern Brazil, with the coordinates 21° 19’ 8” S and 48° 7’ 24” W (Figure 1). The climate of the region is classified as B_2rB’4a’ according to the Thornthwaite climate classification, and the topography in the area is flat and undulating.

Description of the experimental areas

The evaluated areas were managed according to the green harvest system, with different implementation history after conversion from pre-harvest burning: the first had a five-year history of sugarcane green harvest (SG-5) and the second had a 10-year history (SG-10). Both areas had soil classified as *Latossolo Vermelho Eutrófico* (Santos et al., 2013), a Haplustox (USDA, 2014).

After the conversion to a green harvest system, SG-5 had not undergone crop renovation, but in SG-10, renovation occurred six years after implementation and was composed of, initially, mechanical ratoon elimination from the previous crop and subsoiling at a depth of 0.45 m in the planting furrows. Soon after these operations, 2 Mg ha^{-1} of dolomitic limestone was applied. For planting fertilization, 480 kg ha^{-1} of the NPK formulation (10-25-20) was used. A mean of 100 m^3 ha^{-1} of bagasse and 200 kg ha^{-1} of ammonium nitrate was applied in the area.

In each experimental area, 1 ha was delimited where the sampling grid was located with 81 sampling points spaced at 1, 2, and 10 m intervals, in a star shape, with the points directed to different angles to aid in the study of the anisotropy of spatial variability (Figure 1). The points were georeferenced with the help of a total station (Leica® model TC 305) and DGPS (L1/L2 Hiper Lite Plus).

Climatic data

Data on air temperature, rainfall and air humidity are shown in figure 2a; soil temperature is presented in figure 2b. There was no rainfall during the experimental period.

Evaluation of soil CO_2 flux

The evaluation of CO_2 was simultaneously performed in both areas using two chambers at all sampling grid points, during the 2011 dry and 2012 rainy periods, in the morning (7-11 a.m.), using soil chambers manufactured by LI-COR® (Nebraska, USA, model LI-8100). The instrument is a closed system, with an internal volume of 991 cm^3 and a

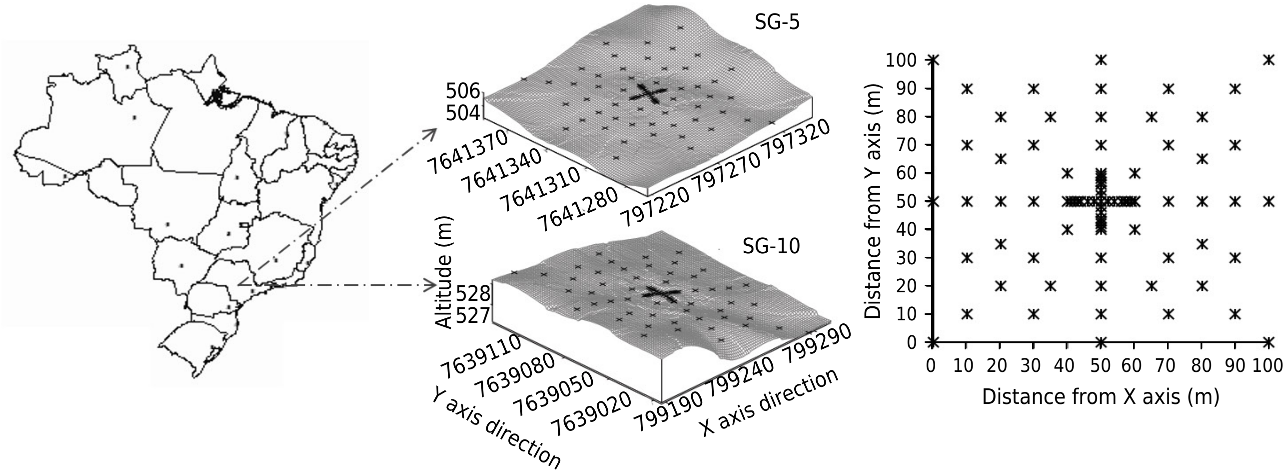

Figure 1. Experiment location and area topography with the sampling grids settled on each one. 5-year sugarcane green harvest system (SG-5) and 10-year sugarcane green harvest system (SG-10).

contact area with the soil of 71.6 cm^2, placed on PVC collars (0.10 m diameter) that were previously inserted (two days before) into the soil at a depth of 0.03 m, only once at each point and site. Soil temperature and moisture were evaluated simultaneously with measurements of the CO_2 concentration by a temperature sensor coupled to the LI-8100 system; for the evaluation of soil water content, TDR-Campbell® equipment was used.

Evaluation of soil properties

Soil penetration resistance test and soil sampling for analysis were performed at the sampling grid points. For the penetration resistance test (Stolf, 1991), an impact penetrometer (model IAA/Planalsucar) was used, with a 30° cone angle.

Undeformed samples were collected to analyze soil porosity and bulk density according to the guidelines of Brazilian Agricultural Research Corporation (Claessen, 1997). Deformed soil samples were collected from the soil surface (0.00-0.10 m depth) and exposed to the air for 24 h, then placed in a sieve set of 6.35 and 2 mm.

Soil aggregates were obtained from samples retained by the 2 mm sieve and were analyzed for mean weight diameter (MWD) of soil aggregates according Kemper and Chepil (1965), while those that went through the sieve were used to evaluate the organic C content (Nelson and Sommers, 1996) as well as pH, P, S, Ca, Mg and Fe (Raij et al., 2001).

Statistical analyses

Data analysis was performed on the descriptive statistics by calculating the mean, standard deviation, maximum and minimum values, and coefficient of variation. Means were compared by the *t*-test at 5 % probability. The hypothesis of data normality was verified by the Kolmogorov-Smirnov test, using SAS software (version 2). Analyses of variance (repeated measures over time) and linear regression were used for the analysis of temporal variability. Spatial dependence was assessed via adjustments of semivariograms (Vieira, 2000) based on the stationarity assumption of the intrinsic hypothesis, which is estimated by:

$$\hat{y}(h) = \frac{1}{2\,N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \qquad \text{Eq. 1}$$

where N(h) is the pair number of the observation points Z(xi) and Z(xi + h) is separated by distance h. The variogram is represented by the graph $\hat{y}(h)$ *versus* h. From the adjustment of a mathematical model to the $\hat{y}(h)$ calculated values, the coefficients of the theoretical model for the variogram were estimated (nugget effect, C_0; sill, C_0+C_1; and range, a). To analyze the spatial dependence degree of the studied properties, the

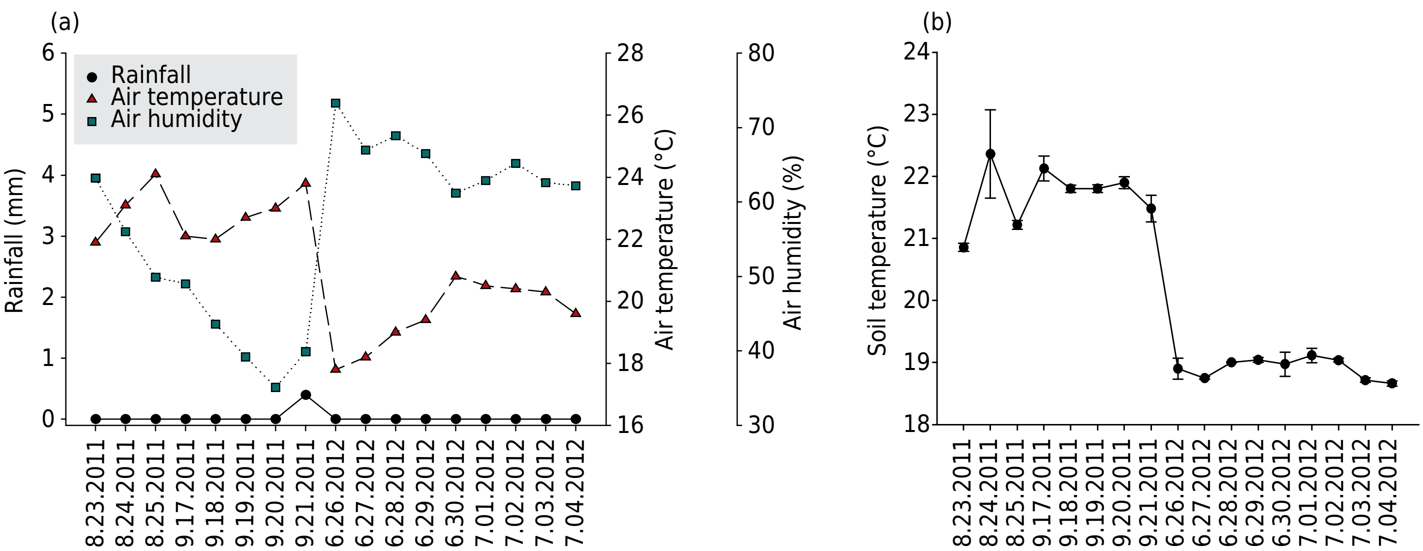

Figure 2. Air temperature, air humidity, and rainfall during the experimental period (a), and soil temperature (b).

classification used was described by Cambardella et al. (1994), who consider a strong spatial dependence for semivariograms with a nugget effect <25 % of the sill; moderate between 25 and 75 %; and weak >75 %.

RESULTS AND DISCUSSION

Temporal variability

The greatest soil FCO_2 was observed in the rainy period, with 2.33 and 2.89 μmol m^{-2} s^{-1} CO_2 in SG-5 and SG-10, respectively, in comparison with the dry period, at 1.19 and 2.62 μmol m^{-2} s^{-1} CO_2; a significant difference ($p<0.05$) was found only for SG-5, with a 33 % increase in the rainy period (Table 1). Other studies have demonstrated greater soil CO_2 emissions in the rainy period (Xu and Qi, 2001; Epron et al., 2004; Kosugi et al., 2007; Song et al., 2013); this is mainly related to greater microbial activity promoted by soil moisture and, or, root activity during plant growth and development. Soil FCO_2 in SG-10 was more consistent over time and an increase associated with the rainy period was not observed as it was in SG-5 (Figure 3).

Soil moisture was higher in the rainy period than in the dry period in both SG-5 (38.41 and 11.16 %) and SG-10 (29.71 and 10.17 %), with a significant difference between periods ($p<0.05$); however, differences in soil moisture were not significant between areas ($p>0.05$) (Table 1). The air-filled pore space (AFPS), calculated from the moisture data, was higher in the dry period, reaching 44.40 and 43.24 % in SG-5 and SG-10, respectively, due to lower water availability during this period. In the rainy period, because of rainfall, pores are filled with water, presenting lower AFPS, i.e. 17.07 % for SG-5 and 26.07 % for SG-10.

Soil temperature showed the same tendency as soil moisture and AFPS (Table 1), and temperature was significantly ($p<0.05$) higher in the rainy period (23.39 °C) than in the dry period (18.90 °C). This happens because summer in the region is characterized by a higher rainfall frequency and temperature, what stimulates soil microbial activity since the ideal conditions for the decomposition process are around 30 °C and 60-80 % soil moisture (Kononova, 1975), thus affecting FCO_2.

Thus, in SG-5, the FCO_2 increase in the rainy period, in comparison with the dry period (Figure 3), was followed by variations in soil moisture, indicating the direct influence of soil moisture on FCO_2. This was confirmed by the calculation of the determination coefficient between both factors (CO_2 and Sm), providing R^2 = 0.73 (Figure 4d). Other studies also

Table 1. Descriptive statistics for CO_2 emission, soil moisture and air-filled pore space in 5- and 10-year sugarcane green harvest areas (SG-5 and SG-10, respectively) in the dry and rainy periods, and soil temperature in the dry and rainy periods (n=81)

	Dry period					Rainy period				
	Mean	SD	Min	Max	CV	Mean	SD	Min	Max	CV
					%					%
SG-5										
FCO_2	1.19 bB	0.90	-0.56	4.59	75.94	2.33 aA	0.77	1.25	5.80	33.31
Sm	11.16 aB	1.85	9.00	17.00	16.62	38.41 aA	2.46	32.33	44.78	6.40
AFPS	44.40 aA	9.66	35.06	86.68	21.76	17.07 bB	9.17	5.86	54.88	53.73
SG-10										
FCO_2	2.62 aA	1.01	1.21	8.26	38.42	2.89 aA	1.42	0.93	8.06	49.42
Sm	10.17 bB	1.42	8.00	14.00	13.96	29.71 aA	2.58	24.00	35.00	8.69
AFPS	43.24 aA	4.81	33.30	57.47	11.20	26.07 aB	9.20	13.90	65.26	35.28
St	18.90 b	0.42	17.20	19.71	2.25	23.39 a	5.67	19.37	46.25	24.26

FCO_2: flow rate of CO_2 (μmol CO_2 m^{-2} s^{-1}); Sm: soil moisture (%); AFPS: air-filled pore space (%); St: soil temperature (°C). SD: standard deviation, Min: minimum, Max: maximum, CV: coefficient of variation. Means followed by the same lower case letters in the column (to compare SG-5 and 10) and upper case letters in the line (to compare dry and rainy) do not differ from each other by the Tukey test at 5 %.

identified the influence of soil moisture on FCO_2 (Kosugi et al., 2007; Panosso et al., 2009; Liu et al., 2011). This effect can be explained by the fact that the rainy period is characterized by more soil moisture and higher temperatures, which are better conditions for microbial activity. As a consequence of this process, the CO_2 flux is greater (Mendonza et al., 2000; Zornoza et al., 2007).

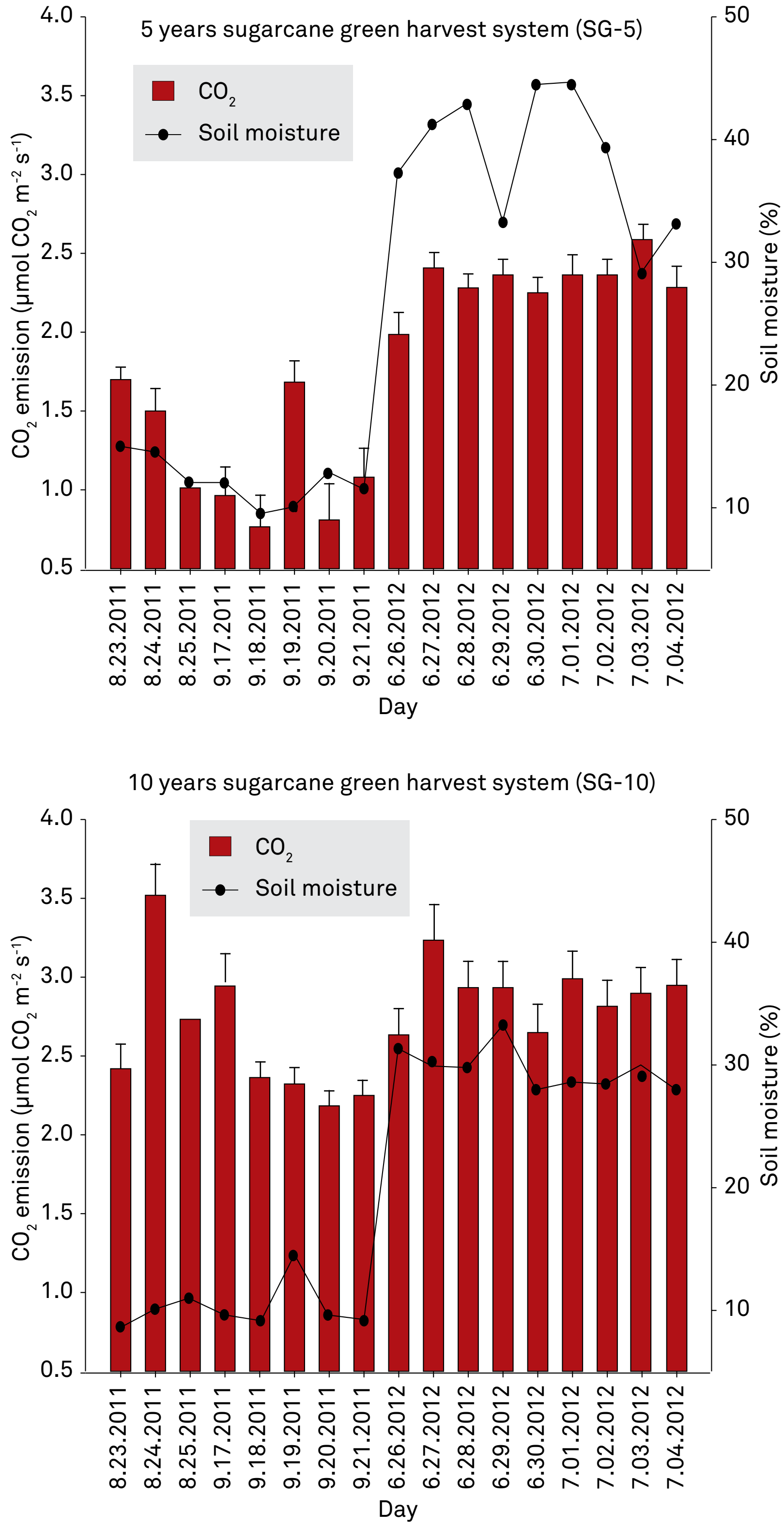

Figure 3. CO_2 emission and soil moisture under 5- and 10-year sugarcane green harvest systems, in 2011/2012, in São Paulo State Northeast/Brazil.

The soil temperature also presented a significant correlation with FCO_2 in SG-5, with R^2 = 0.80 (Figure 4b). Nevertheless, the evaluation of soil temperature must be carefully analyzed, since temperature was influenced by soil moisture in both SG-5 (R^2 = 0.85) and SG-10 (R^2 = 0.90) (Figure 4f). This was also detected in study of Leon et al. (2014) on temporal and spatial variation of soil CO_2 efflux in a water-limited Mediterranean ecosystem; they found that the changes in soil volumetric water content influenced the relationship between CO_2 efflux and soil temperature. Epron et al. (2004), when studying CO_2 emissions from soil cultivated with eucalyptus, concluded that the bivariate model, including soil temperature and moisture, did not explain the temporal variations in CO_2 emission; the univariate model, with the use of soil moisture, was more efficient.

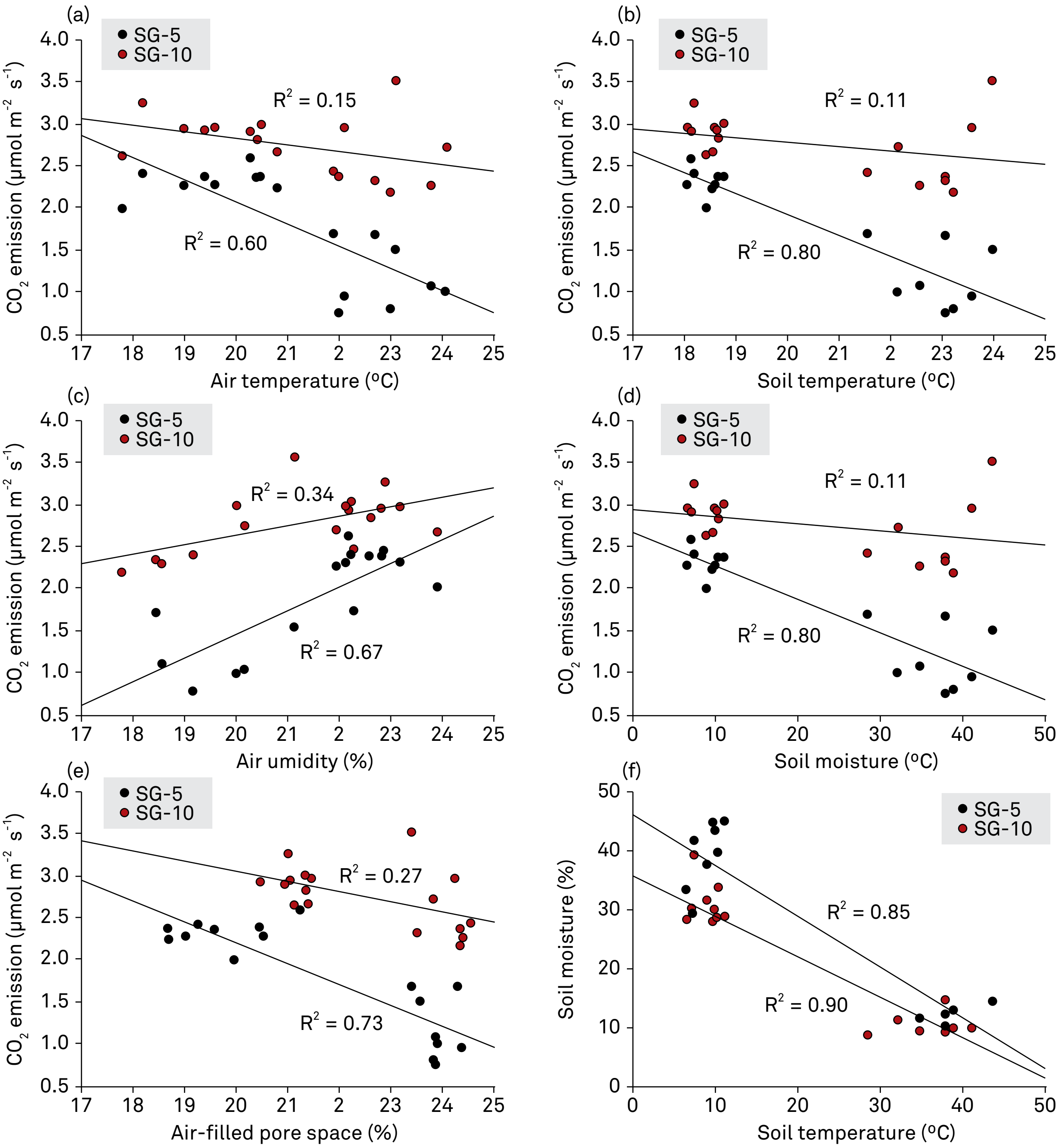

Figure 4. Regression analysis of CO_2 emission according to air temperature (a), soil temperature (b), air humidity (c), soil moisture (d), air-filled pore space (e), and relationship between soil moisture and temperature (f).

Besides soil moisture and temperature, FCO_2 in SG-5 presented an indirect relationship with air-filled pore space of R^2 = 0.73 to SG-5 and R^2 = 0.51 to SG-10 (Figure 4e) and this may be related to the stimulation of microbial activity, which was promoted by higher soil moisture and had a great influence on FCO_2 (Davidson and Swank, 1986), especially in the rainy period, when AFPS was lower than in the dry period.

Regarding SG-10, the temporal variability of FCO_2 was not significant ($p>0.05$) (Table 1, Figure 3). Furthermore, the seasonal factors obtained in this study, such as temperature, soil moisture, air humidity and AFPS did not affect FCO_2 in SG-10. These results indicate that FCO_2 in SG-10 was more stable than in SG-5, with no influence of soil temperature and moisture which, according to some studies, are considered to be the main factors affecting the temporal variability of FCO_2 (La Scala Jr et al., 2000a; Xu and Qi, 2001; Epron et al., 2004; Panosso et al., 2009).

The greater quantity of straw and its longer permanence in SG-10 possibly promoted higher stability in soil FCO_2 during the evaluated period (dry and rainy). This occurred because the straw, apart from improving the physical aspects of soil, stimulates soil microbial activity due to an increased substrate supply, promoting greater FCO_2 and releasing organic compounds into the soil.

Spatial variability

Soil FCO_2 in the SG-5 and SG-10 systems ranged from 1.19 to 2.89 μmol m^{-2} s^{-1} CO_2 (Table 1), similar values to those found by Panosso et al. (2009), who showed a flux of 1.81-2.67 μmol m^{-2} s^{-1} CO_2 from soil submitted to a seven-year sugarcane green harvest system in the same region. La Scala Jr et al. (2000a) obtained a flux of 1.46-2.80 μmol m^{-2} s^{-1} CO_2 from a bare Oxisol.

The descriptive analysis for FCO_2 indicated higher flux ($p<0.05$) in SG-10 (2.33 and 2.89 μmol m^{-2} s^{-1} CO_2 in the dry and rainy periods, respectively) in comparison with SG-5 (1.19 and 2.62 μmol m^{-2} s^{-1} CO_2). The amount of straw in SG-10 possibly influenced FCO_2 as the presence of residue on the soil surface provides the ideal conditions of temperature and moisture for the decomposition process (Medeiros et al., 2011). Furthermore, it improves the soil physical structure, promoting greater gas flow in the soil and stimulating microbial activity (Carbonell-Bojollo et al., 2012).

The SG-10 area, with a longer history of the sugarcane green harvest system, had greater amounts of straw on the soil surface, which represents a larger amount of substrate and energy supply for microorganisms and, consequently, higher CO_2 release. In other studies, straw was found to be fundamental to FCO_2 from soils cultivated with pine (Fang et al., 1998) and eucalyptus (Epron et al., 2004), where greater emissions were found in regions of more plant residue on the soil surface. Medeiros et al. (2011) also detected greater FCO_2 from soil covered with straw (no tillage) in comparison with soil submitted to conventional tillage, and related the effect to an increased stock of organic carbon in soils under no tillage regimes. Lenka and Lal (2013) also found greater FCO_2 from soil with more wheat straw (16 Mg ha^{-1}) in comparison with areas with 0 and 8 Mg ha^{-1}.

Soil porosity is a physical attribute related to gas transportation; high porosity enables O_2 flow (Xu and Qi, 2001; Kosugi et al., 2007; Brito et al., 2009), higher microbial activity and therefore greater soil FCO_2 (Fang et al., 1998). Although SG-5 and SG-10 showed similar soil total porosity ($p>0.05$), the macroporosity was greater ($p<0.05$) in SG-10 (23.48 m^3 m^{-3}) than in SG-5 (18.42 m^3 m^{-3}) (Table 2), indicating better gas transportation in SG-10. This was confirmed by the values of soil penetration resistance, which were lower in SG-10 (3.45 MPa) than in SG-5 (5.04 MPa) (Table 2). A similar result was described by Brito et al. (2009), who studied CO_2 emissions from soil cultivated with sugarcane in different topographic positions, demonstrating higher emissions in areas with greater soil macroporosity.

Table 2. Descriptive statistics for soil chemical and physical properties evaluated in sugarcane green harvest areas after 5 (SG-5) and 10 years (SG-10) of implementation

	SG-5					SG-10				
	Mean	SD	Min	Max	CV	Mean	SD	Min	Max	CV
					%					%
OC (g kg^{-1})	3.24 a	0.89	2.11	6.24	27.63	2.50 b	0.29	1.65	3.08	11.86
TP (g kg^{-1})	54.45 a	6.76	46.45	85.57	12.41	53.38 a	4.16	46.45	66.89	7.79
Macro (g kg^{-1})	18.42 b	4.76	3.58	36.87	25.87	23.48 a	4.96	11.29	43.84	21.15
Bd (Mg m^{-3})	1.27 b	0.13	0.86	1.59	10.71	1.37 a	0.14	1.07	1.72	10.18
PR (MPa)	5.04 a	1.38	2.15	10.21	27.36	3.45 b	1.30	0.56	7.45	37.73
MWD (mm)	1.39 b	0.46	0.67	2.50	33.47	1.74 a	0.49	0.71	3.06	28.31
Clay (g kg^{-1})	522 a	59.45	397	620	11.37	531 a	31.29	350	541	7.25
pH	4.82 a	0.11	4.60	5.20	2.34	4.82 a	0.25	4.20	5.60	5.34
P (mg dm^{-3})	35.50 a	18.19	9.00	95.00	51.25	31.35 b	18.28	10.00	90.00	58.30
S (mg dm^{-3})	7.84 a	4.42	2.00	19.60	65.35	7.26 a	0.26	0.15	1.40	55.49
Ca ($cmol_c$ dm^{-3})	4.17 a	0.94	2.50	7.30	22.63	3.07 b	0.73	1.60	5.00	23.82
Mg ($cmol_c$ dm^{-3})	1.28 a	0.22	0.90	1.80	17.30	0.92 b	0.24	0.50	1.90	26.16
Fe (mg dm^{-3})	39.91 b	9.40	23.50	76.50	23.55	129.45 a	19.93	71.50	184.00	15.40

OC: organic carbon; TP: total porosity; Macro: macroporosity; Bd: bulk density; PR: soil penetration resistance; MWD: mean weight diameter of soil aggregates. SD: standard deviation, Min: minimum, Max: maximum, CV: coefficient of variation. Means followed by the same letter in the line do not differ from each other by the Tukey test at 5 %.

In SG-10, FCO_2 in the dry and rainy periods presented a significant correlation ($p<0.05$) with the evaluated properties; furthermore, in the dry period, FCO_2 was positively correlated with soil temperature (0.23) and negatively with soil moisture (-0.29) (Table 3). A correlation between CO_2 and St was also described by Lenka and Lal (2013).

In the rainy period, FCO_2 in SG-10 presented a significant positive correlation with AFPS, total porosity, and Ca and Mg contents. Xu and Qi (2011) also found a positive correlation between FCO_2 and Mg, which, according to the authors, is related to microbial activity. The contents of Mg and Ca presented a positive correlation with CO_2 in SG-10, which influenced the soil pH, therefore improving microorganism performance during the decomposition process.

Analysis of the correlation between FCO_2 and soil properties in SG-5 showed that it was significant for the dry period (Table 3); it was positive for MWD (0.26) and S (0.30). Such a correlation was also described by Mangalassery et al. (2013), who found greater FCO_2 from soil with more macroaggregates. Similar results were obtained by Brito et al. (2009) and Lenka and Lal (2013), who concluded that C in soil aggregates would be available to microbial attack, thus emitting CO_2. Regarding the relationship between CO_2 and S, it is possible that it is associated with a specific group of soil microorganisms called chemoautotrophs, which use CO_2 as an energy source in the S oxidation process (Alexander, 1999). In SG-5, the sulfur concentration was significantly ($p<0.05$) higher (7.84 mg dm^{-3}) than in SG-10 (0.48 mg dm^{-3}), which possibly explains the correlation between CO_2 and sulfur in SG-5.

The relationship between FCO_2 and other soil properties obtained by spatial variability was different from the temporal variability; according to Xu and Qi (2001), spatial variability does not always agree with the temporal pattern. In this study, in other words, some properties such as soil moisture and temperature, as well as air humidity and temperature, explained the temporal variability of FCO_2 in SG-5, but did not influence FCO_2 in SG-10. Nevertheless, the spatial variability analysis showed that soil temperature and moisture influenced FCO_2 only in SG-10.

Table 3. Coefficients of the linear correlations between CO_2 emissions and soil properties in sugarcane green harvest areas after 5 (SG-5) and 10 years (SG-10) of implementation in the dry (DryP) and rainy (RainP) periods

	SG-5		SG-10	
	FCO_2 (DryP)	FCO_2 (RainP)	FCO_2 (DryP)	FCO_2 (RainP)
FCO_2 (μmol CO_2 m^{-2} s^{-1}) (DryP)	-	-	-	-
FCO_2 (μmol CO_2 m^{-2} s^{-1}) (RainP)	0.008	-	0.26	-
St (°C) (DryP)	0.001	-0.15	0.23	0.09
St (°C) (RainP)	-0.09	-0.14	0.26	0.1
Sm (%) (DryP)	-0.09	-0.16	-0.29	0.04
Sm (%) (RainP)	-0.09	0.05	-0.12	-0.17
AFPS (DryP)	-0.01	0.06	0.08	0.28
AFPS (RainP.)	-0.01	0.02	0.23	0.28
OC (g kg^{-1})	-0.02	0.06	-0.06	0.14
TP (g kg^{-1})	-0.03	0.02	0.04	0.28
Macro (g kg^{-1})	0.02	-0.02	-0.07	-0.09
Bd (Mg m^{-3})	0.0005	-0.02	0.01	0.03
PR (MPa)	-0.02	0.05	0.03	0.04
MWD (mm)	0.26	0.0008	0.01	-0.01
Clay (g kg^{-1})	-0.001	-0.05	0.05	0.09
pH	0.09	-0.09	-0.04	0.12
P (mg dm^{-3})	-0.09	-0.03	0.21	0.17
S (mg dm^{-3})	0.30	-0.05	-0.03	-0.06
Ca ($cmol_c$ dm^{-3})	-0.03	0.02	-0.01	0.23
Mg ($cmol_c$ dm^{-3})	-0.06	0.12	0.05	0.25
Fe (mg dm^{-3})	-0.09	-0.16	0.16	0.14

FCO_2: flow rate of CO_2; St: soil temperature; Sm: soil moisture; AFPS: air-filled pore space; OC: organic carbon; TP: total porosity; Macro: macroporosity; Bd: bulk density; PR: soil penetration resistance; MWD: mean weight diameter of soil aggregates.

In some studies, soil FCO_2 was positively correlated with the organic carbon (OC) content (La Scala Jr et al., 2000b; Medeiros et al., 2011; Lenka and Lal, 2013). In this study, however, SG-10 presented a lower OC content and greater FCO_2. The high microbial activity in that area possibly reduced the OC content, as an increase in cycles of organic matter decomposition by soil microorganisms results in a lower OC content, although it can be more protected and stabilized in microaggregates (Lenka and Lal, 2013). Furthermore, Fang et al. (1998) detected greater CO_2 emissions in regions with a lower OC content in soil cultivated with pine. According to these authors, the decomposition of soil organic matter results in less organic matter being left in the soil.

The experimental variograms showed the spatial dependence pattern of FCO_2 for both areas (Figure 5). In SG-5, the spherical model was adjusted to the semivariograms in both the dry and rainy periods, indicating high spatial continuity of FCO_2 (Isaaks and Srivastava, 1989). A spherical model for FCO_2 was also adjusted to semivariograms in studies performed by Kosugi et al. (2007) and La Scala Jr et al. (2000a). Furthermore, the degree of spatial dependence was moderate, which was also found by Panosso et al. (2009) and La Scala Jr et al. (2000b). Although studies have reported differences of range in CO_2 spatial variability during the dry and rainy periods (Kosugi et al., 2007; Ohashi and Gyokusen, 2007), in this study, the range was of 25 m for both periods.

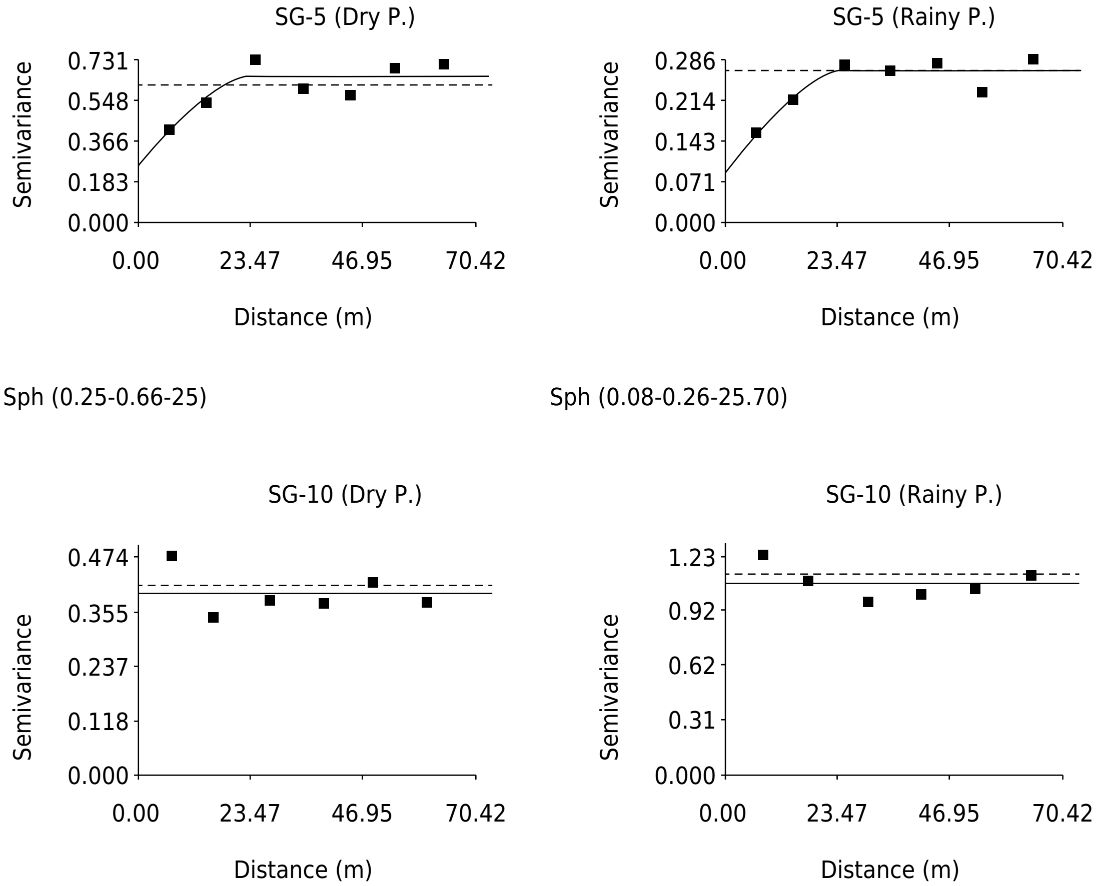

Figure 5. Experimental variograms for soil CO_2 emission in sugarcane green harvest areas after 5- and 10-years of implementation during dry (Dry P) and wet (Rainy P) periods. Model (C_0-C_0+C_1-r). C_0: nugget effect; C_0 +C_1: sill; r: range.

In SG-10, there was an absence of spatial dependence (nugget effect), and it was not possible to adjust any theoretical model to explain the FCO_2 variation. This means that the values of FCO_2 showed a random spatial distribution, or that the space between the points of the grid was not sufficient to detect the spatial dependence of FCO_2 in SG-10. This effect was found in similar studies on CO_2 flux in soil under green cane (Panosso et al., 2009), burned cane (Panosso et al., 2008) and bare soil (La Scala Jr et al., 2000a).

CONCLUSIONS

Soil CO_2 flux (FCO_2) presented differences in spatial and temporal variability patterns dependent on the period of conversion from burned to green cane harvest.

FCO_2 in SG-10 was steadier over time during the dry to rainy period, while in SG-5, fluxes were more affected by precipitation events due to changes in soil moisture.

Spatial variability indicated that FCO_2 in SG-10 was linearly correlated with soil temperature, air-filled pore space, total porosity, Ca and Mg contents, and negatively correlated with soil moisture. On the other hand, in SG-5, FCO_2 was correlated with the mean weight diameter of soil aggregates and sulfur content.

ACKNOWLEDGMENTS

The authors thank FAPESP/SP for financial support and the São Martinho ethanol mill for providing the study area.

REFERENCES

Alexander DB. Bacteria and Archaea. In: Sylvia DM, Fuhrmann JJ, Hartel PG, Zuberer DA, editors. Principles and applications of soil microbiology. New Jersey: Prentice Hall; 1999. p.44-71.

Arbex MA, Santos UP, Martins LC, Saldiva PHN, Pereira LAA, Braga ALF. Air pollution and the respiratory system. J Bras Pneumol. 2012;38:643-55. doi:10.1590/S1806-37132012000500015

Brito LF, Marques Jr J, Pereira GT, Souza ZM, La Scala Jr N. Soil CO_2 emission of sugarcane fields as affected by topography. Sci Agric. 2009;66:77-83. doi:10.1590/S0103-90162009000100011

Cambardella CA, Moorman TB, Novak JM, Parkin TB, Karlen DL, Turco RF, Konopka AE. Field-scale variability of soil properties in Central Iowa Soils. Soil Sci Soc Am J. 1994;58:1501-11. doi:10.2136/sssaj1994.03615995005800050033x

Carbonell-Bojollo R, Torres MAR-R, Rodriguez-Lizana A, Ordóñez-Fernández R. Influence of soil and climate conditions on CO_2 emissions from agricultural soils. Water Air Soil Pollut. 2012;223:3425-35. doi:10.1007/s11270-012-1121-9

Claessen MEC, organizador. Manual de métodos de análise de solo. 2a ed. rev. atual. Rio de Janeiro: Embrapa Solos; 1997. (Documentos, 1). Disponível em: https://www.agencia.cnptia.embrapa.br/Repositorio/Manual+de+Metodos_000fzvhotqk02wx5ok0q43a0ram31wtr.pdf.

Corradi MM, Panosso AR, Martin Filho MV, La Scala Jr N. Crop residues on short-term CO_2 emissions in sugarcane production areas. Eng Agríc. 2013;33:699-708. doi:10.1590/S0100-69162013000400009

Davidson EA, Swank WT. Environmental parameters regulating gaseous nitrogen losses from two forested ecosystems via nitrification and denitrification. Appl Environ Microbiol. 1986;52:1287-92. doi:10.1111/j.1750-3841.2007.00346.x

Epron D, Nouvellon Y, Roupsard O, Mouvondy W, Mabiala A, SaintAndre L, Joffre R, Jourdan J, Bonnefond JM, Berbigier P, Hamel O. Spatial and temporal variations of soil respiration in a eucalyptus plantation in Congo. For Ecol Manage. 2004;202:149-60. doi:10.1016/j.foreco.2004.07.019

Fang C, Moncrieff JB, Gholz HL, Clark KL. Soil CO_2 efflux and its spatial variation in a Florida slash pine plantation. Plant Soil. 1998;205:135-46. doi:10.1023/A:1004304309827

Isaaks EH, Srivastava RM. An introduction to applied geostatistics. New York: Oxford University; 1989.

Kemper WD, Chepil WS. Size distribution of aggregates. In: Black CA, editor. Methods of soil analysis: physical and mineralogical properties, including statistics of measurement and sampling, Madison: Soil Science Society of America; 1965. Pt 1. p.499-510.

Kononova MM. Humus of virgin and cultivated soils. In: Gieseking JE, editor. Soil components. Berlin: Springer; 1975. p.475-526.

Kosugi Y, Mitani T, Itoh M, Noguchi S, Tani M, Matsuo N, Takanashi S, Ohkubo S, Nik AR. Spatial and temporal variation in soil respiration in a Southeast Asian tropical rainforest. Agric For Meteorol. 2007;147:35-47. doi:10.1016/j.agrformet.2007.06.005

La Scala Jr N, Marques Jr J, Pereira, GT, Corá JE. Carbon dioxide emission related to chemical properties of a tropical bare soil. Soil Biol Biochem. 2000b;32:1469-73. doi:10.1016/S0038-0717(00)00053-5

La Scala Jr N, Marques Jr J, Pereira, GT, Corá JE. Short-term temporal changes in the spatial variability model of CO_2 emissions from a Brazilian bare soil. Soil Biol Biochem. 2000a;32:1459-62. doi:10.1590/S0006-87052010000500004

Lenka NK, Lal R. Soil aggregation and greenhouse gas flux after 15 years of wheat straw and fertilizer management in a no-till system. Soil Till Res. 2013;126:78-89. doi:10.1016/j.still.2012.08.011

Leon E, Vargas R, Bullock S, Lopez E, Panosso AR, La Scala Jr N. Hot spots, hot moments, and spatio-temporal controls on soil CO_2 efflux in a water-limited ecosystem. Soil Biol Biochem. 2014;77:12-21. doi:10.1016/j.soilbio.2014.05.029

Liu J, Jiang P, Wang H, Zhou G, Wu J, Yang F, Qian X. Seasonal soil CO_2 efflux dynamics after land use change from a natural forest to Moso bamboo plantations in sub-tropical China. For Ecol Manage. 2011;262:1131-7. doi:10.1016/j.foreco.2011.06.015

Mangalassery S, Sjögersten, S, Sparkes DL, Sturrock CJ, Mooney SJ. The effect of soil aggregate size on pore structure and its consequence on emission of greenhouse gases. Soil Till Res. 2013;132:39-46. doi:10.1016/j.still.2013.05.003

Medeiros JC, Silva AP, Cerri CEP, Fracetto FJC. Linking physical quality and CO_2 emission under long-term no-till and conventional-till in a subtropical soil in Brazil. Plant Soil. 2011;338:5-15. doi:10.1007/s11104-010-0420-4

Mendonza HNS, Lima E, Anjos LHC, Silva LA, Ceddia MB, Antunes MWV. Propriedades químicas e biológicas de solo de tabuleiro cultivado com cana-de-açúcar com e sem queima da palhada. Rev Bras Cienc Solo. 2000;24:201-7. doi:10.1590/S0100-06832000000100022

Nelson DW, Sommer LE. Total carbon, organic carbon and organic matter. In: Page RH, Kenny DR, editors. Methods of soil analysis; chemical and microbiological properties. Madison: Soil Science Society of America; 1996. Pt.2. p. 961-1010.

Ohashi M, Gyokusen K. Temporal change in spatial variability of soil respiration on slope of Japanese cedar (*Cryptomeria japonica* D. Don) forest. Soil Biol Biochem. 2007;39:1130-8. doi:10.1016/j.soilbio.2006.12.021

Panosso AR, Marques Jr J, Milori DMBP, Ferraudo AS, Barbieri M, Pereira GT, La Scala Jr N. Soil CO_2 emission and its relation to soil properties in sugarcane areas under slash-and-burn and green harvest. Soil Till Res. 2011;111:190-96. doi:10.1016/j.still.2010.10.002

Panosso AR, Marques Jr J, Pereira GT, La Scala Jr N. Spatial and temporal variability of soil CO_2 emission in a sugarcane area under green and slash-and-burn managements. Soil Till Res. 2009;105:275-82. doi:10.1590/S0103-90162013000300008

Panosso AR, Pereira GT, Marques Jr J, La Scala Jr N. Variabilidade espacial da emissão de CO_2 em Latossolos sob cultivo de cana-de-açúcar em diferentes sistemas de manejo. Eng Agríc. 2008;28:227-36. doi:10.1590/S0100-69162008000200003

Raij Bvan, Andrade JC, Cantarella H, Quaggio JA. Análise química para avaliação da fertilidade de solos tropicais. Campinas: Instituto Agronômico de Campinas; 2001.

Razafimbelo T, Barthès B, Larré-Larrouy MC, De Luca EF, Laurent JY, Cerri CC, Feller C. Effect of sugarcane residue management (mulching *versus* burning) on organic matter in a clayey Oxisol from southern Brazil. Agric Ecosyst Environ. 2006;115:285-89. doi:10.1016/j.agee.2005.12.014

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreras, JF, Coelho, MR, Almeida JA, Cunha TJF, Oliveira JB. Sistema brasileiro de classificação de solos. 3ª. ed. Brasília, DF: Embrapa; 2013.

Silva-Olaya AM, Cerri CEP, La Scala Jr N, Dias CTS, Cerri CC. Carbon dioxide emissions under different soil tillage systems in mechanically harvested sugarcane. Environ Res Lett. 2013;8:1-8. doi:10.1088/1748-9326/8/1/015014

Sisenando HA, Medeiros SRB, Artax P, Saldiva PHN, Hacon SS. Micronucleus frequency in children exposed to biomass burning in the Brazilian Legal Amazon region: a control case study. BMC Oral Health. 2012;12:6-13. doi:10.1186/1472-6831-12-6

Song Z, Yuan H, Kimberley MO, Jiang H, Zhou G, Wang H. Soil CO_2 flux dynamics in the two main plantation forest types in subtropical China. Sci Total Environ. 2013;444:363-8. doi:10.1016/j.scitotenv.2012.12.006

Stolf R. Teoria, teste experimental de fórmulas de transformação dos dados de penetrômetro de impacto em resistência do solo. Rev Bras Cienc Solo. 1991;15:229-35.

Vieira SR. Geoestatística em estudos de variabilidade especial do solo. Tópicos Cienc Solo. 2000;1:1-53.

United States Department of Agriculture – USDA. Keys to Soil Taxonomy. 20th ed. Washington, DC: Natural Resources Conservation Service; 2014.

Xu M, Qi Y. Soil surface CO_2 efflux and its spatial and temporal variations in a young ponderosa pine plantation in northern California. Global Change Biol. 2001;7:667-77. doi:10.1046/j.1354-1013.2001.00435.x

Zornoza R, Guerreo C, Mataix-Solera J, Arcenegui V, Garcia-Orenes F, Mataix-Beneyto J. Assessing the effects of air-drying and rewetting pre-treatment on soil microbial biomass, basal respiration, metabolic quotient and soluble carbon under Mediterranean conditions. Eur J Soil Biol. 2007;43:120-9. doi:10.1016/j.ejsobi.2006.11.004