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Spatial and temporal variability of soil CO_2 emission in a sugarcane area under green and slash-and-burn managements

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ABSTRACT

Soil management causes changes in physical, chemical, and biological properties that consequently affect soil CO_2 emission (FCO2). Here, we studied the soil carbon dynamics in areas with sugarcane production in southern Brazil under two different sugarcane management systems: green (G), consisting of mechanized harvesting that produces a large amount of crop residues left on the soil surface, and slash-and-burn (SB), in which the residues are burned before manual harvest, leaving no residues on the soil surface. The study was conducted during the period after harvest in two side-by-side grids installed in adjacent areas, having 60 points each. The aim was to characterize the temporal and spatial variability of FCO2, and its relation to soil temperature and soil moisture, in a red latosol (Oxisol) where G and SB management systems have been recently used. Mean FCO2 emission was 39% higher in the SB plot (2.87 μmol m^{-2} s^{-1}) when compared to the G plot (2.06 μmol m^{-2} s^{-1}) throughout the 70-day period after harvest. A quadratic equation of emissions versus soil moisture was able to explain 73% and 50% of temporal variability of FCO2 in SB and G, respectively. This seems to relate to the sensitivity of FCO2 to precipitation events, which caused a significant increase in SB emissions but not in G-managed area emissions. FCO2 semivariogram models were mostly exponential in both areas, ranging from 72.6 to 73.8 m and 63.0 to 64.7 m for G and SB, respectively. These results indicate that the G management system results in more homogeneous FCO2 when spatial and temporal variability are considered. The spatial variability analysis of soil temperature and soil moisture indicates that those parameters do not adequately explain the changes in spatial variability of FCO2, but emission maps are clearly more homogeneous after a drought period when no rain has occurred, in both sites.

1. Introduction

Fluxes of carbon (C) from soil affected by land use or management can impact the existing pool of CO_2 in the atmosphere (Epron et al., 2004; Sartori et al., 2006). Also, it has been argued that the capacity of agricultural soils worldwide to restore atmospheric C as soil organic matter (SOM) could be increased in 60 Pg C, back to the original level of soil C pool (240 Pg C) (Harrison et al., 1993).

It is estimated that in Brazil the C stored in the 0–30 cm soil depth is around 36.4 $\pm$ 3.4 Pg C. Additionally, changes in land use and agricultural practices are responsible for more than two thirds of total greenhouse gases emission (Bernoux et al., 2002).

Presently, Brazil is the world's main sugarcane (*Saccharum* spp.) producer with 7.0 million ha planted; the state of São Paulo is the major producer and responsible for 3.7 million ha. Considering that the total area cropped with sugarcane increased around 13% in São Paulo state in 2008 (National Supply Company – CONAB, 2008), the study of the spatial and temporal changes of soil CO_2 emission (FCO2) in sugarcane agrosystems in the state of São Paulo is of great interest.

However, in Southern Brazil, more important than the agricultural expansion are the changes in management practices occurring in sugarcane areas, where this crop is associated with food, biofuel, and energy production, being considered as an important alternative when the problem of climate change is addressed (Cerri et al., 2007). In sugarcane plantations, large areas have been converted from one production system (slash-and-burn) to another (green). In slash-and-burn (SB) areas, sugarcane is burned in the field a few days before harvesting to facilitate manual slashing by removing leaves and insects. Slash-and-burn management has an immediate and direct effect on the physical and hydrological properties of the soil (Are et al., 2009). On the other hand, in green (G) 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 burning system (Razafimbelo et al., 2006; Cerri et al., 2007). It has been argued that soil management practices

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would result in modifications of the soil's physical and chemical properties, affecting microbial activity and consequently soil CO_2 emission (Sartori et al., 2006; Cerri et al., 2007). Still, little is known about the changes in soil properties when conversion from SB to G agrosystem is considered, and how this may affect the loss of soil CO_2.

The magnitude of FCO2 varies in time and space depending on the environmental conditions, soil characteristics, and agricultural management adopted. The value of the coefficient of variation (CV) of FCO2 is the first indicative of spatial variability of the FCO2; however, this is not enough to compare CO_2 emissions from different studies, especially because no information on the points of the spatial distribution is available (Fang et al., 1998). Geostatistics provide the basis for describing quantitative spatial variations in soil that can be used for estimating soil properties (Webster, 1985; Webster and Oliver, 1990). Indeed, geostatistical analysis has been used to study several soil properties, most of them physical and chemical (Cambardella et al., 1994; Wang et al., 2002), but also biological properties such as FCO2 in various ecosystems, from forests to bare soils (La Scala Jr. et al., 2000; Ishizuka et al., 2005; Ohashi and Gyokusen, 2007; Konda et al., 2008). However, only few studies using geostatistic analysis have been conducted in order to examine the spatial structure of soil CO_2 emission in sugarcane areas (Panosso et al., 2008). Understanding the spatial variability of soil CO_2 emission in agricultural areas in Brazil is important for conducting a controlled and sustained management of cropping. This may help preserving the carbon in the soil and reducing the greenhouse effects.

To be able to estimate the amount of soil respiration it is also imperative to describe its temporal variability and the relationship between soil respiration and environmental variables that can be continuously monitored, such as temperature and soil moisture content. In tropical regions where seasonal variation in soil temperature is small, soil moisture should be tested and considered as the most effective index to estimate the seasonal variation of soil respiration rate (Kosugi et al., 2007).

Here we raised the hypothesis that different harvest practices would result in different soil carbon dynamics in each plot, which in turn could be expressed in terms of spatial and temporal variability, and relations with the main controlling factors: soil temperature and soil moisture. In this study we focused on the spatial and temporal characterization of soil CO_2 emission in sugarcane areas cropped with two contrasting harvest systems: slash-and-burn and green.

2. Materials and methods

This study was done on São Bento farm, which belongs to the São Martinho ethanol plant, in an area that has been devoted to sugarcane production for the last 35 years, located in Guariba city, São Paulo, Brazil (Fig. 1). The geographical coordinates are 21° 24′ S and 48° 09′ W, with mean elevation around 550 m above sea level. Regional climate is classified as Aw (according to Köepen), tropical with rainy summer and dry winter. Mean rain precipitation is around 1425 mm, concentrated mostly between October and March. The mean annual temperature registered in the region during the last 30 years is 22.2 °C.

The studied area has a soil type that is classified as high clay, Oxisol (Eutrustox, USDA Soil Taxonomy). Located in an area with low slope (3–4%), two side-by-side plots were installed. Each plot had its own management system. One was green (G), with a history of mechanized harvest in the last 7 years, resulting in a huge amount of sugarcane crop residues left on the ground after the harvest (12 tons/ha), which occurred on 16 May 2007 (Julian day 136). The other was slash-and-burn (SB) management with a history of sugarcane cropped since 1970; this plot was harvested on 9 June 2007 (Julian day 160). Two identical 190 m × 50 m grids presenting 60 points each were installed in the studied plots, with a minimum distance of 13.3 m between points (Fig. 1).

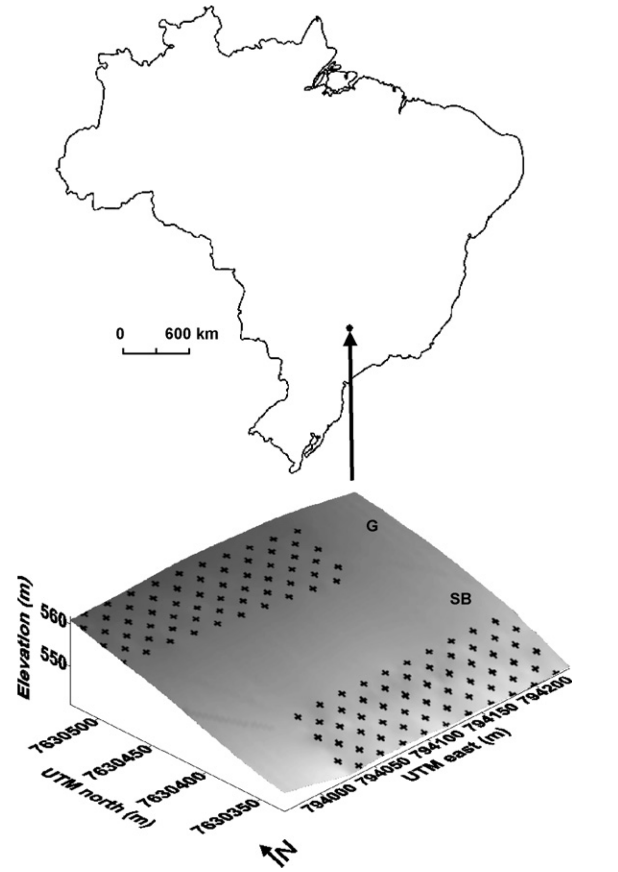

Fig. 1. Map showing the site location and the two grids installed on the green (G) and slash-and-burn (SB) areas.

FCO2 was registered with a portable LI-COR system (LI-8100, Lincoln, NE, USA), during the stage where the crop ratoon was on its initial growth phase. In the measurement mode the LI-8100 system monitors the changes in CO_2 concentration inside the chamber by using an infrared gas analyzer (IRGA). The soil chamber has an internal volume of 854.2 cm^3 with a circular contact area to soil of 83.7 cm^2, and was placed on PVC soil collars previously inserted at a depth of 3 cm into soil grid points. Soil temperature (T_{soil}) was monitored by using a 20 cm depth probe (thermistor based) inserted into the soil close to the collars. Soil moisture (M_{soil}), with its % in volume, was registered with a portable hydrosense system (TDR probe, Campbell, USA). Twenty points were chosen in each grid in order to conduct the temporal variability studies, which occurred up to 70 days after harvest. Those measurements were taken on the following Julian days of the year 2007: 190, 192, 195, 200, 201, 204, 208, 209, 215, 227, 234, 241, 255, and 260. They were done once a day, in the mornings (7–9 am). For the spatial variability studies, measurements were taken in each one of the grids on days 191, 200, and 248 (G) and 192, 201, and 246 (SB), in the mornings (7–10 am).

Descriptive statistics (mean, standard deviation, standard error, minimum, maximum, and coefficient of variation) was used to classify the variability of FCO2, T_{soil}, and M_{soil}. Additionally, variance and non-linear regression analysis was applied to the temporal variability data. The spatial variability dependence was analyzed by applying geostatistic techniques (Webster and Oliver, 1990) to all of the variables studied. We considered that when conditions specified by the intrinsic hypothesis are fulfilled, the semivariogram has the form of (Burrough and McDonnell, 1998):

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

where $\hat{\gamma}(h)$ is called semivariance at separation distance h; N is the number of pairs separated by h distance (in this work the semivariance for a given distance was calculated with N greater than 50); $Z(x_i)$ is the value of variable Z at point x_i; and $Z(x_i + h)$ is the value of variable Z at point $x_i + h$. Plotting $\hat{\gamma}(h)$ against h gives the semivariogram, which either exhibits purely random behavior or some systematic behavior described by theoretical models (linear, spherical, exponential, Gaussian, and power law models). Model coefficients were determined by the best fit to all the semivariance data. For variables that depended on separation distance, it was expected that the values of $Z(x_i) - Z(x_i + h)$ would increase with the distance h up to a given distance, after which point the values would stabilize. The semivariance value in which the semivariogram curve stabilized is called sill and it was represented by the symbol $C_0 + C_1$. It was similar to the variance of the analyzed data. The distance in which the stabilization of semivariogram occurred, called the range distance, was represented by a and defined as the spatial dependence limit. The C_1 value represented the structured spatial variability of data. The nugget effect, represented by the symbol C_0, is the semivariance value found at the intercept with the Y axis. Theoretically, this value should be zero for a lag distance (h) of zero, however, sampling error measurements and short-scale variability can cause deviation from zero. Therefore, the nugget effect represents the amount of variance not explained or modeled as spatial correlation. The parameters C_0, $C_0 + C_1$, and a are currently used in semivariogram fitting equations and were presented here to compare the spatial variability models of soil CO_2 emission, soil temperature, and soil moisture (Trangmar et al., 1985; Isaaks and Srivastava, 1989). The ratio between nugget effect and sill ($C_0/C_0 + C_1$), expressed as a percentage, was used to classify the spatial dependence of the studied properties, according to the work of Cambardella et al. (1994). As such, strong, moderate, or weak spatial dependence were considered to exist when $(C_0/C_0 + C_1) \leq 0.25$, $0.25 < (C_0/C_0 + C_1) < 0.75$, and $(C_0/C_0 + C_1) \geq 0.75$, respectively. Before the geostatistic analyses, a lognormal transformation was applied to normalize skewed frequency distribution of FCO2.

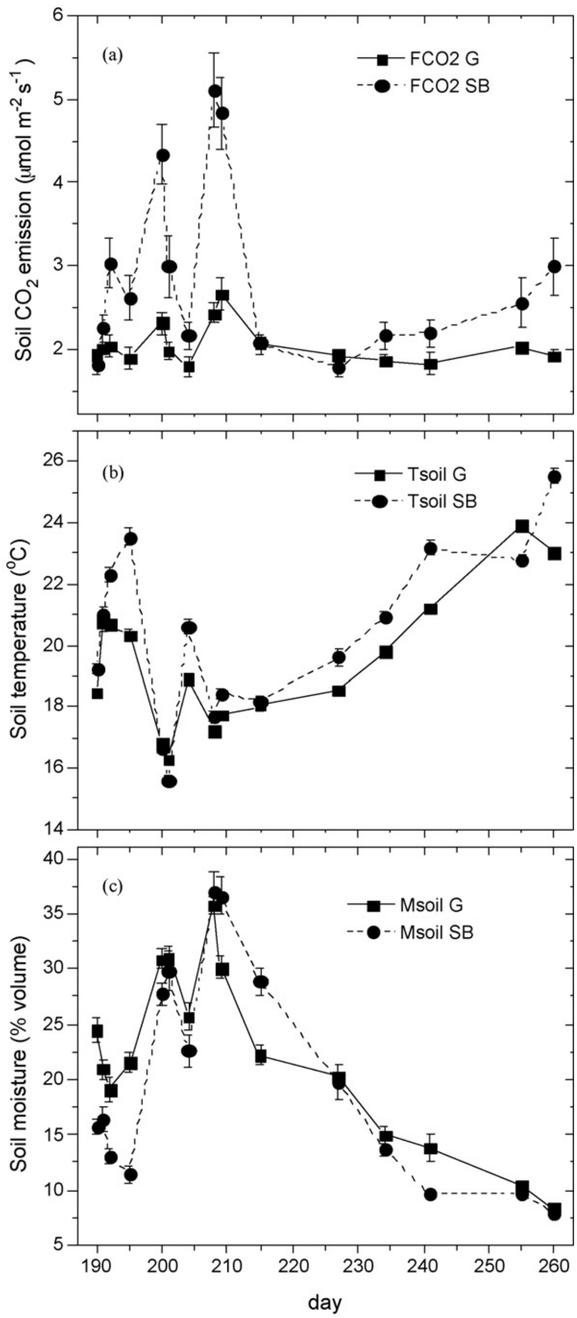

Fig. 2. Temporal variability of (a) soil CO_2 emission; (b) soil temperature; (c) soil moisture in slash-and-burn and green during 70 days of study.

Only isotropic semivariograms were considered in this study. Experimental semivariograms were adjusted for the following theoretical models: (a) exponential, $\hat{\gamma}(h) = C_0 + C_1\{1 - \exp[-3(h/a)]\}$, $h > 0$ and (b) spherical, $\hat{\gamma}(h) = C_0 + C_1[3/2(h/a) - 1/2(h/a)^3]$, $0 \leq h \leq a$, and $\hat{\gamma}(h) = C_0 + C_1$, $h > a$. The cross-validation procedure, which consists of removing each observation that belongs to the dataset and the subsequent estimate of its value by interpolation, was used to verify the reliability of the mathematical model. The model chosen was the one that adjusted the observed and estimated values closer, i.e., the one that produced a linear regression equation between the observed and estimated values that was closer to the bisectrix (Isaaks and Srivastava, 1989). The semivariance and the subsequent semivariogram adjusted models were conducted by using GS+ software (Gamma Design Software, 1998). By using the adjusted models we performed estimates of soil CO_2 emission, soil temperature, and soil moisture in non-sampled places by means of kriging (Trangmar et al., 1985).

3. Results and discussions

3.1. Temporal variability study

Temporal variability of FCO2, T_{soil}, and M_{soil} in SB and G managed systems is shown in Fig. 2, while the descriptive statistics are presented in Table 1. Mean value ± standard error indicates that mean FCO2 was 39% higher in the SB (2.87 ± 0.28 μmol m^{-2} s^{-1}) and significantly different ($p < 0.05$) when compared to the G (2.06 ± 0.06 μmol m^{-2} s^{-1}) emissions during the 70-day period studied. Emission values found here are similar to the ones registered in the same season and region, in which values from 1.70 to 2.21 μmol m^{-2} s^{-1} were registered (Brito et al., 2009). Total emissions from the managed systems, at the end of the 70-day period, were 692 and 537 g CO_2 m^{-2} for SB and G, respectively. Hence, an additional amount of 42.3 g C–CO_2 m^{-2} was released to the atmosphere in the SB plot when compared to the G plot. Our results corroborate those from McCool et al. (2008), who observed higher

Table 1
Descriptive statistics of soil CO_2 emission (FCO2, μmol m^{-2} s^{-1}), soil temperature (T_{soil}, °C) and soil moisture (M_{soil}, vol.%) for slash-and-burn (SB) and green (G) managed systems.

	Mean	SD	SE	Minimum	Maximum	CV (%)
Green						
Soil CO_2 emission	2.06	0.24	0.06	1.81	2.67	11.7
Soil temperature	19.44	2.22	0.57	16.29	23.90	11.4
Soil moisture	21.95	7.96	2.05	8.30	35.80	36.2
Slash-and-bun						
Soil CO_2 emission	2.86	1.07	0.28	1.79	5.11	37.2
Soil temperature	20.35	2.79	0.72	15.58	25.54	13.7
Soil moisture	20.00	9.85	2.54	7.90	37.00	49.3

$N = 20$; SD: standard deviation; SE: standard error; CV: coefficient of variation.

microbial respiration in the top 5 cm of burned soil when compared to a conventionally managed plot of wheat. This might be explained by a higher portion of carbon available to microbes added from residues.

T_{soil} means were 20.3 and 19.4 °C, while M_{soil} means were 20 and close to 22%, in SB and G, respectively (Table 1). Fig. 2a–c presents the temporal variability of studied properties, indicating that FCO2 and T_{soil} in SB were frequently higher than in G, while M_{soil} kept lower values in G on most of the studied days. We noticed that significant differences in FCO2 were mostly observed in the first 20 of the 70 days studied, during the growing season. Maximum FCO2 values were registered on day 208 in SB and G (Fig. 2a), coinciding with the same day when M_{soil} reached its highest values (Fig. 2c). Considering the total porosity in the first 25 cm of soil layer (50% for G and 48% for SB), we assumed that maximum emissions in both plots were found when water filled 60% and 77% of total porosity in G and SB, respectively. The SB-studied variables presented higher CV values, when compared to G ones, especially for FCO2 and M_{soil} (as seen in Table 1, or even Fig. 2). However, CV values found here are similar to those observed in forests (Fang et al., 1998; Xu and Qi, 2001; Ohashi and Gyokusen, 2007; Konda et al., 2008) and reported in previous studies in bare soil (La Scala Jr. et al., 2000). As the crop residues in the G plot surface favor lower temperatures and higher soil moisture as, for instance, on day 195, T_{soil} was more than 3 °C cooler and M_{soil} was 10% higher in G than in the SB plot (Fig. 2b and c). Consequently, as temporal variability of FCO2 is governed by the changes in T_{soil} and M_{soil} (Xu and Qi, 2001; Tedeschi et al., 2006; Kosugi et al., 2007; Ohashi and Gyokusen, 2007; Concilio et al., 2009), the G plot's lower FCO2 and its lower CV value are certainly related to the surface residues, especially during the first weeks of our study.

The analysis of variance (one-way analysis) of repeated measures indicates a high significance ($p < 0.0001$) between crop management systems and time (days) for all studied variables. Therefore, FCO2 does not have the same temporal variability pattern when both management systems are compared. For the G management system, there were no significant differences ($p > 0.05$) in FCO2 over time as opposed to the SB system, which presented high oscillations in FCO2 during the studied period ($p < 0.01$). This is most likely related to the fact that the FCO2 in the SB system was further affected by climatic events, such as precipitation that occurred during the experimental period. Increases in FCO2 in the SB plot were observed after rain occurred on days 198 and 205, with 21 and 127 mm, respectively. These events happened around the day when emissions reached values as high as 5.11 μmol m^{-2} s^{-1} (day 208).

Interestingly, Epron et al. (2004) found no effect of rainfall on FCO2, a result which was similar to what we observed for the G-managed plot. The changes in FCO2 after precipitation indicate a higher sensitivity of FCO2 in relation to M_{soil} in the SB system when compared to the G system.

To better understand the relation between sensitivity of FCO2 and changes in soil moisture caused by precipitation, we conducted a linear regression analysis between FCO2 and M_{soil}. This analysis indicated that soil moisture determined the time changes of emissions in both plots. On the other hand, no significant correlation was found between emission and soil temperature ($p > 0.10$), in both systems. This may be explained by the fact that during the course of the experiment, soil temperature was always around an optimal condition for microbial activity (around 20 °C). In this case, our result is similar to the one found by Epron et al. (2004), where bivariate models including soil temperature and soil water content did not explain seasonal variation of soil respiration better than univariate models, when considering soil water content with soil moisture only. In our study, M_{soil} alone explains 37% and 42% of FCO2 variability in G and SB systems, respectively. However, better results were obtained for a quadratic relationship between FCO2 and M_{soil}, as similar to other studies (Schwendenmann et al., 2003; Epron et al., 2004; Kosugi et al., 2007). Our coefficient of determination was as high as 0.73 for SB in predicting the temporal changes of FCO2 based on soil moisture (Table 2). As it can be seen by the estimated parameters ± standard error presented in Table 2, parameters are mostly significant ($p < 0.05$) for the SB regression. It is also noticeable that a_1 and a_2 extracted parameters for the SB model have higher values than the ones derived for the G model, indicating also a higher sensitivity of FCO2 to M_{soil} in that system. This effect is similar to that observed by Ussiri and Lal (2009), who measured a higher sensitivity value in a conventional tillage plot when compared to no-till, when the relation of soil CO_2 emission to soil temperature and soil moisture were considered.

3.2. Spatial variability study

Mean values of FCO2 observed in G-managed grids were 1.97, 2.03, and 2.18 μmol m^{-2} s^{-1} on days 192, 201, and 246, respectively. For SB grids, the means were 2.03, 5.29, and

Table 2
Parameters of the quadratic regression between soil CO_2 emission (FCO2) and soil moisture (M_{soil}) derived for both management systems.

Management system	Quadratic regression FCO2 = $a_0 + a_1 \times M_{soil} + a_2 \times M_{soil}^2$			
	a_0	a_1	a_2	R^2
Green	2.1983 ± 0.3416	−0.0388 ± 0.0331 [NS]	0.0013 ± 0.0007 [NS]	0.50
Slash-and-burn	4.6367 ± 0.9169	−0.2820 ± 0.0951	0.0079 ± 0.0021	0.73

[NS] Non-significant as $p > 0.05$. a_0: μmol m^{-2} s^{-1}. a_1: μmol m^{-2} s^{-1} (vol.%)$^{-1}$. a_2: μmol m^{-2} s^{-1} (vol.%)$^{-2}$.

Table 3
Means ± standard error, CV, models and estimated parameters of experimental semivariograms obtained for soil CO_2 emission (μmol $m^{-2}s^{-1}$), soil temperature (°C) and soil moisture (vol.%) in green and slash-and-burn management systems.

Day	Mean ± SE	CV	Model	C_0	C_0+C_1	a	SSR	R^2	DSD
Soil CO_2 emission (μmol $m^{-2}s^{-1}$)									
Green									
192	1.97 ± 0.07	26.1	Exp	0.018	0.079	73.8	2.62E−4	0.72	0.23
201	2.03 ± 0.07	26.2	Exp	0.022	0.056	72.6	1.76E−5	0.91	0.39
246	2.16 ± 0.06	22.6	NE	–	–	–	–	–	–
Slash-and-burn									
191	2.03 ± 0.12	45.6	Exp	0.016	0.122	63.0	1.27E−3	0.67	0.13
200	5.29 ± 0.43	63.5	Exp	0.019	0.147	64.7	1.50E−3	0.77	0.12
248	2.86 ± 0.16	43.6	NE	–	–	–	–	–	–
Soil temperature (°C)									
Green									
192	20.06 ± 0.12	4.5	Sph	0.278	0.585	54.0	8.10E−4	0.97	0.47
201	16.93 ± 0.14	6.4	Sph	0.147	0.749	53.9	1.71 E−2	0.87	0.20
246	22.82 ± 0.11	3.8	Sph	0.375	0.773	59.2	9.31E−3	0.83	0.48
Slash-and-burn									
191	19.87 ± 0.17	6.5	Sph	0.148	1.950	51.4	2.61E−1	0.84	0.08
200	17.29 ± 0.12	5.5	Sph	0.154	0.807	57.4	1.36E−2	0.94	0.19
248	24.90 ± 0.11	3.5	Sph	0.258	0.730	42.7	4.92E−2	0.58	0.35
Soil moisture (vol.%)									
Green									
192	18.98 ± 0.54	22.2	NE	–	–	–	–	–	–
201	33.30 ± 0.81	18.9	NE	–	–	–	–	–	–
246	11.22 ± 0.29	20.1	NE	–	–	–	–	–	–
Slash-and-burn									
191	17.17 ± 0.74	33.2	Exp	1.70	25.330	48.9	2.96E+1	0.78	0.07
200	28.97 ± 0.78	20.8	Exp	10.42	28.500	48.9	6.53E+1	0.49	0.37
248	9.03 ± 0.20	17.5	Sph	1.00	2.552	45.5	2.79E−1	0.72	0.39

$N = 60$; DSD: degree of spatial dependence = $C_0/(C_0 + C_1)$, strong for values smaller than 0.25, moderate for values between 0.25 and 0.75; weak for values higher than 0.75 (Cambardella et al., 1994); SSR: sum-square residue; Exp: exponential; Sph: spherical; NE: nugget effect.

2.86 μmol m^{-2} s^{-1} on days 191, 200, and 248, respectively. Those are comparable to results found by Xu and Qi (2001), who observed high values of FCO2 in a forest study (4.7, 3.4, and 4.2 μmol m^{-2} s^{-1}), but superior to Konda et al. (2008), who found FCO2 values around 0.739 μmol m^{-2} s^{-1} in a leguminous tree plantation. The maximum daily FCO2 mean observed in SB was 5.29 μmol m^{-2} s^{-1} at day 200 (Table 3). Precipitation of 21 mm occurred between days 197 and 198, and could be the reason for

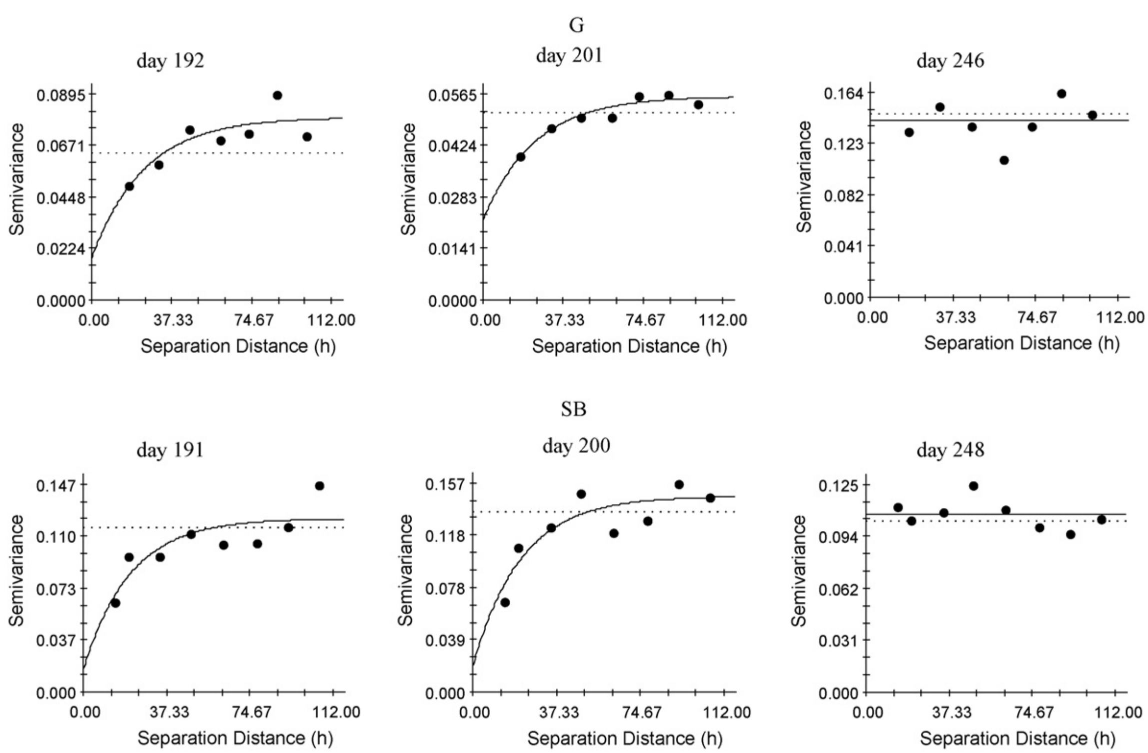

Fig. 3. Semivariograms of CO_2 emission on six studies days. G: green, days 192, 201 and 246; SB: slash-and-burn, days 191, 200 and 246.

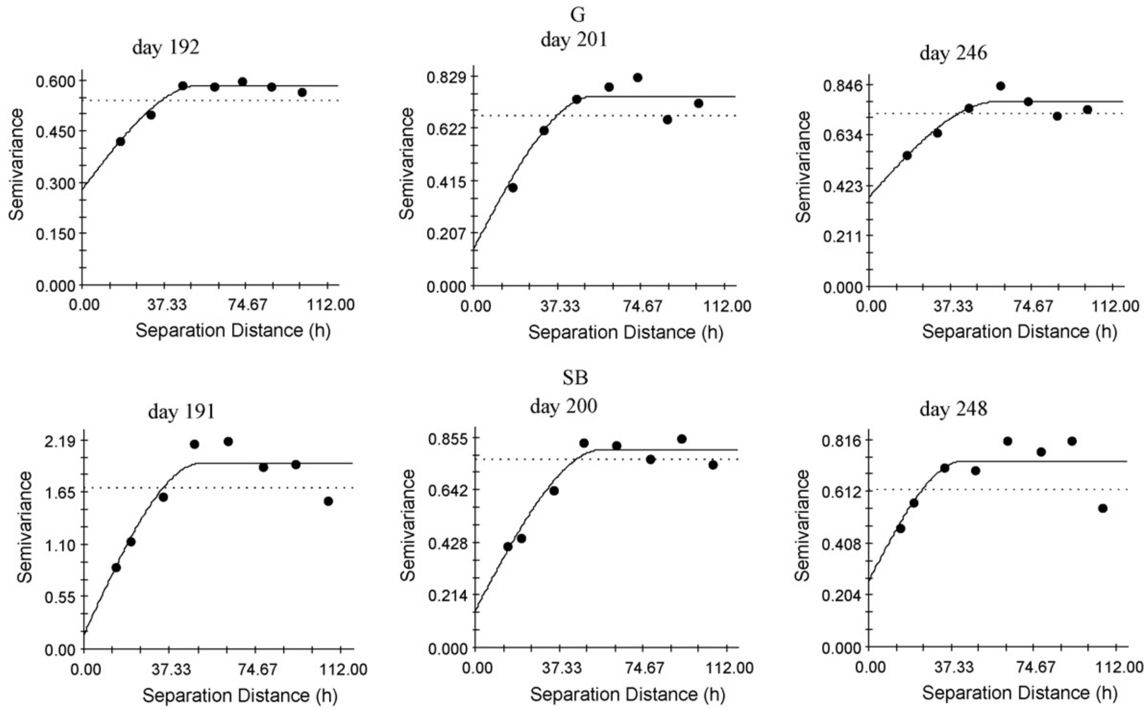

Fig. 4. Semivariograms of soil temperature on studies days. G: green, days 192, 201 and 246; SB: slash-and-burn, days 191, 200 and 246.

the 160% emission increase from days 191 to 200, in SB plots. In a similar study, La Scala Jr. et al. (2000) observed an increase of 63% in FCO2 from a bare Oxisol after a rainy period (14.4 mm). The same observation was not made in the G system, where the values of FCO2 were around 2.05 μmol m^{-2} s^{-1} during the experimental period, without a significant increase on standard error values, after a precipitation event. Based on mean emission values and standard errors presented in Table 3, it is possible to state that emissions in the SB plot differ mostly from day to day, while in the G plot, emissions are more constant and around 2.05 μmol m^{-2} s^{-1}.

The CV coefficients of FCO2 sampled in the grids ranged from a minimum of 22.6% to a maximum of 63.5% observed in G (day 246) and SB (day 200), respectively (Table 3). The CV values of FCO2 are in agreement with those reported in the literature (Rochette et al., 1991; Dasselaar et al., 1998; La Scala Jr. et al., 2000; Schwenden-

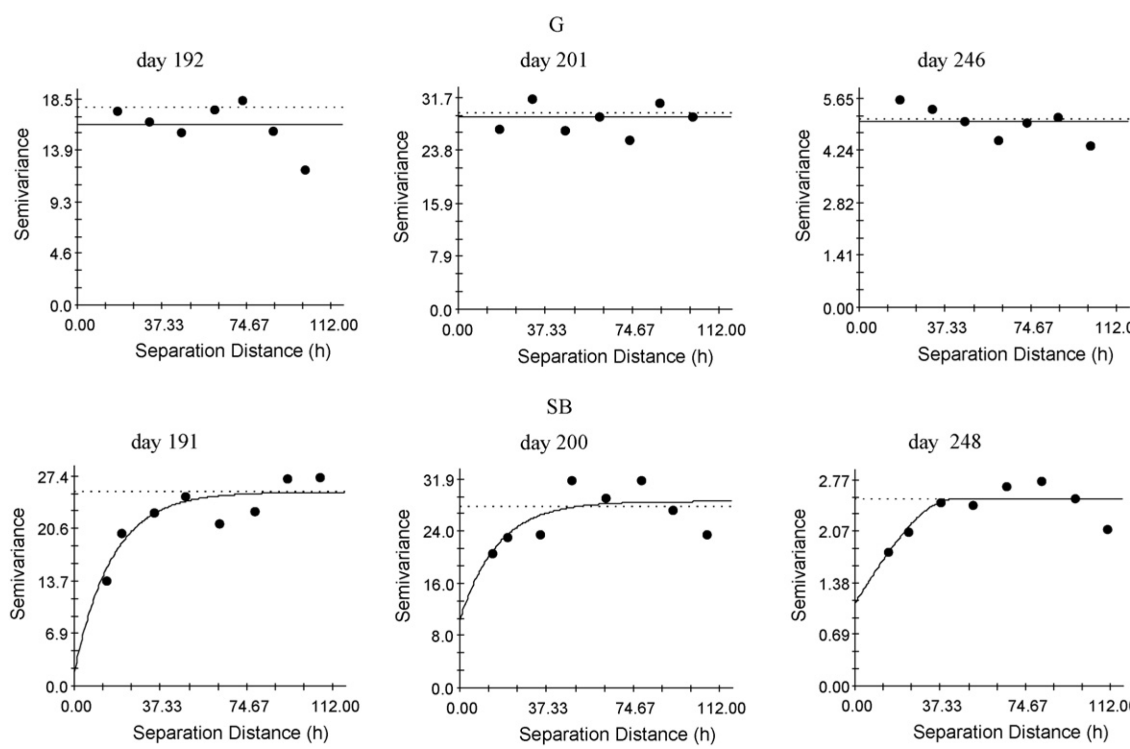

Fig. 5. Semivariograms of soil moisture on studies days. G: green, days 192, 201 and 246; SB: slash-and-burn, days 191, 200 and 246.

mann et al., 2003; Epron et al., 2004; Tedeschi et al., 2006; Konda et al., 2008). Lowest CV values were found for T_{soil} analysis (3.5–6.5%), while intermediate CV values (between 18% and 33%) were observed in M_{soil}, in both areas. Generally, CV values decreased throughout the days studied for all properties. So, based on CV, spatial variation in T_{soil} was less than for FCO2, suggesting a minimal effect of T_{soil} on spatial variation of FCO2. The M_{soil} decreased almost monotonically during days 208–260, due to a drought period over the experimental site (Fig. 2c). According to the classification criteria of spatial variability of soil properties, proposed by Warrick and Nielsen (1980), the CV values found for FCO2 could be considered moderate for the G plot only on day 246 (12% < CV < 24%). For all the other days, FCO2 CV values could be considered high (>24%). CV values for T_{soil} could be considered low (<12%) for all the days studied in both areas. The M_{soil} showed moderate CV values, except for day 191, in the SB area, when the CV value was considered high (33.2%).

Soil management interfered directly on the variability, as we observed higher CV values in FCO2 when SB is compared to the G management system, especially after the rain that occurred close to day 199. Therefore, the management associated with the rain caused higher FCO2 emissions and even higher variability of emissions in the SB plot, when compared to G. The increase of the FCO2 value after precipitation has been observed in other studies (Rochette et al., 1991; Davidson et al., 2000). In such cases, where CV values are high, geostatistical techniques are justified in order to characterize the spatial variability pattern of studied properties.

The adjusted semivariogram models for FCO2 in both areas were mostly exponential (Table 3 and Fig. 3), except for days 246 (G) and 248 (SB), which did not present a spatial variability structure (nugget effect). Most of the adjusted models had a high coefficient of determination, as presented by their R^2 values. The exponential model is better adjusted to erratic phenomena at closer distance, while spherical models describe variables with high spatial continuity, or less erratic at closer distance (Isaaks and Srivastava, 1989). Stoyan et al. (2000) adjusted exponential models for semivariograms derived from FCO2 in poplar and wheat plots. Most of the spatial variability models of FCO2 have been described with spherical models (Dasselaar et al., 1998; La Scala Jr. et al., 2000; Ishizuka et al., 2005; Kosugi et al., 2007; Konda et al., 2008) or changes in models between spherical and exponential (Tedeschi et al., 2006; Ohashi and Gyokusen, 2007). The lack of a spatial variability structure also agrees with the days that CV presented lower values, in a dry period with no precipitation occurring in the previous 50 days. Changes in the spatial variability pattern and models of FCO2 were similar in both management systems (Fig. 4), with a modifying exponential to nugget effect after a dry period, also characterized by a huge reduction of M_{soil} from days 201 to 246 and 200 to 248, in G and SB, respectively. The T_{soil} presented spherical models for all days in both areas with spatial variability structures which were also very similar (Fig. 5, Table 3). For spatial variability of M_{soil} models they were exponential for days 191 and 208 and spherical for day 248 in SB, while the G management system showed pure nugget effect for all days studied.

Spatial variability of FCO2 at small scales is similar in both management systems, as they present similar C_0 values. When analyzing the spatial variability structure, expressed by C_1 values, we observed that their higher values were found in SB, in agreement with their CV characterization, also presenting higher values. The degree of spatial dependence (DSD), expressed by the ratio between the nugget effect (C_0) and total variance ($C_0 + C_1$) or sill (Cambardella et al., 1994), was classified as strong for FCO2 in SB (days 191 and 200), while in G, this value was classified as strong and moderate for days 192 and 201, respectively. Other studies have shown a weak degree of spatial dependence (Ishizuka et al., 2005) or moderate (La Scala Jr. et al., 2000; Stoyan et al., 2000) on FCO2, in which variation depended on the seasons (Ohashi and Gyokusen, 2007) and plot size (Konda et al., 2008).

Ranges (a) of FCO2, T_{soil}, and M_{soil} found that adjusted semivariograms show small changes from day to day (Table 3). This was mostly observed for SB T_{soil} and M_{soil}, where values ranged from 42.7 to 57.4 m and 45.5 to 48.9 m, respectively. Minor changes were observed in range values from days 192–201 (G) and 200–248 (SB), until the last days of the study, when no spatial variability structure was observed in either system. Changes in range of spatial variability models of FCO2 have been reported from season to season (Ohashi and Gyokusen, 2007), month to month (Stoyan et al., 2000), after rain (La Scala Jr. et al., 2000), or even according to the plot size (Rayment and Jarvis, 2000; Konda et al., 2008). Kosugi et al. (2007) reported values for respiration rate from 4.4 m in the rainy period to 7.9 and 14.1 m in the dry period, with values for soil water content ranging between 5.3 m in the dry period and 16.6 m in the rainy period. In our study, M_{soil} shows variation of spatial autocorrelation from before and after a rainy period of 48.9 m and 45.5 m, even after 50 days without rain, but this pattern was observed only in SB. We observed spatial variability in soil CO_2 emission, but this variability cannot be attributed to spatial variability in soil temperature and soil moisture, in the SB plot.

The average ranges of spatial variability models were around 73.2 and 63.9 m, for G and SB emissions. Such values can provide

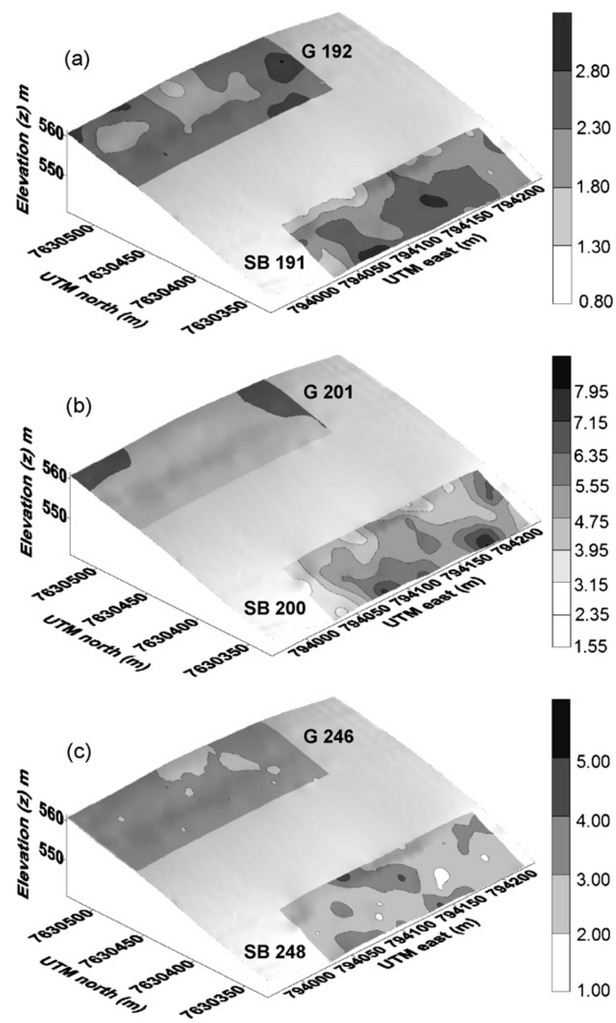

Fig. 6. Maps of spatial pattern of soil CO_2 emission (μmol m^{-2} s^{-1}) in green (G) and slash-and-burn areas (SB) in days (a) 191 and 192, (b) 200 and 201 and (c) 246 and 248.

information on heterogeneity of spatial distribution regarding the studied properties in each management system (Trangmar et al., 1985). The higher range value of FCO2 spatial variability structure found in G when compared to the SB area, suggests a more homogeneous distribution of FCO2 in the system where crop residues are kept on the soil surface, similar also to what we observed in temporal variability. Therefore, a smaller number of points would be needed to estimate mean values of FCO2 in G systems than in SB, in agreement with a similar study conducted in a different site but on the same soil type, where nugget effect was observed in spatial variability model in the SB plot but not in the G plot, that presented a range distance around 33 m (Panosso et al., 2008).

The kriging maps of FCO2 drawn based on the studied days, for both managed systems, can be seen in Fig. 6. The spatial variability analysis presents the higher spatial discontinuity of FCO2 in the SB location when compared to G, as confirmed by the higher CV values for all studied days. Spatial variability of FCO2 seems to be even more homogenous in both managed systems after a drought period, when no rain has occurred for 50 days (days 200–248). This effect could be also due to the increase of root respiration into the total FCO2 throughout the 70-day period after harvest, showing the complexity of this phenomenon.

4. Conclusions

Mean of FCO2 was 39% superior in SB, corresponding to an additional 155.2 g CO_2 m^{-2} emission in a 70-day period, when compared to the G plot. Temporal variability of FCO2 was higher in SB, according to CV values. This is explained by the sensitivity of its emission to soil moisture, which is affected by rain. Spatial variability analysis indicates no effect of soil temperature on spatial variation in FCO2. Semivariogram models for FCO2 were exponential in both management systems, indicating a more homogeneous distribution in the G plot, in which a small number of points is needed to characterize the plot emission, when compared to the SB plot. Sugarcane management practices affected temporal and spatial FCO2 variability, suggesting that management causes changes in soil carbon dynamics in time and space, and their relation to the controlled variables T_{soil} and M_{soil}.

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References

Are, K.S., Oluwatosin, G.A., Adeyolanu, O.D., Oke, A.O., 2009. Slash and burn effect on soil quality of an Alfisol: soil physical properties. Soil Till. Res. 103, 4–10.

Bernoux, M., Carvalho, M.C.S., Volkoff, B., Cerri, C.C., 2002. Brazil's soil carbon stocks. Soil Sci. Soc. Am. J. 66, 888–896.

Brito, L.F., Marques Jr., J., Pereira, G.T., Souza, Z.M., La Scala Jr., N., 2009. Soil CO_2 emission of sugarcane field as affected by topography. Sci. Agric. 66, 77–83.

Burrough, P.A., McDonnell, R.A., 1998. Principles of Geographical Information System. Oxford University Press, UK, p. 333.

Cambardella, C.A., Moorman, T.B., Novak, J.M., Parkin, T.B., Karlen, D.L., Turco, R.F., Konopka, A.E., 1994. Field-scale variability of soil properties in central Iowa soils. Soil Sci Soc. Am. J. 58, 1501–1511.

Cerri, C.E.P., Sparovek, G., Bernoux, M., Easterling, W.E., Melillo, J.M., Cerri, C.C., 2007. Tropical agriculture and global warming: impacts and mitigation options. Sci. Agric. 64, 83–99.

Concilio, A., Chen, J., MA, S., North, M., 2009. Precipitation drives interannual variation in summer soil respiration in a Mediterranean-climate, mixed-conifer forest. Climatic Change 92, 109–122.

Dasselaar, A.V.P.V., Corré, W.J., Priemé, A., Klemedtsson, Å.K., Weslien, P., Stein, A., Klemedtsson, L., Oenema, O., 1998. Spatial variability of methane, nitrous oxide and carbon dioxide emissions from drained grassland. Soil Sci. Soc. Am. J. 62, 810–817.

Davidson, E.A., Verchot, L.V., Cattânio, J.H., Ackerman, I.L., Carvalho, J.E.M., 2000. Effects of soil water content on soil respiration in forests and cattle pastures of eastern Amazonia. Biogeochemistry 48, 53–69.

Epron, D., Nouvellon, Y., Roupsard, O., Mouvondy, W., Mabiala, A., Saint-André, L., Joffre, R., Jourdan, C., Bonnefond, J., Berbigier, P., Hamel, O., 2004. Spatial and temporal variations of soil respiration in a Eucalyptus plantation in Congo. Forest Ecol. Manage. 202, 149–160.

Fang, C., Moncrieff, J.B., Gholz, H.L., Clark, K.L., 1998. Soil CO_2 efflux and its spatial variation in a Florida slash pine plantation. Plant Soil. 205, 135–146.

Gamma Design Software, 1998. GS+: Geostatistics for the Environmental Sciences 3.07. Gamma Design Software, MI, USA.

Harrison, K.G., Broecker, W.S., Bonani, G., 1993. The effect of changing land use on soil radiocarbon. Science 262, 725–726.

Isaaks, E.H., Srivastava, R.M., 1989. An Introduction to Applied Geostatistics. Oxford University Press, New York.

Ishizuka, S., Iswandi, A., Nakajima, Y., Yonemura, S., Sudo, S., Tsuruta, H., Muriyarso, D., 2005. Spatial patterns of greenhouse gas emission in a tropical rainforest in Indonesia. Nutr. Cycl. Agroecosys. 71, 55–62.

Konda, R., Ohta, S., Ishizuka, S., ARIA, S., Ansori, S., Tanaka, N., Hardjono, A., 2008. Spatial structures of N_2O, CO_2, and CH_4 fluxes from Acacia mangium plantation soils during a relatively dry season in Indonesia. Soil Biol. Biochem. 40, 3021–3030.

Kosugi, Y., Mitani, T., Ltoh, M., Noguchi, S., Tani, M., Matsuo, N., Takanashi, S., Ohkubo, S., Nik, A.R., 2007. Spatial and temporal variation in soil respiration in a Southeast Asian tropical rainforest. Agric. Forest Meteorol. 147, 35–47.

La Scala Jr., N., Marques Júnior, J., Pereira, G.T., Corá, J.E., 2000. Short-term temporal changes in the spatial variability model of CO_2 emissions from a Brazilian bare soil. Soil Biol. Biochem. 32, 1459–1462.

McCool, D.K., Pannkuk, C.D., Kennedy, A.C., Fletcher, P.S., 2008. Effects of burn/low-till on erosion and soil quality. Soil Till. Res. 101, 2–9.

National Supply Company – CONAB, 2008. Acompanhamento da safra brasileira de cana-de-açúcar – safra 2008 segundo levantamento, agosto/2008. URL: http://www.conab.gov.br/conabweb/download/safra/cana.pdf.

Ohashi, M., Gyokusen, K., 2007. Temporal change in spatial variability of soil respiration on a slope of Japanese cedar (*Cryptomeria japonica* D. Don) forest. Soil Biol. Biochem. 39, 1130–1138.

Panosso, A.R., Pereira, G.T., Marques Junior, J., La Scala Jr., N., 2008. Variabilidade espacial da emissão de CO_2 em latossolos sob cultivo de cana-de-açúcar em diferentes sistemas de manejo. Eng Agric. 28, 227–236.

Rayment, M.B., Jarvis, P.G., 2000. Temporal and spatial variation of soil CO_2 efflux in a Canadian boreal forest. Soil Biol. Biochem. 32, 35–45.

Razafimbelo, T., Barthès, B., Larré-Larrouy, M.C., DE LUCA, E.F., Laurent, J.Y., Cerri, C.C., Feller, C., 2006. Effect of sugarcane residue management (mulching versus burning) on organic matter in a clayey Oxisol from southern Brazil. Agric. Ecosyst. Environ. 115, 285–289.

Rochette, P., Desjardins, R.L., Pattey, E., 1991. Spatial and temporal variability of soil respiration in agricultural fields. Can. J. Soil Sci. 71, 189–196.

Sartori, F., LAL, R., Ebinger, M.H., Parrish, D.J., 2006. Potential soil carbon sequestration and CO_2 offset by dedicated energy crops in the U.S.A. Crit. Rev. Plant Sci. 25, 441–472.

Schwendenmann, L., Veldkamp, E., Brenes, T., O'Brien, J.J., Mackensen, J., 2003. Spatial and temporal variation in soil CO_2 efflux in an old-growth neotropical rain forest, La Selva, Costa Rica. Biogeochemistry 64, 111–128.

Stoyan, H., De-Polli, H., Böhm, S., Robertson, G.P., Paul, E.A., 2000. Spatial heterogeneity of soil respiration and related properties at the plant scale. Plant Soil. 222, 203–214.

Tedeschi, V., Rey, A., Manca, G., Valentini, R., Jarvis, P.L., Borghetti, M., 2006. Soil respiration in a Mediterranean oak forest at different developmental stages after coppicing. Global Change Biol. 12, 110–121.

Trangmar, B.B., Yost, R.S., Uehara, G., 1985. Application of geostatistics to spatial studies of soil properties. Adv. Agron. 38, 45–94.

Ussiri, A.N., Lal, R., 2009. Long-term tillage effects on soil carbon storage and carbon dioxide emissions in continuous corn cropping system from an alfisol in Ohio. Soil Till. Res. 104, 39–47.

Wang, G., Gertner, G., Singh, V., Shinkareva, S., Parysow, P., Anderson, A., 2002. Spatial and temporal prediction and uncertainty of soil loss using the revised universal soil loss equation: a case study of the rainfall-runoff erosivity R factor. Ecol. Model. 153, 143–155.

Warrick, A.W., Nielsen, D.R., 1980. Spatial variability of soil physical properties in the field. In: Hillel, D. (Ed.), Applications of Soil Physics. Academic Press, New York.

Webster, R., 1985. Quantitative spatial analysis of soil in the field. In: Stewart, B.A. (Ed.), Advances in Soil Science. Springer, New York.

Webster, R., Oliver, M.A., 1990. Statistical Methods in Soil and Land Resource Survey. Oxford University Press, Oxford, UK, p. 316.

Xu, M., Qi, Y., 2001. Soil-surface CO_2 efflux and its spatial and temporal variations in a Young ponderosa pine plantation in northern California. Global Change Biol. 7, 667–677.