

Soil CO₂ emission and its relation to soil properties in sugarcane areas under Slash-and-burn and Green harvest

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ABSTRACT

Soil CO₂ emission (FCO₂) has been related to soil properties that are strongly influenced by agricultural management. The objective of this work was to study FCO₂ and its relation to soil properties in adjacent areas cropped with sugarcane managed with Slash-and-burn (SB) and Green (G) harvest. FCO₂ was significantly higher ($p < 0.01$; $2.74 \mu\text{mol m}^{-2} \text{s}^{-1}$ in SB and $2.07 \mu\text{mol m}^{-2} \text{s}^{-1}$ in G) in SB. Total emission in the 70-day period after harvest was also higher in the SB plot ($729 \text{ g CO}_2 \text{ m}^{-2}$) when compared to the G ($557 \text{ g CO}_2 \text{ m}^{-2}$) plot. Organic matter content and carbon stock (0–25 cm) were 13% and 20% higher in SB, respectively, when compared to G. Other soil properties that presented significant difference between plots were pH, available phosphorus, sum of bases, cation exchange capacity, texture, and humification index of soil organic matter. The SB plot presented higher spatial variations in the majority of the soil properties, including FCO₂, when compared to the G plot. Principal component analysis sustains the distinction of two groups, G soil samples and SB soil samples, separately. Regression analysis was able to explain up to 75% and 45% of the FCO₂ spatial variability in SB and G harvested areas, respectively, and indicates that the humification index of soil organic matter, and its interaction with soil bulk density, is an important factor not just to differentiate emissions in each plot. Linear correlation between humification and FCO₂ in each management system shows a positive correlation ($p < 0.10$) in the G area and negative correlation ($p < 0.05$) in the SB area. In addition, the interaction between humification index and bulk density relates better than others properties with soil CO₂ emission, with this property being the most important to understand the emission variability in the Slash-and-burn area.

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1. Introduction

Management practices in agricultural areas are believed to affect soil CO₂ emission (FCO₂) and consequently the greenhouse effect (Lal, 2009; Sartori et al., 2006). For sugarcane management, especially in southern Brazil, two different practices are being used: Slash-and-burn (SB) and Green (G) harvest. Currently, Brazil is the world's biggest sugarcane producer with 630 million tons in 2009 in a cropped area of close to 8 million ha (CONAB, 2009). Approximately 50% of this production is harvested with no residue burn, and it is estimated that 80% of the production will be under Green harvest in the next 10 years (Galdos et al., 2009). Traditional sugarcane management involves residue burning in order to facilitate manual harvest, in contrast to mechanized harvest.

This shift alone already represents a substantial reduction of greenhouse gas emission and also a contribution to the increase in the long-term soil organic matter level, as most of the crop residues that are not burned can be incorporated into the soil (Ceri et al., 2007; Razafimbelo et al., 2006). Therefore, changes in soil management in sugarcane areas could result in significant changes in regional soil carbon balance (Razafimbelo et al., 2006). This was also observed in other studies that indicated that burning has a great effect on the chemical and physical properties of the soil (Are et al., 2009; Blair, 2000; Wood, 1991). On the other hand, the mechanized harvest practice, with addition of crop residues in the soil surface, has also been shown to affect the soil organic matter quality (Dieckow et al., 2009; Cerri et al., 2009; Bauer et al., 2006; Graham et al., 2002).

The FCO₂ in agricultural areas is a complex phenomenon, with high spatial variability due to its confounding relation to several soil properties (Scott-Denton et al., 2003; Shibistova et al., 2002; La Scala et al., 2000). In addition, FCO₂ in tropical areas presents great magnitude, much higher compared with those in temperate

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climates (Panosso et al., 2008; Kosugi et al., 2007; Sotta et al., 2004; Hashimoto et al., 2004), with complexity in its spatial variability structure. Hence, a better understanding is needed on how the change from burn to no-burning management would alter FCO₂ dynamics and its relation to soil properties.

Here we analyzed the relation of FCO₂ with soil properties in sugarcane areas under SB and G harvest, and the correlation of FCO₂ with soil properties in each of the harvest systems. We hypothesized that a change of the harvest system in sugarcane areas would cause significant changes in soil properties, resulting in modifications of FCO₂.

2. Materials and methods

This study was performed at the São Bento farm, which belongs to the São Martinho ethanol plant, an area that has been devoted to sugarcane production for the last 35 years, located in Guariba city, São Paulo, Brazil (Fig. 1). The geographic coordinates of the area 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 Köppen), tropical with rainy summers and dry winters. 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.

Soil was classified as high clay, Oxisol (Eutruxox, USDA Soil Taxonomy), located in an area with low slope (3–4%). The areas studied here are adjacent to each other but recently they have undergone different management practices. One area has been Green harvested (G), with no burning in the 7 years before our experiment started, with mechanical harvest that leaves a great amount of sugarcane crop residues in the soil surface (mean 12 tons per hectare per year), with the last mechanized operation having been conducted on 16 May 2007 (day 136 of our study) (Fig. 1). The other area is managed with Slash-and-burn (SB), with burning having been done prior to manual harvest since 1970; the last burn before our study was initiated on 9 June 2007 (day 160). The sugarcane variety cropped in both plots in the previous years was CTC-6. On 25 June 2007 (day 176) two regular grids (190 × 10 m) were installed in each of the studied areas containing 20 points each with a minimum distance between points in each grid of 13.3 m.

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 CO₂ concentration inside the chamber using an infrared gas analyzer (IRGA). The soil chamber has an internal volume of 854.2 cm³ with a circular contact area to soil of 83.7 cm², and was placed on PVC soil collars previously inserted at a depth of 3 cm into soil grid points. Once the chamber is closed in the measurement mode, it takes around 1.5 min to run the time-change interpolation of CO₂ concentration inside the chamber (account for each 2.5 s) and the determination of FCO₂. To avoid further root respiration into the FCO₂, measurements were performed between crop lines. Soil temperature (Ts) was monitored by a 20 cm depth probe (thermistor based) inserted into the soil close to the collars. Soil moisture (Ms), with its % in volume, was registered with a portable hydrosense system (TDR probe, Campbell, USA). Measurements of FCO₂, Ts, and Ms were conducted simultaneously in both grid points in Julian days 190, 200, 209, 215, 227, 234, 241, 255, and 260, between 9 July and 17 September 2007 (70 days), in the morning (7:00–9:00 AM).

Soil sample analysis (0–25 cm) was performed in the 20 points where FCO₂ was studied in SB and G harvested plots. Samples were dried and sieved (passing through a 2 mm sieve) before being submitted to the following further analysis: soil organic matter content (SOM) and available phosphorus (P), K, Ca, Mg, and H + Al content (Raij et al., 1987), resulting in the derivation of the sum of bases (Bases) and cation exchange capacity (CEC). Particle size distribution (sand, silt, and clay) was determined by the pipette method, after dispersion of soil by adjusting the pH to 10–11 with 1 M NaOH and sand sieving. Soil carbon stock (Cstock, 0–25 cm) was calculated using the following equation (Bayer et al., 2000): $C_{stock} = (OC \times D_s \times E) / 10$, 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 soil layer depth (=10 cm).

Soil bulk density (D_s) was determined in non-deformed samples collected by a suitable sampler adapted to cylinders with an average size of 5.0 cm in internal diameter and 4.0 cm in height (EMBRAPA, 1997). Total pore volume (TPV) was measured using soil bulk density values with macro porosities calculated using a porous plate under 60 cm saturated water tension column (EMBRAPA, 1997). The air-filled pore space (AFPS) fraction was calculated as the difference between the total pore volume (TPV) and the fraction of porosity filled by water (WFPS), which is equivalent to the soil moisture (Ms) defined previously.

Prior to Laser-Induced Fluorescence Spectroscopy (LIFS) and Laser Induced Breakdown Spectroscopy (LIBS) analyses, soil

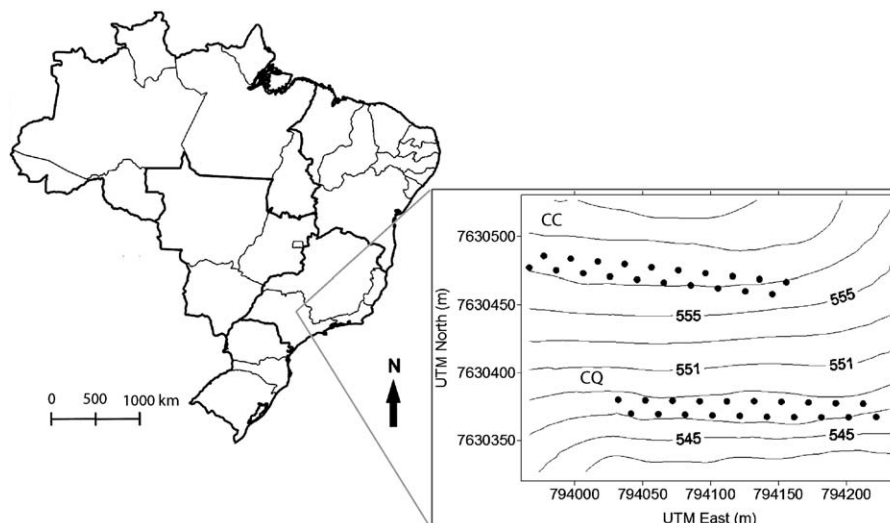


Fig. 1. Schematic map indicating the location of the studied sites and both grid in Slash-and-burn (SB) and Green (G) harvested areas.

sample aliquots of approximately 0.5 g from each of the experimental points were further ground to pass through a 250- μm mesh, and were pressed into pellets of 1 cm diameter and 2-mm thickness. Pellets were prepared by applying 10 tons of pressure on the samples during 2 min.

Laser Induced Breakdown Spectroscopy (LIBS) is an emerging analytical technique based on atomic and ionic emission of elemental sample constituents. The LIBS spectra of pellets were captured using the system model LIBS2500, from Ocean Optics (USA). This system comprises 7 spectrometers allowing resolution of ~ 0.1 nm (FWHM) for spectral analysis from 190 to 900 nm, a Q-switched Nd:YAG laser at 1064 nm (single-pulse energy 50 mJ, pulse duration 1 ns) manufactured by Quantel (Big Sky Laser Ultra50), an ablation chamber, a lens for laser focalization, and an optical system to collect plasma emission and to conduct plasma emission to the spectrometers made up of a lens and a fiber optic bundle. Ten spectra were captured from different regions of each pellet, with each spectrum corresponding to two accumulated laser pulses. A previous laser pulse was always used to clean the pellet surface, before capturing a spectrum. The average of ten spectra in each pellet was considered as a single measurement (Ferreira et al., 2009).

The humification index of soil organic matter (H_{LIFS}) was determined using the LIFS technique. The pellets were inserted into a home-assembled apparatus to run LIFS measurements. The samples were excited with 458 nm ultraviolet radiation emitted by Ar laser equipment (Coherent Innova 90-6, Coherent Inc., Santa Clara, CA), with exit power of 300 mW. A prism was placed in front of the laser exit to remove background gas fluorescence. The back-scattering fluorescence emitted by excited samples was collected through a convergent lens and focused on the slit of a monochromator (focal distance of 240 mm, 1200 g mm^{-1} and blaze in 500 nm – CVI). Signals were multiplied by a Hamamatsu photomultiplier (Hamamatsu, Hamamatsu City, Japan), adjusted to the maximum sensitivity in the visible region (530 nm), and filtered and amplified by a lock-in amplifier. The system functioning and the data acquisition were controlled through home-developed software. The spectral resolution was adjusted to 4 nm. The area of a fluorescence spectrum obtained by excitation at the blue wavelengths is proportional to the humification degree of

the sample and could thus be used as a humification index (Milori et al., 2006). The total area of the LIFS spectrum obtained for each soil sample was divided by its corresponding C content obtained by LIBS technique, obtaining the normalized fluorescence for each soil sample, defined as the humification index of soil organic matter in each of the studied points (H_{LIFS}).

The results are presented in terms of descriptive statistics (mean, standard error of means, minimum, maximum, and coefficient of variation) and the significance differences of soil properties between management systems were determined by Student's *t*-test ($p < 0.01$). Principal component analysis was applied to the studied properties in order to condense the meaningful data into a smaller set of orthogonal variables (eigenvectors), composed of a linear combination of the original soil properties studied. A multiple regression analysis was conducted for each management system, G and SB, with a method stepwise to variable selection. The variance inflation factor (VIF) of the exploratory variables was used to examine the multicollinearity and choose the set of soil properties, previously selected by PCA analysis, to use in the multivariate regression analyses ($VIF < 10$). The stepwise method was applied in each sugarcane management system, in different variable subsets. In this application of the stepwise option, the significant levels for *F*-test used to judge entry of a variable into an existing model and to judge removal of a variable from a model are $p = 0.15$. Simultaneously to the statistical analysis, the basic assumptions of ANOVA and multiple regression, normality of errors, and homogeneity of variances were tested for all study variables (data not shown). Statistical analysis (descriptive statistics, linear and multiple regression) was performed using SAS (SAS version 9, SAS institute, Cary, NC, USA). Principal component analysis was conducted using STATISTICA 7.0.

3. Results and discussion

Table 1 presents the descriptive statistics of soil properties with discrimination of their significant differences (Student's *t*-test, $p < 0.01$), considering the management systems. Seven years after conversion from SB to G harvest, FCO₂ was 32% greater in SB (2.74 $\mu\text{mol m}^{-2} \text{s}^{-1}$) when compared to G (2.07 $\mu\text{mol m}^{-2} \text{s}^{-1}$).

Table 1

Descriptive statistics, mean, standard error (SE), minimum (Min), maximum (Max) and coefficient of variation (CV) of soil CO₂ emission, temperature, moisture, physical and chemical attributes in 0–0.25 m layer of Green and Slash-and-burn areas.

	Green				Slash-and-burn			
	Mean	SE	Min/max	CV	Mean	SE	Min/max	CV
FCO ₂	2.07b	0.06	1.66/2.74	13.8	2.74a	0.14	1.45/3.96	23.0
Ts	19.72b	0.07	18.88/20.18	1.6	20.50a	0.07	20.11/20.91	1.5
Ms	19.50a	0.50	14.90/22.90	11.7	18.90a	0.50	14.00/23.10	10.9
Ds	1.25a	0.02	1.13/1.36	12.1	1.28a	0.03	1.08/1.55	15.6
Ms × Ds	24.30a	0.70	18.88/29.92	5.5	24.20a	0.80	15.89/0.43	11.1
TPV	52.00a	0.60	47.10/56.45	4.9	50.50a	2.30	39.00/87.80	20.1
AFPS	32.5a	0.70	27.2/39.6	9.7	31.7a	2.30	20.78/67.5	32.1
Macro	16.50a	0.90	11.50/21.92	23.1	13.98a	2.24	3.56/49.77	71.7
pH	4.54b	0.05	4.00/4.90	4.8	5.30a	0.05	4.90/5.70	4.6
SOM	23.79b	0.85	14.88/32.35	15.9	26.86a	0.70	19.84/31.94	11.6
Cstock	1659.00b	64.00	956.70/2252.20	17.1	1987.00a	71.00	1373.10/2619.30	16.0
P	15.70b	0.90	8.07/27.93	26.8	107.00a	9.00	56.12/203.49	35.1
Bases	3.00b	0.20	1.75/4.64	23.9	5.40a	0.20	3.23/6.89	17.1
CEC	6.90b	0.20	5.18/8.44	12.3	8.11a	0.20	5.25/9.59	13.2
Sand	290b	3.0	220/380	8.4	329a	2.0	293.00/370.00	5.4
Silt	74a	3.0	61/160	30.0	58b	2.0	30.00/92.00	22.7
Clay	636a	3.0	584/713	3.4	613b	3.0	562.00/652.00	3.5
H_{LIFS}	231a	5.0	198/2801	9.0	180b	3.0	158/204	8.0

N = 20; means followed by the same letters on rows do not differ (Student's *t*-test; $p < 0.01$). FCO₂ = soil CO₂ emission ($\mu\text{mol m}^{-2} \text{s}^{-1}$); Ts = soil temperature ($^{\circ}\text{C}$); Ms = soil moisture (%); Ds = soil bulk density (g cm^{-3}); Ms × Ds = gravimetric water content (g cm^{-3}); TPV = total pore volume (%); AFPS = air-filled pore space (%); Macro = macroporosity (%); SOM = soil organic matter (g dm^{-3}); Cstock = carbon stock (g m^{-2}); P = available phosphorous (mg dm^{-3}); Bases = sum of bases (mmol c dm^{-3}); CEC = cations exchange capacity (mmol c dm^{-3}); Sand = sand content (g kg^{-1}); Silt = silt content (g kg^{-1}); Clay = clay content (g kg^{-1}); H_{LIF} = humification index (arbitrary unity).

Other properties considered here were also significantly affected by the change from SB to G harvest. These were soil temperature (Ts), pH, soil organic matter (SOM), soil carbon stock (Cstock), available phosphorus (P), sum of bases (Bases), cation exchange capacity (CEC), texture (sand, silt, and clay), humification index of soil organic matter (H_{LIFS}), and the interaction of humification index and soil density ($H_{LIFS} \times Ds$). The differences observed in Ts are probably related to the presence of soil crop residues in soil surface of the G area, which favors a lower temperature in relation to SB, possibly resulting in lower FCO₂. This effect has been observed in a similar study conducted in sugarcane areas in our region (Panosso et al., 2008). Other important aspects that may be related to the differences observed in FCO₂ are the superior values of SOM and Cstock in SB, which are 13 and 20%, respectively, when compared to the G harvested plot. It is well known that SOM is the main source of CO₂ production in soil, promoted by microbial activity (Kemmitt et al., 2008; Dominy and Haynes, 2002; Ball et al., 1999). However, it is important to consider that the higher SOM and Cstock in SB differs from that described by Razafimbelo et al. (2006), who observed a higher organic carbon content (15% higher) in latosols Green harvested in the first 10 cm layer when compared to Slash-and-burn, six years after conversion. On the other hand, Blair (2000), in an experiment conducted in Australia, observed a higher soil organic carbon content in Slash-and-burn areas, when compared to no-burn four years after conversion. Certainly, soil temperature and organic matter stocks are important aspects in order to understand the greater FCO₂ level observed in SB when compared to G harvested areas.

Similar to the results found by Blair (2000), in our study the chemical soil properties differed more between harvest systems than the physical ones. Our findings also agree with those reported by Are et al. (2009), who found a significant change in soil clay content induced by the burn of agricultural areas. This effect could be explained by an increase in the erosion process (Resende et al., 2006) as the site with no crop residue cover (SB) is more vulnerable to soil losses than the site covered by crop residues (G). Other aspects could also be related to the higher FCO₂ observed in the SB plot. For instance, the soil P available was superior in SB, and it is known that phosphorus could be a limiting factor for microbial activity (Duah-Yentumi et al., 1998). Mendonza et al. (2000),

comparing the effects of Slash-and-burn and Green harvest on Argisol chemical properties in Brazil, observed the same effect of higher P content in SB as observed here. The deposition of ash on soil surface in the sugarcane burn helps soil fertilization with immediate deposition of other minerals (K, Ca, Mg), increasing the sum of bases in SB (Scheuner et al., 2004; Niemeyer et al., 2005) as observed in our study (Table 1). But the benefits of this practice are specific to certain chemical properties only, worsening most of the soil physical properties, like erosion, which is increased in burned areas (Are et al., 2009). Soil pH was also different, as a smaller value was observed in G when compared to the SB plot, the same effect observed by Noble et al. (2003) after conversion of sugarcane areas from SB to G in Australia.

As in deformed soil sample analysis done in laboratory conditions, such as spectroscopy analysis, bulk density multiplied by H_{LIFS} better accounts for the total amount of humic acids in each of the points than H_{LIFS} alone. This is similar to what is usually done when converting from organic carbon to carbon stocks. The humification index of soil organic matter (H_{LIFS}) and the interaction with soil bulk density ($H_{LIFS} \times Ds$) were also significantly different when both studied areas were compared. Few studies have reported soil organic quality as affected by management systems, but recently Dieckow et al. (2009) observed different humification indexes of soil organic matter being affected by tillage in the south of Brazil.

With the so-called principal components a bidimensional representation known as a biplot (Fig. 2) has been created. With this it is possible to picture the structure of soil properties, which explains the maximum variability of the whole set of soil properties studied. In this study, we considered the two first principal components, PC1 and PC2, the eigenvalues for which were superior to the unity (Kaiser, 1958), accounting for 70.6% of the total variance of soil properties. In our work 52.1% of total variance of soil properties was explained by PC1 while the other 18.5% was explained by PC2. We observed the formation of two distinct groups: group I, located on the left side of the biplot graph (Fig. 2), with more clustering points, and formed by soil samples originated mainly from the G system area; and group II, located on the right side of the biplot, less clustered (i.e., more spread in the two-dimensional representation), and consisting of the soil

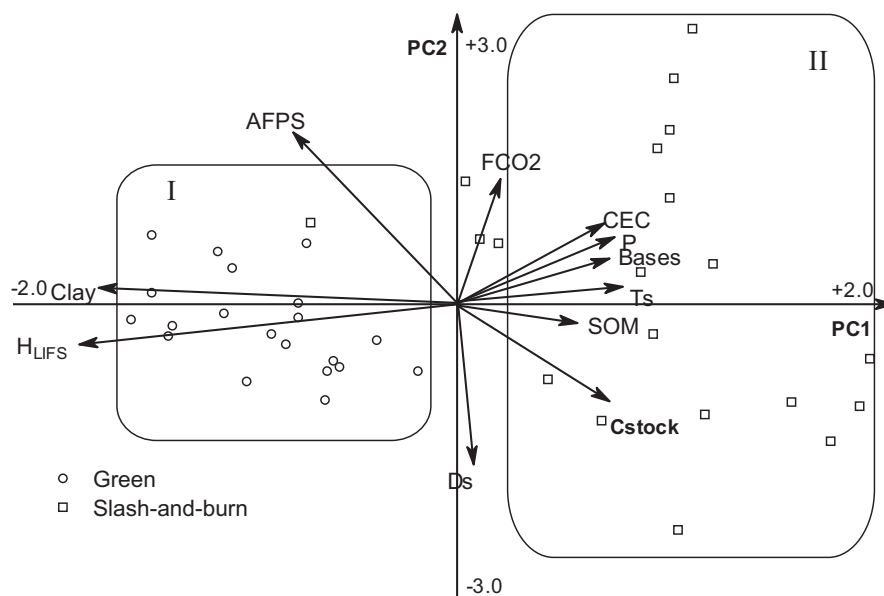


Fig. 2. Biplot of principal components PC1 and PC2 of the principal components analysis with all soil samples and variables: soil CO₂ emission (FCO₂); soil temperature (Ts); soil bulk density (Ds); air-filled pore space (AFPS); soil organic matter (SOM); carbon stock (Cstock); available phosphorus (P); sum of bases (Bases); cations exchange capacity (CEC); clay content (Clay); humification index (H_{LIF}).

samples from the SB system area. The contribution of each of the soil properties in each principal component was calculated by the individual linear correlation of the property with the principal components. In order of significance, the properties that best related to PC1 were Bases (0.93), H_{LIF} (-0.86), SOM (0.81), P (0.80), CEC (0.80), Cstock (0.78), Clay (-0.73), and Ts (0.78). The properties that best related to PC2 were Ds (-0.83), AFPS (0.77), FCO2 (0.59), and Cstock (-0.52). Those correlations are shown in Fig. 2, and are represented by the arrow of each soil property and its projection in the graph. H_{LIFS} and Clay, which had negative correlation with PC1, were the soil properties responsible for the discrimination of group I, which was basically formed by the set of soil properties measured in samples collected from the G plot. On the other hand, group II was formed by Ts, SOM, P, Bases, CEC, and Cstock, those mostly from SB soil sample analysis, located at the right side of PC1, meaning a positive correlation with this vector. FCO2 and AFPS were the properties that presented positive correlation with PC2, as indicated in the upper part of Fig. 2. On the other hand, Ds and Cstock presented a negative correlation with PC2.

Hence, the soil properties that presented a positive linear correlation with PC1 were mainly from the SB plot while the ones that presented negative correlation with the PC1 vector were basically from the G plot. Scott-Denton et al. (2003), studying the spatial variability of soil respiration in a coniferous forest in Colorado, USA, applied the principal component analysis and found 6 independent components, which explained 74% of soil properties variance, with the first principal component being mainly related to soil carbon. In our study the first principal component was mainly related to the chemical soil properties, with the exception of Ts and clay content that also contributed to the PC1 vector.

The high coefficient of variation (CV) indicated in Table 1, as well as the higher dispersion of the soil properties especially in group II, points to a higher variability in soil properties extracted from SB when compared to the G plot. FCO2 is among those, with P and AFPS also presenting higher variability (when classified by CV values, Warrick and Nielsen, 1980) in the SB area (Table 1). On the other hand, in the G plot FCO2 is among the properties with smaller CV values. This is a typical aspect of CO₂ emission from G when compared to SB plot, and has been observed in other studies (Panosso et al., 2008). Fig. 3 presents total FCO2 in each of the 20 studied points in G and SB areas. Not only was the total emission

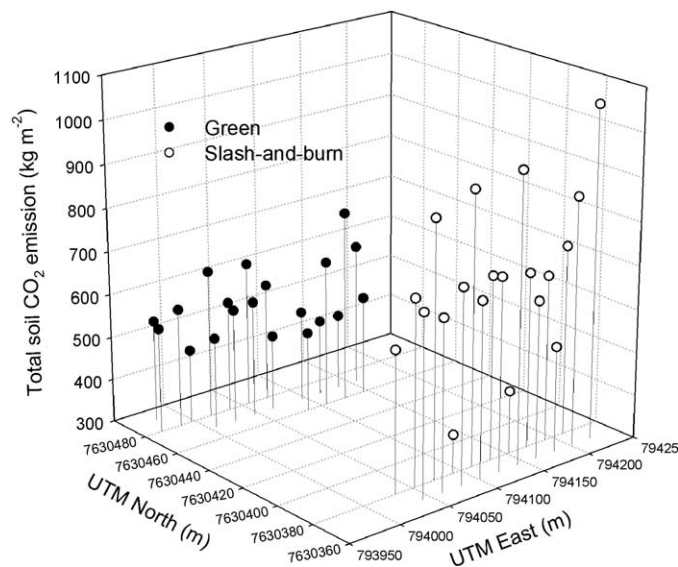


Fig. 3. Spatial representation of total soil CO₂ emission during 70 experimental days for each sample points in Green and Slash-and-burn management systems.

less in G (557 g CO₂ m⁻²) when compared to SB (729 g CO₂ m⁻²), but also FCO2 in the G plot changed less in space when compared to the SB area. Apparently, the presence of crop residues in the soil surface and the more intense mechanical management in the G area results in a smaller variability in several soil properties when compared to SB, among them FCO2 (Noble et al., 2003).

The linear correlation coefficients between FCO2 and some soil properties were significant ($p < 0.10$) in both areas. The Ts, Ms × Ds, pH, H_{LIFS} , and $H_{LIFS} \times Ds$ showed to correlate to FCO2 in G while Ms × Ds, Ds, Cstock, H_{LIFS} , and $H_{LIFS} \times Ds$ correlated to FCO2 in the SB area. The calculated soil gravimetric water content (Ms × Ds) has been indicated as an important aspect related to the temporal variability of FCO2, but some studies have also reported this property as associated to the FCO2 spatial variability (Kosugi et al., 2007). Ryu et al. (2009), studying the effect of burn on soil properties, indicated a negative linear correlation between FCO2 and soil moisture, which explains the 14 and 7% of FCO2 spatial variability found in burned and non-burned areas, respectively. Our results indicate that in the G harvested area Ms × Ds explains 31% while this property alone explains 41% of FCO2 variability in the SB plot, but most of this variability is due to soil bulk density changes in space, especially in the SB area. In this condition, CO₂ transport may be limited due to a decrease in the effective diffusion coefficient with increasing Ms (Jassal et al., 2004; Fang and Moncrief, 1999).

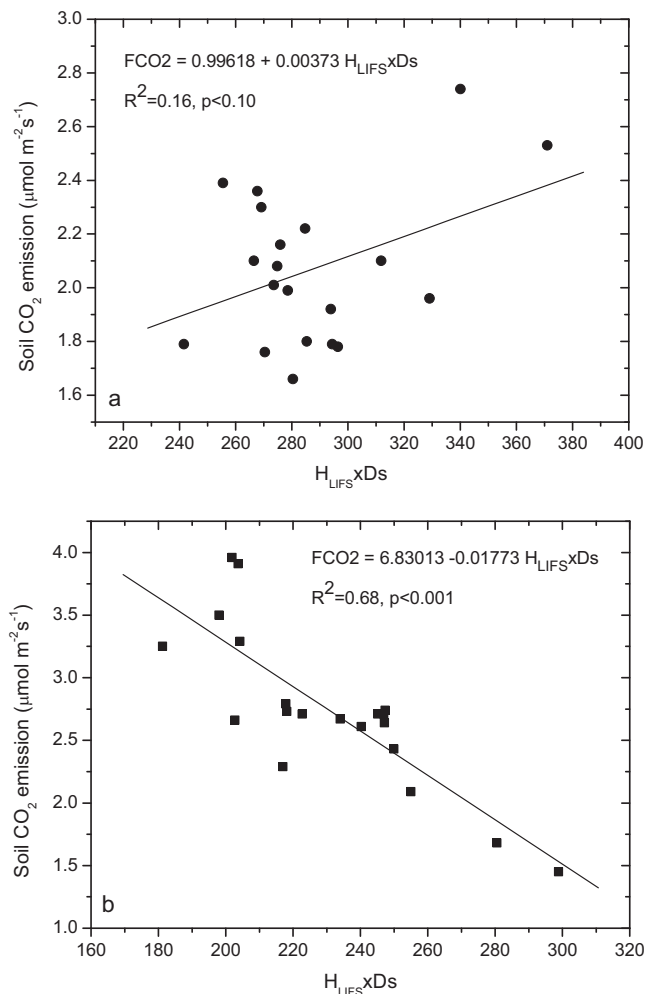


Fig. 4. Linear relation between soil CO₂ emission and the interaction of humification index and soil bulk density ($H_{LIFS} \times Ds$) in Green (a) and Slash-and-burn (b) management systems.

The interaction of humification index of soil organic matter with soil bulk density ($H_{LIFS} \times Ds$) was also linearly related to FCO2 in both studied areas. Differently from soil moisture, FCO2 presented a negative linear correlation with $H_{LIFS} \times Ds$ in SB while the correlation was positive in the G area (Fig. 4). This indicates that the humification of soil organic matter multiplied with soil bulk density would explain 68% of spatial changes in FCO2 of the SB plot ($p < 0.01$) while the same property explains 16% of FCO2 variability in the G plot ($p < 0.10$). Soil organic matter presented a higher humification index (based on H_{LIFS} or $H_{LIFS} \times Ds$) in G when compared to the SB area (Table 1). But the higher humification of SOM in the G plot would mean lower relative levels of labile carbon in its SOM when compared to SB soil. Hence, the smaller FCO2 in G harvested soil, relative to SB, would be concomitant with smaller carbon stock and SOM content (Table 1), and with a higher humification index of its SOM.

The positive correlation between FCO2 and $H_{LIFS} \times Ds$ in the G plot would be in agreement with Fontaine et al. (2007), who reported that fresh biomass input in soil could stimulate the mineralization of stable carbon present in the humic substances. Therefore, under this condition, the carbon source of energy used by microbes would also involve the decay of stable carbon, or the most humified parts of SOM, that would be emitted in CO₂ form by soil respiration. This would explain the positive correlation between humification index of SOM and FCO2, as humified SOM would be also an important source to microbes in those green areas. On the other hand, the negative correlation between FCO2 and $H_{LIFS} \times Ds$ in the SB plot could indicate that the humified SOM would not be the main source of carbon in FCO2 of SB area. The energy supply used by microbes in SB soil would be related to labile carbon only, because the increase of non-labile carbon (increases of H_{LIFS} or $H_{LIFS} \times Ds$) would result in a reduction of FCO2. Therefore, carbon emitted in soil CO₂ flux would come mostly from labile carbon decay in SB, while in the G plot this would be also associated to the humified parts of SOM.

For a better understanding of the FCO2 spatial variability in each of the studied areas, we conducted a multiple regression analysis in which FCO2 was related to all other soil properties studied (Table 2). For the G plot, the first property selected in the model was $H_{LIFS} \times Ds$, which explained 16% of FCO2 variability. When AFPS was included in the model, the rate increased to 18%. Finally, Cstock was also selected, adding 12% and totaling $R^2 = 0.46$, or 46% of FCO2 variability. The estimated parameters for all variables were positive, confirming their individual correlation with FCO2. The positive parameter for AFPS could be related to the negative effect of the soil moisture on gas diffusion, as already reported (Kosugi et al., 2007; Schwendenmann et al., 2003; Davidson et al., 2000). Soil temperature is a primary controlling factor of soil microbial activity but it is not usually shown as negatively correlated to FCO2. Also, carbon is known as the basic element used by soil microorganisms during

the decomposition process (Singh and Gupta, 1977). A positive association between CO₂ emissions and soil organic carbon was also found by Brito et al. (2009) and Xu and Qi (2001). The multiple linear regression model adjusted in the SB plot included $H_{LIFS} \times Ds$ as the first variable, alone explaining 68% of FCO2 variability. According to Galdos et al. (2009) soil carbon stock is more appropriate than soil carbon content, as the first is a measure of the total carbon mass in a specific soil volume. Hence, the interaction between humification index of SOM (H_{LIFS}) with soil bulk density (Ds) relates better with FCO2, with this property being the most important to understand the emission variability in the SB area. Following this, AFPS is included in the model, and is negatively related to FCO2, contributing an additional 5% to explain FCO2 in SB. These results indicate a better prediction capacity in understanding FCO2 spatial variability in the SB area than in the G area. We believe that this effect is related to the fact that SB presents higher spatial variability in almost all the properties here studied. Ryu et al. (2009), applying multiple regression models to understand FCO2 in California, USA, found higher determination coefficients in burned when compared to non-burned plots, with soil temperature and soil moisture being the main properties to model FCO2 spatial variability. Possibly the more intense mechanized management and the presence of a greater amount of crop residues in the soil surface of the G plot results in a smaller variability of most of the soil properties that could be affecting FCO2.

4. Conclusion

The 7-year record of conversion from Slash-and-burn to Green harvest resulted in significant changes in soil properties, not only in their mean values but also in their variability, in each management system. The conversion resulted in a smaller soil CO₂ emission in the green plot when compared to the burned plot. This seems related to the changes observed in some physical and chemical properties, especially the humification index of the soil organic matter and air-filled pore space. The humification index, with its linear relation to emission, indicates that soil carbon losses in the green area could be due to the decay of the most humified soil organic matter, differently from the burned area that presented a negative linear correlation between emission and humified soil carbon. Further investigations are important in order to elucidate how the quality of soil organic matter would be related to the soil carbon losses by CO₂ emission in both areas and longer term studies.

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Table 2

Multiple linear regression models of soil CO₂ emission (FCO2) for Green and Slash-and-burn areas.

Variables	Estimated parameter	SE	p-Value	R ²
Green				
Intercept	-2.14710	1.20584	0.094	
$H_{LIFS} \times Ds$	0.00523	0.00182	0.076	0.16
AFPS	0.06132	0.02057	0.009	0.34
Cstock	4.3434E-04	0.00022893	0.011	0.46
Slash-and-burn				
Intercept	8.12203	0.93182	<0.0001	
$H_{LIFS} \times Ds$	-0.02097	0.00320	<0.0001	0.73
AFPS	-0.01718	0.00921	0.0793	0.75

SE = standard error; R² = determination coefficient.

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