Agriculture, Ecosystems and Environment 189 (2014) 206–215

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Spatial variability structure of soil CO_2 emission and soil attributes in a sugarcane area

E.S. Bicalho[a,*], A.R. Panosso[b], D.D.B. Teixeira[a], J.G.V. Miranda[c], G.T. Pereira[a], N. La Scala[a]

[a] Universidade Estadual Paulista, Departamento de Ciências Exatas—FCAV/UNESP, Via de Acesso Prof. Paulo Donato Castellane s/n, 14884-900 Jaboticabal, SP, Brazil

[b] Universidade Estadual Paulista, Departamento de Matemática—FEIS/UNESP, Avenida Brasil, 56, 15385-000 Ilha Solteira, SP, Brazil

[c] Instituto de Física, Universidade Federal da Bahia—UFBA, Campus Universitário de Ondina, 40210-340 Salvador, BA, Brazil

ARTICLE INFO

Article history:
Received 26 August 2013
Received in revised form 21 March 2014
Accepted 23 March 2014
Available online 18 April 2014

Keywords:
Soil respiration
Geostatistics
Fractal dimension
Mechanized harvest

ABSTRACT

Soil CO_2 emission (F_{CO_2}) is influenced by chemical, physical and biological factors that affect the production of CO_2 in the soil and its transport to the atmosphere. F_{CO_2} varies in time and space depending on environmental conditions, including the management of the agricultural area. The aim of this study was to investigate the spatial variability structure of F_{CO_2} and soil attributes in a mechanically harvested sugarcane area (green harvest) using fractal dimension (D_F) derived from isotropic variograms at different scales (fractograms). F_{CO_2} showed an overall average of 1.51 μmol CO_2 m^{-2} s^{-1} and correlated significantly ($P < 0.05$) with soil physical attributes, such as soil bulk density, air-filled pore space, macroporosity and microporosity. Topologically significant D_F values were obtained from the characterization of F_{CO_2} at medium and large scales (above 20 m), with values of 2.92 and 2.90, respectively. The variations in D_F with scales indicate that the spatial variability structure of F_{CO_2} was similar to that observed for soil temperature and total pore volume and was the inverse of that observed for other soil attributes, such as soil moisture, soil bulk density, microporosity, air-filled pore space, silt and clay content, pH, available phosphorus and the sum of bases. Thus, the spatial variability structure of F_{CO_2} presented a significant relationship with the spatial variability structure for most soil attributes, indicating the possibility of using fractograms as a tool to better describe the spatial dependence of variables along the scale.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

Human activities related to fossil fuel burning and land use change have caused significant modifications in atmospheric composition (Schneider et al., 2001). Increases in atmospheric concentrations of greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have been recorded since the beginning of the industrial age, resulting in a further heating of the Earth's surface, known as the additional greenhouse effect (Forster et al., 2007). Several studies have indicated that the CO_2 concentration in the atmosphere has increased by 110 ppm in the last 250 years, increasing from 280 ppm in the pre-industrial era to approximately 379 ppm in 2005 (Forster et al., 2007) and 389 ppm in 2010 (Chen et al., 2011).

Agricultural activities influence soil CO_2 emissions to the atmosphere because agricultural management alters the gains and losses of soil organic matter (Lal, 2009). Thus, the appropriate management of crop residues and their maintenance on the soil surface could result in the sequestration of carbon from the atmosphere and increases in the soil organic carbon content, helping to mitigate the greenhouse effect (Lal, 2007; Teixeira et al., 2013a). Thus, sugarcane production could play an important role in soil CO_2 emissions via photosynthesis and carbon phytomass incorporation. By converting sugarcane areas from burned/manual to mechanical harvest (green harvest), part of the soil carbon lost through residue burning is retained on the soil surface, promoting a greater accumulation of soil organic matter and the reduction of soil CO_2 emissions (Razafimbelo et al., 2006; Cerri et al., 2007). Brazil is the top sugarcane producer worldwide, with a total sugarcane crop area of approximately 8.8 million hectares (Conab, 2013), which presents a tremendous greenhouse gas mitigation potential. For this reason, the study of the spatial and temporal

* Corresponding author. Tel.: +55 16 3209 2625.
E-mail addresses: eltonbicalho@ig.com.br (E.S. Bicalho), arpanosso@yahoo.com.br (A.R. Panosso), daniel.dbt@hotmail.com (D.D.B. Teixeira), vivas@ufba.br (J.G.V. Miranda), genertp@fcav.unesp.br (G.T. Pereira), lascala@fcav.unesp.br (N. La Scala).

http://dx.doi.org/10.1016/j.agee.2014.03.043
0167-8809/© 2014 Elsevier B.V. All rights reserved.

variability of soil CO_2 emissions and its relationship to the main soil attributes or controlling factors is important.

Soil CO_2 emission (F_{CO_2}) results from several physical, chemical and biological processes, most of them related to soil temperature and soil moisture (Epron et al., 2006; Ohashi and Gyokusen, 2007; Concilio et al., 2009; Ryu et al., 2009), organic matter content (Dominy et al., 2002; Kemmitt et al., 2008), microbial activity (Lloyd and Taylor, 1994; Epron et al., 2006; Ryu et al., 2009; Oyonarte et al., 2012), phosphorus content (Duah-Yentumi et al., 1998), the C/N ratio (Allaire et al., 2012; Ngao et al., 2012) and pH (Fuentes et al., 2006), in addition to physical soil attributes, such as soil density and soil porosity, which are responsible for the oxygen levels and gas diffusion within the soil (Xu and Qi, 2001; Epron et al., 2006).

As an alternative to evaluate the complexity of the relationships among these factors, geostatistics allows the derivation of the spatial and temporal variability patterns of F_{CO_2} and other soil attributes in developing a variability model dependent on the scale and direction of sampling (Burrough, 1981; Palmer, 1988). The characterization of fractal dimension (D_F) applied to the derivation of non-continuous spatial and temporal phenomena (Mandelbrot, 1977) could be used in spatial variability studies, especially in studying phenomena that are scale dependent (Perfect and Kay, 1995; Eghball et al., 1999). In a recent study on the relationship between F_{CO_2} and soil attributes, Allaire et al. (2012) showed that the spatial variability of those attributes is scale dependent. Certainly, new approaches and more research are needed to better understand the spatial variability of F_{CO_2} at different scales.

Fractal dimension represents an overall estimation of the scale regularity of an irregular behavior, which, when applied to the characterization of soil attributes, could be used to derive the homogeneous/heterogeneous features induced by soil management and the patterns of soil variability (Pachepsky and Crawford, 2004). Many studies have referred to D_F characterization of soil attributes and its influence on landscape, rain precipitation, vegetation cover, soil tillage and other factors (Eghball et al., 1999; Vidal Vázquez et al., 2005, 2010; La Scala et al., 2009; Usowicz and Lipiec, 2009). These factors consequently affect other soil attributes related to CO_2 production and its transport in the soil, such as the soil carbon content, soil porosity, soil moisture and soil oxygen content (La Scala et al., 2009; Panosso et al., 2012). Some recent results have shown that harvest machinery in sugarcane areas could alter the spatial organization of soil compaction zones (Pérez et al., 2010), affecting the soil water content and aeration and consequently affecting the soil microbial activity (Piotrowska and Dlugosz, 2012).

Considering the presence of spatial variability structure and its behavior over several scales, studies that characterize F_{CO_2} at different scales are important, especially if associated with soil attributes and soil management practices. According to Grunwald et al. (2011), efforts to map soil attributes and the fluxes between soil and biosphere have been hampered by several factors, such as the difficulty in understanding its real variability scale. Furthermore, mapping on coarse scales may hamper the understanding of the overall process and lead to an increase in the uncertainty of the estimates (Trumbore, 1997; Grunwald et al., 2011). Although it is one of the most important sources of GHG emissions in agriculture, F_{CO_2} is not commonly taken into account in the elaboration of GHG inventories, mainly due to its variation in both space (La Scala et al., 2000a; Panosso et al., 2009; Brito et al., 2010; Teixeira et al., 2011) and time (Herbst et al., 2010; Teixeira et al., 2011), in addition to being influenced by chemical, physical and biological factors. Thereby, to ensure that soil CO_2 emissions can be incorporated accurately in future GHG inventories and to understand its emission process, knowledge of its variability scale is necessary. Hence, the objective of this work was to investigate the correlation of spatial variability structure between F_{CO_2} and soil attributes, as characterized by fractal dimension and fractograms.

2. Materials and methods

The experimental plot was located at the Santa Olga farm in the city of Guariba, São Paulo State, Brazil, and the geographical coordinates are 21° 21′S and 48° 11′W. The soil is classified as a high-clay Oxisol (Eutrustox, USDA Soil Taxonomy), and the slope was determined to be 4%. The regional climate was classified as $B_2rB'_4a'$ by the Thornthwaite system (Thornthwaite, 1948), indicating a mesothermal region with rainy summers and dry winters. The mean precipitation was approximately 1438 mm, concentrated between October to March, and the mean annual temperature over the last 30 years was 22.2 °C.

This study was conducted in a production area with a 38-year history of sugarcane (*Saccharum* spp.) crop cultivation. The studied area had been mechanically harvested for the last 8 years prior to the study (July of 2010), with approximately 12–15 t ha^{-1} of crop residues remaining on the soil surface after harvest in each of those years. The sugarcane plantation was established in February 2002, and the variety cultivated was SP86-155, which was harvested for the last time prior to this study on June 28, 2010, in the ratoon stage. During the study period, there was no agricultural management in the experimental area.

In this area, on July 13, 2010 (Julian day 194), a 60 × 60-m grid was installed containing 141 points spaced at distances ranging from 0.5 to 10 m (Fig. 1) to characterize the spatial variability of F_{CO_2} and soil attributes. Three portable LI-8100 automated soil CO_2 flux systems (LI-COR, Lincoln, NE, USA) were used to measure the in situ F_{CO_2}; the devices were tested and calibrated with each other before the beginning of the experiment. The LI-8100 system uses optical absorption spectroscopy in the infrared spectrum to monitor changes in the CO_2 concentration inside a closed chamber. The chamber is a closed system with an internal volume of 854.2 cm^3 and a circular soil contact area of 83.7 cm^2. The chamber was coupled to the soil PVC collars that had been installed 24 h prior to the beginning of the measurements at all 141 sample points to reduce the disturbance caused during the insertion of the PVC collars in the soil (La Scala et al., 2000a; Panosso et al., 2009; Brito et al., 2010). Once the chamber was closed, approximately 1.5 minutes were required to record the F_{CO_2} measurements at each point.

A portable sensor from the LI-8100 system was used to measure the soil temperature (T_s). A 20-cm probe (thermistor based) was inserted 10 cm into the soil near the soil PVC collars. Soil moisture in % of volume (M_s) was measured using a Time Domain Reflectometry (TDR) system (Hydrosense TM, Campbell Scientific Inc., Logan, UT, USA). In the TDR system, two 12-cm probes are inserted into the soil, also near the soil PVC collars. Measurements of F_{CO_2}, T_s and M_s at all the grid points were recorded on Julian days 195, 196, 197, 200, 201, 204 and 207 in July, 2010. On all days, the measurements were recorded in the morning from 8:00 to 9:30 h.

This short period of measurements (13 days) is related to the main period of soil respiration during which F_{CO_2} is influenced by soil organic carbon losses (Cerri et al., 2011), as the soil presents little vegetation during this period post-harvest. Teixeira et al. (2013b) mentions the impact of the main agricultural operations due to harvesting and other management practices that contribute to increased rates of soil respiration and the rapid vegetative growth of sugarcane, which makes the quantification of F_{CO_2} over longer periods a difficult task, in addition to the intense root respiration being combined with soil respiration. Additionally, studies commonly evaluate F_{CO_2} for short periods after harvest as well as after tillage operations (La Scala et al., 2000a; Brito et al., 2010; Panosso et al., 2011).

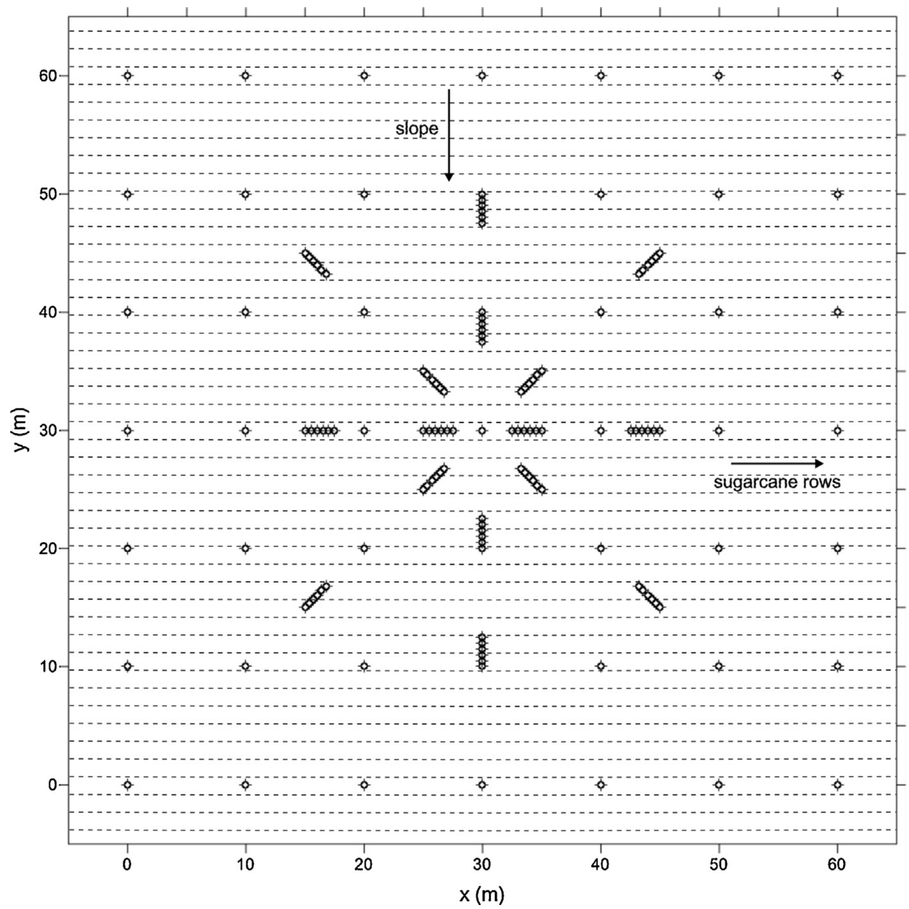

Fig. 1. Representation of the sampling grid with the sugarcane rows location and the 141 points used to characterize the spatial variability of soil CO_2 emission and soil attributes in the experimental area.

On the last day of the study, after all the F_{CO_2} measurements had been recorded, soil samples from a depth of 0–10 cm were obtained from all 141 grid points. The samples were dried and sieved through a 2-mm mesh prior to the analyses. These analyses included the soil organic matter content (SOM) estimated by the soil organic carbon, which was determined by the wet oxidation method (modified Walkley–Black method), and the available phosphorus (P), K, Ca, Mg and H + Al contents (Raij et al., 2001), which allowed for the calculation of the sum of bases (Bases) and cation exchange capacity (CEC). The total content of soil nitrogen (N) was obtained using a dry combustion technique in the presence of oxygen at 1440 °C.

The particle size distribution (sand, silt and clay) was determined by the pipette method after dispersion of the soil by adjusting the pH to 10–11 with 1 M NaOH and sand sieving (Embrapa, 1997). The soil carbon stock (C_{stock}, 0–10 cm) was calculated using the following equation (Veldkamp, 1994): $C_{stock} = (OC \times D_s \times E)/10$, where C_{stock} is the soil carbon stock (Mg ha^{-1}), OC is the organic carbon content (g kg^{-1} = SOM/1.724), D_s is the bulk soil density (kg dm^{-3}) and E is the depth of soil layer (10 cm).

The soil bulk density (D_s) was determined using the volumetric ring method, which consists of non-deformed samples collected by a sampler adapted to cylinders with an average internal diameter of 5.0 cm and a height of 4.0 cm (Embrapa, 1997). To determine the total pore volume (TPV, macropores and micropores), undisturbed soil samples were saturated for 48 h in a pan filled with water to two-thirds the height of the ring. After the saturation period, the samples were drained to a potential equal to −0.006 MPa using a porous plate (Embrapa, 1997). The air-filled pore space (AFPS, in % of volume) fraction was calculated as the difference between the TPV (in % of volume) and M_s, as defined above.

In this work, the D_F was used to represent the spatial dependence of the attribute studied, which was determined by means of an experimental variogram analysis (Webster and Oliver, 1990; Vidal Vázquez et al., 2005). The semivariance of points separated at distance h in the grid is defined by

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

where N is the number of pairs of points separated by h distance, $Z(x_i)$ is the value of the attribute at position x_i and $Z(x_i + h)$ is the value of the same attribute in position $x_i + h$.

The spatial structure of fractal surfaces can be described by means of a power law, as shown in the following relation:

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

where z is the value of the attribute at x location, h is the separation distance and H is the fractal codimension or Hölder exponent (Huang and Bradford, 1992). If $0 < H \leq 1$, the fractal codimension is defined as follows:

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

where D_F is the fractal dimension and d is the Euclidian dimension of the system in which the fractal distribution has been described. For lines, surfaces and volumes, d = 1, 2 and 3, respectively. Hence, for a distribution of a soil attribute, the fractal dimension is given by $D_F = 3 - H$.

Thus, comparing Eqs. (1) and (2), we can derive the following expression to denote a fractal characteristic at a given scale:

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

or, expressed in another way:

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

According to Eq. (4b), the slope of the experimental variogram on the log–log scale is equal to 2H. The H exponent can then be obtained by means of a linear regression taken in this log–log graph by the following equation (Perfect and Kay, 1995):

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

When $H = 0$, the value of D_F is equal to 3, which represents the lack of a spatial variability structure, as there would be no relationship between the way the attribute varies in space and the distance between points. In this case, there is no fractal dimension, and the methodology does not apply. However, when $0 < H < 3$, the fractal dimension has values that characterize the presence of the spatial variability structure and the dependence of the attribute studied with h (Palmer, 1988).

F_{CO_2}, T_s and M_s and other soil attributes were first analyzed by applying descriptive statistics (mean, median, standard error, minimum, maximum, coefficient of variation, skewness and kurtosis) determined using SAS (SAS 9.2, SAS Institute Inc., Cary, NC, USA) and then by spatial variability. The fractal dimension of F_{CO_2} and other soil attributes was derived from empirical isotropic variograms ($\log(\hat{\gamma}) \times \log(h)$), which were performed using the methodology developed by Miranda (2000).

3. Results and discussion

3.1. Descriptive statistics

The means of F_{CO_2} during the studied days varied from 1.26 μmol CO_2 m^{-2} s^{-1} (Julian day 197) to 1.77 μmol CO_2 m^{-2} s^{-1} (Julian day 195) (Table 1) and were similar to those observed in experiments conducted previously in our region with sugarcane crops (Brito et al., 2010; Panosso et al., 2012). The F_{CO_2} coefficients of variation (CV) generally increased as the mean value of F_{CO_2} decreased during those days, varying from 38.16% (1.77 μmol CO_2 m^{-2} s^{-1}) to 90.87% (1.26 μmol CO_2 m^{-2} s^{-1}). With the exception of the Julian days 196 and 197, which presented high CV values, the results from the other days were quite similar to the results already presented in the literature from soil respiration studies of various ecosystems, with CV values varying from 38.16% to 51.74% (La Scala et al., 2000a; Epron et al., 2004; Konda et al., 2008; Brito et al., 2009; Teixeira et al., 2011; Allaire et al., 2012; Oyonarte et al., 2012). The highest CV values of F_{CO_2} in our study were observed on the Julian days 196 and 197 (Table 1), which also presented higher values of skewness coefficients (1.40 and 1.65, respectively) and kurtosis (1.32 and 2.23, respectively). By studying the spatial variability of microbial properties in a Luvisol, Piotrowska and Dlugosz (2012) observed soil respiration skewness coefficients of 1.15 and 1.55 and kurtosis values of 2.78 and 4.31, slightly greater than those observed in our work. Teixeira et al. (2011) found skewness and kurtosis coefficients varying from 0.72 to 1.09 and from 0.12 to 1.10, respectively, upon assessing the diurnal spatial variability of soil CO_2 emission of an agricultural area in Brazil. The normal distribution of data is not a previous condition in geostatistics analysis; it is important that the data not provide distributions with very long tails such that the difference between the mean and the median should be small. The highest differences between the mean and median of F_{CO_2} (Table 1), in contrast with the soil temperature and soil moisture, indicate a positively skewed distribution of the data, indicating that the F_{CO_2} values were influenced by high emissions values. Thus, prior to the variogram analyses, a lognormal transformation was applied to correct the skewness of the F_{CO_2} distribution.

In a bare soil with a wheat crop in Ottawa, Canada, the CV values were observed to vary from 25% to 69% in a study that investigated the spatial variability of soil CO_2 emissions (Rochette et al., 1991). Similarly, in an oak forest in central Italy, the CV of soil respiration varied between 31% and 48% (Tedeschi et al., 2006). In sugarcane-cultivated soils under green harvest in southern Brazil, F_{CO_2} varied from 1.39 μmol CO_2 m^{-2} s^{-1} to 2.15 μmol CO_2 m^{-2} s^{-1} as a function of the topography, with CVs ranging between 24.5% and 34.2% (Brito et al., 2010). In addition, spatial and temporal variability models of

Table 1
Descriptive statistics of soil CO_2 emission (μmol CO_2 m^{-2} s^{-1}), soil temperature (°C) and soil moisture (% volume) for all the studied days in July 2010.

Julian Day	Mean	Median	SE	Min	Max	CV	Skew	Kurt
Soil CO_2 emission (μmol CO_2 m^{-2} s^{-1})								
195	1.77	1.66	0.06	0.22	3.73	38.16	0.58	0.19
196	1.42	0.91	0.10	0.20	5.24	80.70	1.40	1.32
197	1.26	0.78	0.10	0.02	5.28	90.87	1.65	2.23
200	1.47	1.05	0.09	0.16	4.43	73.40	1.12	0.34
201	1.48	1.33	0.06	0.27	3.48	48.08	0.75	−0.03
204	1.61	1.48	0.07	0.26	3.79	47.48	0.81	0.18
207	1.50	1.28	0.07	0.24	3.53	51.74	0.76	−0.20
Soil temperature (°C)								
195	19.32	19.29	0.03	18.27	20.36	1.79	0.27	0.69
196	18.84	18.83	0.03	17.92	20.15	1.97	0.31	0.78
197	20.08	20.07	0.05	18.36	21.25	3.04	−0.29	−0.06
200	20.23	20.11	0.08	18.01	23.61	4.29	0.99	2.16
201	19.03	19.02	0.05	17.90	21.03	3.25	0.47	0.23
204	19.61	19.61	0.04	18.27	21.56	2.65	0.25	1.52
207	18.67	18.72	0.05	16.99	20.33	3.19	−0.10	0.38
Soil moisture (% volume)								
195	20.29	21	0.43	8.00	35.00	25.46	0.13	−0.50
196	20.85	21	0.41	10.00	32.00	23.11	0.01	−0.64
197	19.05	19	0.35	10.00	34.00	21.99	0.66	0.55
200	20.70	20	0.36	12.00	32.00	20.89	0.41	−0.29
201	19.00	19	0.33	12.00	31.00	20.61	0.55	−0.11
204	20.23	19	0.35	11.00	33.00	20.27	0.71	0.43
207	17.62	17	0.33	10.00	29.00	22.53	0.57	−0.02

$N = 141$; SE—standard error; Min—minimum; Max—maximum; CV—coefficient of variation (%); Skew—skewness; Kurt—kurtosis.

Table 2
Descriptive statistics, mean, standard error (SE), minimum (Min), maximum (Max) and coefficient of variation (CV) of soil CO_2 emission, soil temperature, soil moisture and other soil physical and chemical attributes in the 0–0.10-m layer.

Variable	Mean	SE	Min	Max	CV
F_{CO_2} (μmol CO_2 m^{-2} s^{-1})*	1.51	0.03	0.02	5.28	61.46
T_s (°C)*	19.40	0.03	16.99	23.61	4.18
M_s (%)*	19.68	0.14	8.00	35.00	22.84
D_s (g cm^{-3})	1.50	0.01	1.11	1.86	9.19
AFPS (%)	33.97	0.43	22.00	46.36	14.90
TPV (%)	53.89	0.37	43.67	65.15	8.03
Macro (%)	14.72	0.41	6.47	28.13	33.09
Micro (%)	39.21	0.23	33.35	45.10	6.78
Sand (g kg^{-1})	365.17	1.20	335.90	404.27	3.83
Silt (g kg^{-1})	130.14	1.89	73.16	186.76	17.21
Clay (g kg^{-1})	506.80	1.91	456.55	561.48	4.47
pH	5.12	0.02	4.50	5.50	4.16
SOM (g dm^{-3})	47.65	0.47	34.78	61.26	11.53
C_{stock} (Mg ha^{-1})	12.69	0.15	8.66	17.28	14.03
C/N	44.52	2.59	10.42	138.82	65.54
P (mg dm^{-3})	23.21	0.38	12.00	35.26	19.17
Bases (mmol$_c$ dm^{-3})	65.65	0.56	46.55	79.95	10.01
CEC (mmol$_c$ dm^{-3})	108.55	0.47	94.66	122.24	5.10

N = 141; * general mean of all studied days; F_{CO_2} —soil CO_2 emission; T_s—soil temperature; M_s—soil moisture; D_s—soil bulk density; AFPS—air-filled pore space; TPV—total pore volume; Macro—macroporosity; Micro—microporosity; Sand—sand content; Silt—silt content; Clay—clay content; SOM—soil organic matter; C_{stock}—carbon stock; C/N—carbon to nitrogen ratio; P—available phosphorus; Bases—sum of bases; CEC—cation exchange capacity.

F_{CO_2} in southern Brazil have been studied by Panosso et al. (2009) in sugarcane areas. When the contrasting management systems are considered, CV values have been reported from 22.6% to 26.2% (means of 1.97 to 2.16 μmol CO_2 m^{-2} s^{-1}) for mechanical harvest and from 43.6% to 63.5% (means of 2.03 to 5.29 μmol CO_2 m^{-2} s^{-1}) for burned/manual harvest. These results from the literature show us that even in different regions and in different crops, considerable variation can be found in soil CO_2 emissions, which can be influenced by several physical, chemical and biological factors.

The mean of T_s presented small changes during the studied period, varying from 18.67 °C (Julian day 207) to 20.23 °C (Julian day 200) (Table 1). The M_s varied from 17.62% to 20.85% on the Julian days 207 and 196, respectively. These small changes in T_s and M_s values in the grid were possibly related to the presence of crop residues on the soil surface, which could lead to a more homogeneous distribution of those attributes and be reflected in the F_{CO_2} variations over the studied days. Thus, the presence of crop residues on the soil surface could promote lower values of T_s, in addition to the variations in F_{CO_2} being less sensitive to M_s after the occurrence of rain precipitation, when compared to areas under burned harvest (Panosso et al., 2009). However, in some cases, the contribution of T_s and M_s to F_{CO_2} could have lesser importance when the spatial variability is considered (Yim et al., 2003; Tedeschi et al., 2006). In a sugarcane area experiment, no relationship in the spatial variability models was observed between F_{CO_2}, T_s and M_s in a green harvest system (Panosso et al., 2008). In contrast, in sugarcane areas under burned harvest, where few crop residues are left on the soil surface, a significant relationship was observed between those attributes.

For the seven days of measurement (general mean), F_{CO_2} presented a value of 1.51 μmol CO_2 m^{-2} s^{-1}, with a minimum of 0.02 μmol CO_2 m^{-2} s^{-1}, a maximum of 5.28 μmol CO_2 m^{-2} s^{-1} and a CV of 61.46% (Table 2). Similarly, T_s varied from 16.99 °C to 23.61 °C, with a mean of 19.40 °C and CV of 4.18%. The M_s values presented a minimum of 8% and a maximum of 35%, with a mean of 19.68% and a CV of 22.84%. These general means are lower than those obtained in a study conducted in a sugarcane area under green harvest in southern Brazil in which an F_{CO_2} variation from 2.97 to 7.01 μmol CO_2 m^{-2} s^{-1} and a mean of 4.99 μmol CO_2 m^{-2} s^{-1} were observed, with T_s mean values of 25.3 °C and M_s mean values of 43.1% (La Scala et al., 2006). This study, however, was conducted in a period during which the average temperature and precipitation are typically greater, which could explain the higher values of F_{CO_2} when compared to our values.

SOM and C_{stock} are important factors related to F_{CO_2}. SOM is the main source of CO_2 production in soil, and its decay is promoted by microbial activity (Ball et al., 1999; Dominy et al., 2002; Kemmitt et al., 2008). The mean value of SOM in the present study was 47.65 g dm^{-3} (Table 2), which is superior to the values typically found in sugarcane areas under green harvest (Blair, 2000; Panosso et al., 2012) but similar to those reported by other studies conducted close to our site (Razafimbelo et al., 2006). In addition, the quality of soil carbon, which is usually related to the C/N ratio, could also influence F_{CO_2}. The higher the soil C/N ratio is, the greater the difficulty for microorganisms to decay the SOM and the lower the F_{CO_2}. In fact, some studies have shown that a low C/N ratio in a shallow layer results in an increase of microbial activity and a rapid decay of plant material (Khomik et al., 2006; Vesterdal et al., 2008). Khomik et al. (2006) reported a spatially negative relationship between soil CO_2 efflux and the C/N ratio in a soil shallow layer. In our study, the high value observed for the C/N ratio (44.52, Table 2), combined with other factors, could have contributed to the SOM presenting this relatively high mean.

The soil physical attributes, in general, presented moderate or low CV values, with the exception of macroporosity (Table 2). The presence of vegetation cover on the soil could have contributed to a more homogeneous distribution of D_s, TPV and microporosity. However, this homogeneity observed for the attributes of sand and clay contents are more related to the soil parent material because the experimental area is small and has the same parent material. Similar results were observed in other similar studies (Brito et al., 2009; Panosso et al., 2012). According to Piotrowska and Dlugosz (2012), when fields are cultivated with a crop rotation, more variability is created in F_{CO_2} and other soil physical and chemical attributes. D_s presented a high value (1.50 g cm^{-3}, Table 2), which could be related to the higher tractor traffic on the area. Soil porosity and soil density are known to be responsible for soil gaseous transport (Xu and Qi, 2001; Jassal et al., 2004; Epron et al., 2006). High D_s values, as presented in our study, could limit oxygen entry into the soil due to the decrease in the number of pores, which could be a limiting factor for microbial activity and subsequent soil CO_2 emissions. In contrast, a higher soil porosity could facilitate soil oxygenation, favoring microbiological activity and increasing F_{CO_2} (Fang et al., 1998).

3.2. Linear correlation analysis between soil CO_2 emission and soil attributes

The linear correlation coefficient between F_{CO_2} and other soil attributes (Table 3) was significant ($P < 0.05$) only for certain variables related to soil porosity. The attributes D_s ($r = -0.32$) and microporosity ($r = -0.18$) presented a negative linear correlation with F_{CO_2}, whereas macroporosity ($r = 0.21$) and AFPS ($r = 0.18$) presented a positive linear correlation with F_{CO_2}. Correlations between F_{CO_2} and D_s, macroporosity and AFPS have been cited in the literature several times (Xu and Qi, 2001; Epron et al., 2006; Panosso et al., 2011; Teixeira et al., 2013c), suggesting the importance of these soil physical attributes to soil microbial activity and gas exchange between soil and the atmosphere. This positive linear correlation between F_{CO_2} and macroporosity and AFPS indicates that when the pore volume occupied by water is high, i.e., when the values of AFPS are low, microbial activity is hampered due to the limitation of oxygen in the soil profile, and hence F_{CO_2} decreases (Fang and Moncrief, 1999). However, if there is no water available in the soil, microbial activity is also hampered, and CO_2 production is reduced. Thus, the same factors that can promote microbial

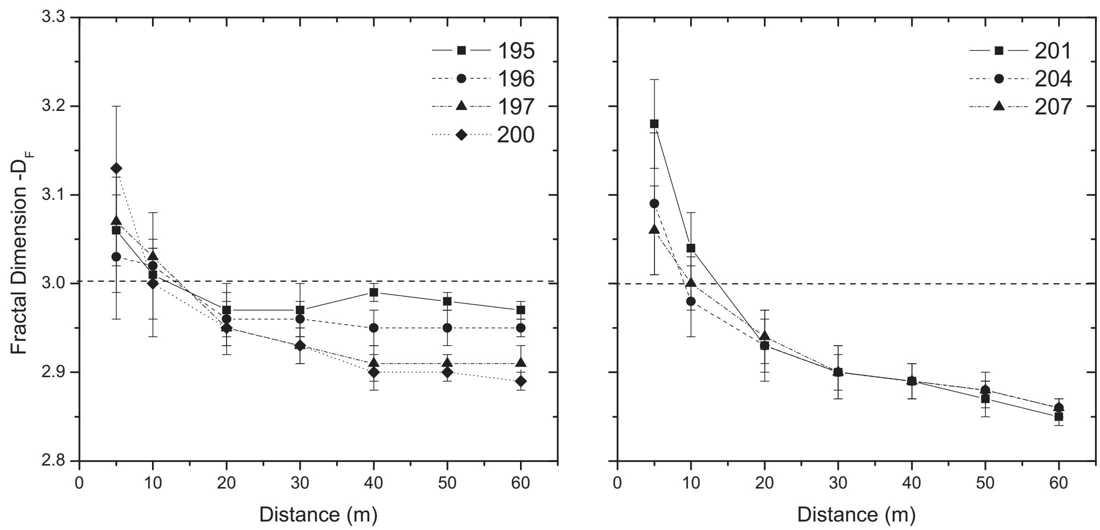

Fig. 2. Fractograms calculated from isotropic variograms, with the values of fractal dimension (D_F) as a function of scale for soil CO_2 emission for all the studied days.

activity and hence soil CO_2 emission may also limit its activity, including soil temperature, moisture, aeration, nutrients, pH, mineralogy and light (Killham, 1994), leading to a decrease in F_{CO_2}.

Other studies have also reported significant correlations between F_{CO_2} and soil attributes. In a rainforest soil of French Guiana, high negative correlation coefficients between soil respiration and M_s, D_s and pH were observed, whereas positive linear correlations were observed between F_{CO_2} and T_s and soil carbon (Epron et al., 2006). The positive correlation between F_{CO_2} and T_s is most likely due to an increase in the decay of SOM promoted by soil microbial activity (Lloyd and Taylor, 1994; Epron et al., 1999, 2006; Burton and Pregitzer, 2003; Ryu et al., 2009). In contrast, studies conducted in the same region as our study, under similar soil and climate conditions, have shown non-significant relationships between soil CO_2 emission and T_s, indicating that T_s alone is not able to explain the temporal and, especially, the spatial variability of soil CO_2 emissions (La Scala et al., 2003). In a bare soil, the cation exchange capacity and total carbon exhibited a positive relationship with F_{CO_2}, whereas the iron oxide content extracted from the clays presented a negative linear correlation with F_{CO_2} (La Scala et al., 2000b). According to that study, a more complex relationship exists between clay minerals and soil microbial activity, as related to the physical and chemical activity of the clays and their interaction with SOM (Dominy et al., 2002).

Table 3
Pearson correlation coefficients between the soil CO_2 emission and soil temperature, soil moisture and other soil physical and chemical attributes.

Attribute	r	Attribute	r
T_s	0.05	Clay	0.05
M_s	−0.05	SOM	0.11
D_s	−0.32*	C_{stock}	0.07
AFPS	0.18*	C/N	0.03
TPV	0.12	pH	−0.11
Macro	0.21*	P	−0.01
Micro	−0.18*	Bases	0.04
Sand	0.01	CEC	0.15
Silt	−0.09		

* Significant Pearson correlation coefficient values ($P < 0.05$); T_s—soil temperature; M_s—soil moisture; D_s—soil bulk density; AFPS—air-filled pore space; TPV—total pore volume; Macro—macroporosity; Micro—microporosity; Sand—sand content; Silt—silt content; Clay—clay content; SOM—soil organic matter; C_{stock}—carbon stock; C/N—carbon to nitrogen ratio; P—available phosphorus; Bases—sum of bases; CEC—cation exchange capacity.

As in other studies (La Scala et al., 2000a; Ohashi and Gyokusen, 2007; Panosso et al., 2009, 2011; Herbst et al., 2010), our results showed weak correlation coefficients between F_{CO_2} and other soil attributes (Table 3) and in most cases non-significant correlations. In these studies, overall, small correlations between soil CO_2 emission and soil physical, chemical and mineralogical attributes have been observed. The difficulty in linearly correlating F_{CO_2} and soil attributes is related to the complex nature of soil respiration, the determinant factors of which are often strongly interrelated, with no single determinant factor in this process (Schwendenmann et al., 2003). Therefore, the complexity in studying F_{CO_2} highlights the need of using more refined techniques to better establish those relationships.

3.3. Fractal dimension and spatial structure correlation analysis

The fractal dimension analysis of F_{CO_2} and other soil attributes was derived from isotropic experimental variograms ($\log(\hat{\gamma}) \times \log(h)$). By using D_F values at different scales, we constructed the so-called fractogram, by which we characterized the complete spatial variability structure (Palmer, 1988; Cantero et al., 1998). The fractogram allows us to interpret the scales at which the spatial variability could be considered as homogeneous ($D_F \geq 3$, i.e., without topological significance) or heterogeneous ($D_F < 3$, i.e., with topological significance) (Palmer, 1988). The fractogram analysis of F_{CO_2} shows topologically significant D_F values ($D_F < 3$) for scales ranging from 20 to 60 m on the majority of the studied days, except for Julian day 195, when D_F was topologically significant only at scales from 50 to 60 m (Fig. 2). D_F is not a property known to be constant in scale, and its pattern of variation could not be repeated from one scale to another (Palmer, 1988). Hence, it is possible to observe a general decreasing tendency in D_F values throughout the studied days and with an increase in the scale sampled, indicating an improved spatial variability structure for medium and large scales (above 20 m). The decrease in D_F values could be related to a tendency of stabilization of the soil CO_2 emissions over the days after the post-harvest period. Several factors may lead to greater or lesser F_{CO_2} stabilization in the short term, such as the agricultural management, rain precipitation and crop residues on the soil surface (Corradi et al., 2013; Moitinho et al., 2013; Silva-Olaya et al., 2013; Teixeira et al., 2013a). In our experimental area, in addition to the presence of crop residues on the soil surface, there was no interference in the studied period from such factors as

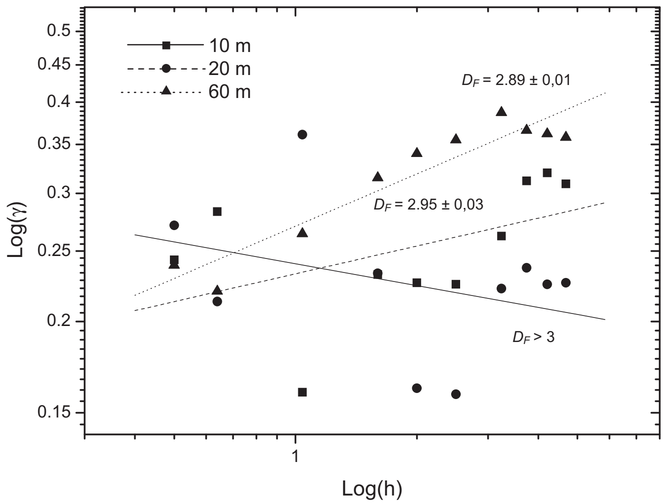

Fig. 3. Log–log plot of semivariance ($\hat{\gamma}$) versus distance (h) to scales of 10, 20 and 60 m for the mean of soil CO_2 emission.

Table 4
Pearson correlation coefficients between the fractogram of soil CO_2 emission and the fractograms of soil temperature, soil moisture and other soil physical and chemical attributes, presenting the similarity of the spatial variability structure of those attributes.

Attribute	r	Attribute	r
T_s	0.85*	Clay	−0.97*
M_s	−0.97*	SOM	−0.55
D_s	−0.77*	C_{stock}	0.53
AFPS	−0.84*	C/N	0.27
TPV	0.76*	pH	−0.91*
Macro	0.08	P	−0.99*
Micro	−0.91*	Bases	−0.81*
Sand	−0.39	CEC	−0.72
Silt	−0.91*		

* Significant Pearson correlation coefficient values (P < 0.05); T_s—soil temperature; M_s—soil moisture; D_s—soil bulk density; AFPS—air-filled pore space; TPV—total pore volume; Macro—macroporosity; Micro—microporosity; Sand—sand content; Silt—silt content; Clay—clay content; SOM—soil organic matter; C_{stock}—carbon stock; C/N—carbon to nitrogen ratio; P—available phosphorus; Bases—sum of bases; CEC—cation exchange capacity.

agricultural management and rain precipitation. Thus, all these factors could have led to the stabilization of F_{CO_2} on our area, which was reflected in its temporal and spatial distribution, and in a better variability structure, resulting in lower values of D_F over the study days. Similarly, the standard error associated with D_F estimations decreases as the scale increases, which could be associated with a less-structured spatial variability at smaller scales.

Non-topologically significant D_F values ($D_F \geq 3$) were found for ranges with limits up to 10 m (smaller scale), and the slope of the straight line regression between $\log(\hat{\gamma}) \times \log(h)$ was small when compared with those for 20 and 60 m (Fig. 3), indicating no spatial variability structure. Similarly, in a study conducted in a soybean-cropped area, topologically significant D_F values were not found for the isotropic spatial variability structure of F_{CO_2} at a small scale during the 12 days of the study (La Scala et al., 2009). In this case, the temporal changes in D_F observed were considered to be related to changes in the heterogeneity of the spatial variability models and mostly related to such controlling factors as T_s and M_s (Epron et al., 2006). Several studies have indicated that the scale, location and orientation of the sampling grid could influence the estimation of D_F values (Burrough, 1981; Klinkenberg, 1992; Xu et al., 1993; Sun et al., 2006; Abedini and Shaghaghian, 2009). In our study, the non-topologically significant D_F values of F_{CO_2} at the small scale could be related to the high variability of the CO_2 emission phenomena at this scale. We believe that an anthropic effect related to the distance between the crop lines and the use of agricultural machinery could have been responsible for causing an increase in the variability to the point that it was no longer possible to find a spatial pattern for F_{CO_2} at a small scale, reaching a pure nugget effect. Due to the distance between the sugarcane rows (Fig. 1), the fractal dimension analysis at the small scale was not able to capture the effect of root respiration in the crop line because the grid points were distributed between rows. In the case of a large scale, in addition to the sampling points of the interrow, the fractal analysis also took into account the closest points to the sugarcane rows, thus also capturing the effect of root respiration. Therefore, it is likely that at the large scale, the anthropic effect is reduced because the spatial dependence structure, which is mainly due to inherent soil characteristics, such as relief and geology could be expressed more sharply than the anthropic effect.

For the general mean of F_{CO_2}, the D_F values varied from 3.05 over a small scale (5 m) to 2.89 over a large scale (60 m), presenting a heterogeneous spatial variability structure only after 20 m (Figs. 3 and 4a). However, Panosso et al. (2012) investigated the anisotropy of soil respiration in a green harvest sugarcane area in southern Brazil (50 m × 50 m grid with 89 sampling points) and observed a tendency for D_F values to increase with scale for most of the studied directions. Conversely, in our study, no anisotropy for F_{CO_2} or other soil attributes was observed, which highlights the variation in the complexity and interaction of the factors that control F_{CO_2} and the role of scale-dependent processes in controlling the spatial variability of soil CO_2 emission and other soil attributes, directly influencing the estimate of D_F. The attributes T_s (Fig. 4a) and TPV (Fig. 4b) presented changes in D_F with scale, similar to the results for F_{CO_2}, i.e., the D_F values decreased with an increase in scale. This finding can be confirmed by analyzing the positive and significant correlation coefficients between the fractogram of F_{CO_2} and the fractograms of these attributes (Table 4), which show the similarity between the spatial dependence of these variables across the different scales analyzed. Thus, even though a significant linear correlation between F_{CO_2} and other soil attributes was not observed (Table 3), the attributes T_s and TPV varied in space of a way similar to F_{CO_2} over the studied grid, with similar spatial variability structures.

The attributes M_s (Fig. 4a), microporosity (Fig. 4b) and silt and clay contents (Fig. 4c) presented an inverse trend in the fractogram when compared to F_{CO_2}, with an increase in D_F values as the scale increased, and all the D_F values were smaller than 3.0, especially for M_s, silt and clay contents. This result is confirmed by the negative linear correlation between the fractogram of F_{CO_2} and the fractograms of those soil attributes. In these cases, the decreasing D_F values of F_{CO_2} along the scales are associated with increasing D_F values for those variables, showing that the spatial variability structure differs along scales but is correlated between them. According to Palmer (1988), the correlation between two attributes at one scale is most likely a result of the relationship between them and not merely a coincidence of spatial variability models. Hence, this correlation between the fractograms could be a useful tool to distinguish variables that would be related to or even influence the spatial variability structure of F_{CO_2}. Studying the spatial variability of soil CO_2 emission and its relationship with soil physical and chemical attributes at small and large scales, Allaire et al. (2012) observed a significant correlation coefficients between F_{CO_2} and soil attributes at different scales. In addition, the authors observed a negative correlation between soil respiration and the C/N ratio and AFPS at large spatial scales. According to Martin and Bolstad (2009), F_{CO_2} can be governed by spatial and temporal factors at many scales; some of these factors are only applicable at certain scales, and additional factors may overshadow others as the spatial and temporal scales change.

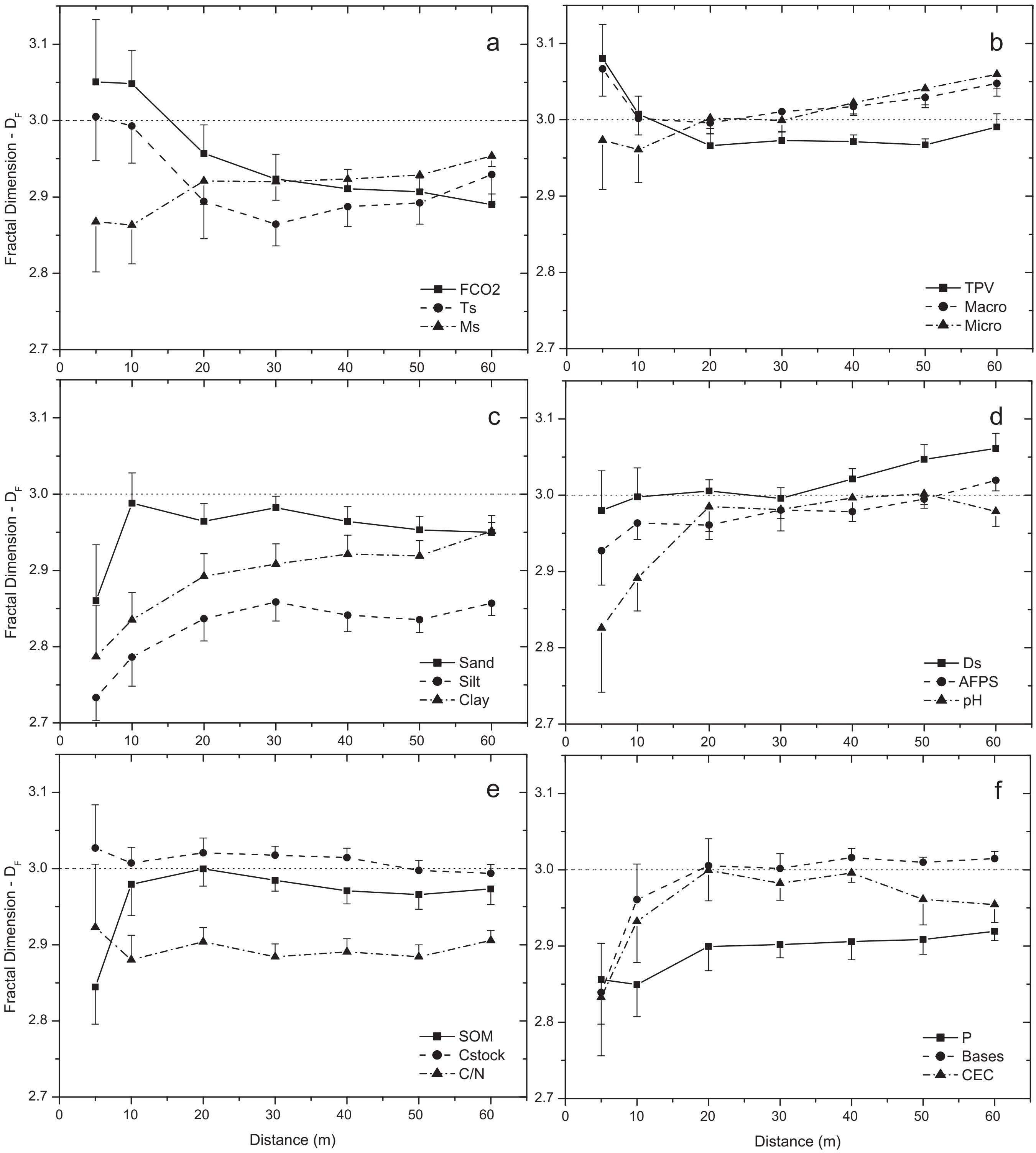

Fig. 4. Fractograms calculated from isotropic variograms, with the values of fractal dimension (D_F) as a function of scale for different attributes: (a) F_{CO_2} —soil CO_2 emission; T_s—soil temperature; M_s—soil moisture; (b) TPV—total pore volume; Macro—macroporosity; Micro—microporosity; (c) Sand—sand content; Silt—silt content; Clay—clay content; (d) D_s—soil bulk density; AFPS—air-filled pore space; (e) SOM—soil organic matter; C_{stock}—carbon stock; C/N—carbon to nitrogen ratio; (f) P—available phosphorus; Bases—sum of bases; CEC—cation exchange capacity.

Analogously, a significant linear correlation between the spatial variability structure of F_{CO_2} and other soil attributes was found with D_s (r = −0.77), microporosity (r = −0.91), AFPS (r = −0.84), silt content (r = −0.91), clay content (r = −0.97), pH (r = −0.91), P (r = −0.98), Bases (r = −0.81) and M_s (r = −0.97) (Fig. 4a, c, d and f), as characterized by the fractograms, all with negative linear correlations (Table 4). For soil pH, the D_F values were topologically significant smaller than 3.0 at small (5 m and 10 m) and large scales (60 m), with values of 2.83, 2.89 and 2.97, respectively. The variability in AFPS showed a heterogeneous spatial variability structure at small and medium scales, whereas the sum of bases showed such a structure only at a small scale (5 m), with non-topologically significant

D_F values for larger scales. In contrast, the available phosphorus content presented topologically significant D_F values for all scales, contrary to D_S, for which no spatial dependence was observed at any scale, indicating no spatial variability structure or a homogeneous variability structure. In a temporal variability study of F_{CO_2}, some points of the sampling grid were correlated linearly and significantly over time (La Scala et al., 2009). According to this study, regarding the points where this variability pattern was similar, it is likely that the difference between the soil CO_2 emission from one point to another over time is closer than for points for which no significant relationship was observed. Although in that study, no investigation was performed on how the spatial variability structure changes with scale for F_{CO_2} and other soil attributes, the results show that the maintenance of the variability structure of a particular attribute is more likely when there is a similar pattern of behavior in their variation. This leads directly to our results that showed a similar spatial variability structure when a positive linear correlation was observed between the fractograms or a dissimilar spatial variability structure when a linear correlation between the fractograms was negative.

It should be emphasized that it is often not possible to determine the controlling factors of soil CO_2 emissions based only on linear correlations and that it is important to spatially evaluate F_{CO_2} and other soil attributes to understand how the phenomenon of soil CO_2 emission occur in the field. The fractal dimension, through fractograms, enables this visualization spatially and the behavior of F_{CO_2} and other soil attributes at different scales, showing the similarity or dissimilarity between the variables and in which spatial scales the similarity or dissimilarity occurs. Thus, taking into account the great importance of CO_2 as the gas of reference for calculating GHG emissions, it would be possible to show through the fractal dimension and the use of fractograms which soil attributes could be possible secondary variables, which would help in a better understanding and quantification of soil CO_2 emission in large areas.

4. Conclusion

In a sugarcane area under green harvest, the soil CO_2 emission presented a significant spatial variability structure at medium (20–30 m) and large (40–60 m) scales, as characterized by means of a fractogram derived from isotropic experimental variograms. Soil CO_2 emission presented no significant linear correlation with most of the soil attributes considered in this study but showed a significant correlation in its spatial variability structure, similar or dissimilar to most of the soil attributes, as characterized by changes in the fractal dimension with the scale. Furthermore, the fractograms allowed the observation of the behavior of the spatial dependence of soil CO_2 emission and other soil attributes along scales and its patterns of homogeneity and heterogeneity.

References

Abedini, M.J., Shaghaghian, M.R., 2009. Exploring scaling laws in surface topography. Chaos, Solitons Fractals 42, 2373–2383.

Allaire, S.E., Lange, S.F., Lafond, J.A., Pelletier, B., Cambouris, A.N., Dutilleul, P., 2012. Multiscale spatial variability of CO_2 emissions and correlations with physico-chemical soil properties. Geoderma 170, 251–260.

Ball, B.C., Scott, A., Parker, J.P., 1999. Field N_2O, CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. Soil Tillage Res. 53, 29–39.

Blair, N., 2000. Impact of cultivation and sugar-cane green trash management on carbon fractions and aggregate stability for a Chromic Luvisol in Queensland, Australia. Soil Tillage Res. 55, 183–191.

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

Brito, L.F., Marques Jr., J., Pereira, G.T., La Scala, N., 2010. Spatial variability of soil CO_2 emission in different topographic positions. Bragantia 69, 19–27.

Burrough, P.A., 1981. Fractal dimensions of landscapes and other environmental data. Nature 294, 240–242.

Burton, A.J., Pregitzer, K.S., 2003. Field measurements of root respiration indicate little to no seasonal temperature acclimation for sugar maple and red pine. Tree Physiol. 23, 273–280.

Cantero, J.J., Leon, R., Cisneros, J.M., Cantero, A., 1998. Habitat structure and vegetation relationships in central Argentina salt marsh landscapes. Plant Ecol. 137, 79–100.

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.

Cerri, C.C., Galdos, M.V., Maia, S.M.F., Bernoux, M., Feigl, B.J., Powlson, D., Cerri, C.E.P., 2011. Effect of sugar cane harvesting systems on soil carbon stocks in Brazil: an examination of existing data. Eur. J. Soil Sci. 62, 23–28.

Chen, W., Hou, Y., Hung, C., 2011. A theoretical analysis of the capture of greenhouse gases by single water droplet at atmospheric and elevated pressures. Appl. Energy 88, 5120–5130.

Conab, Companhia Nacional de Abastecimento, 2013. Acompanhamento de safra brasileira: cana-de-açúcar, terceiro levantamento, dezembro/2013. Conab, Brasília.

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

Corradi, M.M., Panosso, A.R., Martins Filho, M.V., La Scala, N., 2013. Crop residues on short-term CO_2 emissions in sugarcane production areas. Eng. Agríc. 33, 699–708.

Dominy, C.S., Haynes, R.J., van Antwerpen, R., 2002. Loss of soil organic matter and related soil properties under long-term sugarcane production on two contrasting soils. Biol. Fertil. Soils 36, 350–356.

Duah-Yentumi, S., Ronn, R., Christensen, S., 1998. Nutrients limiting microbial growth in a tropical forest soil of Ghana under different management. Appl. Soil Ecol. 8, 19–24.

Eghball, B., Hergert, G.W., Lesoing, G.W., Ferguson, R.B., 1999. Fractal analysis of spatial and temporal variability. Geoderma 88, 349–362.

Embrapa, Empresa Brasileira de Pesquisa Agropecuária, 1997. Manual de métodos de análise de solo, second ed. Embrapa, Brasília, pp. 212.

Epron, D., Farque, L., Lucot, E., Badot, P., 1999. Soil CO_2 efflux in a beech forest: dependence on soil temperature and soil water content. Ann. For. Sci. 56, 221–226.

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. For. Ecol. Manage. 202, 149–160.

Epron, D., Bosc, A., Bonal, D., Freycon, V., 2006. Spatial variation of soil respiration across a topographic gradient in a tropical rain forest in French Guiana. J. Trop. Ecol. 22, 565–574.

Fang, C., Moncrief, J.B., 1999. A model for soil CO_2 production and transport 1: Model development. Agric. For. Meteorol. 95, 225–236.

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.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Van Dorland, R., 2007. Changes in atmospheric constituents and in radiative forcing. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M.M.B., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge, NY, pp. 129–234.

Fuentes, J.P., Bezdicek, D.F., Flury, M., Albrecht, S., Smith, J.L., 2006. Microbial activity affected by lime in a long-term no-till soil. Soil Tillage Res. 88, 123–131.

Grunwald, S., Thompson, J.A., Boettinger, J.L., 2011. Digital soil mapping and modeling at continental scales: finding solutions for global issues. Soil Sci. Soc. Am. J. 75, 1201–1213.

Herbst, M., Prolingheuer, N., Graf, A., Huisman, J.A., Weihermüller, L., Vanderborght, J., Vereecken, H., 2010. Multivariate conditional stochastic simulation of soil heterotrophic respiration at plot scale. Geoderma 160, 74–82.

Huang, C.H., Bradford, J.M., 1992. Applications of a laser scanner to quantify soil microtopography. Soil Sci. Soc. Am. J. 56, 14–21.

Jassal, R.S., Black, T.A., Drewitt, G.B., Novak, M.D., Gaumont-Guay, D., Nesic, Z., 2004. A model of the production and transport of CO_2 in soil: predicting soil CO_2 concentrations and CO_2 efflux from a forest floor. Agric. For. Meteorol. 124, 219–236.

Kemmitt, S.J., Lanyon, C.V., Waite, I.S., Wen, Q., Addiscott, T.M., Bird, N.R.A., O'Donnell, A.G., Brookes, P.C., 2008. Mineralization of native soil organic matter is not regulated by the size, activity or composition of the soil microbial biomass—a new perspective. Soil Biol. Biochem. 40, 61–73.

Khomik, M., Arain, M.A., McCaughey, J.H., 2006. Temporal and spatial variability of soil respiration in a boreal mixedwood forest. Agric. For. Meterol. 140, 244–256.

Killham, K., 1994. Soil Ecology. Cambridge University Press, Cambridge, UK, pp. 242.

Klinkenberg, B., 1992. Fractals and morphometric measures: is there a relationship? Geomorphology 5, 5–20.

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.

Lal, R., 2007. Soil science and the carbon civilization. Soil Sci. Soc. Am. J. 71, 1425–1437.

Lal, R., 2009. Challenges and opportunities in soil organic matter research. Eur. J. Soil Sci. 60, 158–169.

La Scala, N., Marques Jr., J., Pereira, G.T., Corá, J.E., 2000a. Short-term temporal changes in the spatial variability model of CO_2 emissions from a Brazilian bare soil. Soil Biol. Biochem. 32, 1459–1462.
La Scala, N., Marques Jr., J., Pereira, G.T., Corá, J.E., 2000b. Carbon dioxide emission related to chemical properties of a tropical bare soil. Soil Biol. Biochem. 32, 1469–1473.
La Scala, N., Panosso, A.R., Pereira, G.T., 2003. Modelling short-term temporal changes of bare soil CO_2 emissions in a tropical agrosystem by using meteorological data. Appl. Soil Ecol. 24, 113–116.
La Scala, N., Bolonhezi, D., Pereira, G.T., 2006. Short-term soil CO_2 emission after conventional and reduced tillage of a no-till sugar cane area in southern Brazil. Soil Tillage Res. 91, 244–248.
La Scala, N., Panosso, A.R., Pereira, G.T., Gonzalez, A.P., Miranda, J.G.V., 2009. Fractal dimension and anisotropy of soil CO_2 emission in an agricultural field during fallow. Int. Agrophys. 23, 353–358.
Lloyd, J., Taylor, A., 1994. On the temperature dependence of soil respiration. Funct. Ecol. 8, 315–323.
Mandelbrot, B.B., 1977. Fractals: Form, Chance, and Dimension. W.H. Freeman, San Francisco, CA, pp. 365.
Martin, J.G., Bolstad, P.V., 2009. Variation of soil respiration at three spatial scales: components within measurements, intra-site variation and patterns on the landscape. Soil Biol. Biochem. 41, 530–543.
Miranda, J.G.V., 2000. Análisis fractal del microrrelieve del suelo. In: Ph.D. Thesis. Universidad de a Coruña, Coruña.
Moitinho, M.R., Padovan, M.P., Panosso, A.R., La Scala, N., 2013. Efeito do preparo do solo e resíduo da colheita de cana-de-açúcar sobre a emissão de CO_2. Rev. Bras. Cienc. Solo 37, 1720–1728.
Ngao, J., Epron, D., Delpierre, N., Breda, N., Granier, A., Longdoz, B., 2012. Spatial variability of soil CO_2 efflux linked to soil parameters and ecosystem characteristics in a temperate beech forest. Agric. For. Meteorol. 154, 136–146.
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.
Oyonarte, C., Rey, A., Raimundo, J., Miralles, I., Escribano, P., 2012. The use of soil respiration as an ecological indicator in arid ecosystems of the SE of Spain: spatial variability and controlling factors. Ecol. Indic. 14, 40–49.
Pachepsky, Y., Crawford, J.W., 2004. Fractal analysis. In: Hillel, D. (Ed.), Encyclopedia of Soils in the Environment, 2. Academic Press, Waltham, MA, pp. 85–98.
Palmer, M.W., 1988. Fractal geometry: a tool for describing spatial patterns of plant communities. Vegetatio 75, 91–102.
Panosso, A.R., Pereira, G.T., Marques Jr., J., La Scala, 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.
Panosso, A.R., Marques Jr., J., Pereira, G.T., La Scala, N., 2009. Spatial and temporal variability of soil CO_2 emission in a sugarcane area under green and slash-and-burn managements. Soil Tillage Res. 105, 275–282.
Panosso, A.R., Marques, J., Milori, D.M.B.P., Ferraudo, A.S., Barbieri, D.M., Pereira, G.T., La Scala, N., 2011. Soil CO_2 emission and its relation to soil properties in sugar cane areas under Slash-and-burn and Green harvest. Soil Tillage Res. 111, 190–196.
Panosso, A.R., Perillo, L.I., Ferraudo, A.S., Pereira, G.T., Miranda, J.G.V., La Scala, N., 2012. Fractal dimension and anisotropy of soil CO_2 emission in a mechanically harvested sugarcane production area. Soil Tillage Res. 124, 8–16.
Pérez, L.D., Millán, H., González-Posada, M., 2010. Spatial complexity of soil plow layer penetrometer resistance as influenced by sugarcane harvesting: a prefractal approach. Soil Tillage Res. 110, 77–86.
Perfect, E., Kay, B.D., 1995. Applications of fractals in soil and tillage research: a review. Soil Tillage Res. 36, 1–20.
Piotrowska, A., Dlugosz, J., 2012. Spatio-temporal variability of microbial biomass content and activities related to some physicochemical properties of Luvisols. Geoderma 173, 199–208.
Raij, B. van, Andrade, J.C., Cantarella, H., Quaggio, J.A. (Eds.), 2001. Análise química para avaliação da fertilidade de solos tropicais. Instituto Agronômico, Campinas, p. 284.
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.
Ryu, S., Concilio, A., Chen, J., North, M., Ma, S., 2009. Prescribed burning and mechanical thinning effects on belowground conditions and soil respiration in a mixed-conifer forest, California. For. Ecol. Manage. 257, 1324–1332.
Schneider, S., Sarukhan, J., Adejuwon, J., Azar, C., Baethgen, W., Hope, C., Moss, R., Leary, N., Richels, R., Ypersele, J. van, 2001. Overview of impacts, adaptation, and vulnerability to climate change. In: McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S. (Eds.), Climate Change 2001: Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge, NY, pp. 75–103.
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.
Silva-Olaya, A.M., Cerri, C.E.P., La Scala, N., Dias, C.T.S., Cerri, C.C., 2013. Carbon dioxide emissions under different soil tillage systems in mechanically harvested sugarcane. Environ. Res. Lett. 8, 1–8.
Sun, W., Xu, G., Gong, P., Liang, S., 2006. Fractal analysis of remotely sensed images: a review of methods and applications. Int. J. Remote Sens. 27, 4963–4990.
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.
Teixeira, D.D.B., Panosso, A.R., Cerri, C.E.P., Pereira, G.T., La Scala, N., 2011. Soil CO_2 emission estimated by different interpolation techniques. Plant Soil 345, 187–194.
Teixeira, L.G., Corradi, M.M., Fukuda, A., Panosso, A.R., Reicosky, D., Lopes, A., La Scala, N., 2013a. Soil and crop residue CO_2–C emission under tillage systems in sugarcane-producing areas of southern Brazil. Sci. Agric. 70, 327–335.
Teixeira, D.D.B., Bicalho, E.S., Cerri, C.E.P., Panosso, A.R., Pereira, G.T., La Scala, N., 2013b. Quantification of uncertainties associated with space-time estimates of short-term soil CO_2 emissions in a sugar cane area. Agric. Ecosyst. Environ. 167, 33–37.
Teixeira, D.D.B., Bicalho, E.S., Panosso, A.R., Cerri, C.E.P., Pereira, G.T., La Scala, N., 2013c. Spatial variability of soil CO_2 emission in a sugarcane area characterized by secondary information. Sci. Agric. 70, 195–203.
Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Georgr. Rev. 38, 55–94.
Trumbore, S.E., 1997. Potential responses of soil organic carbon to global environmental change. Proc. Nat. Acad. Sci. U.S.A. 94, 8284–8291.
Usowicz, B., Lipiec, J., 2009. Spatial distribution of soil penetration resistance as affected by soil compaction: the fractal approach. Ecol. Complexity 6, 263–271.
Veldkamp, E., 1994. Organic carbon turnover in three tropical soils under pasture after deforestation. Soil Sci. Soc. Am. J. 58, 175–180.
Vesterdal, L., Schmidt, I.K., Callesen, I., Nilsson, L.O., Gundersen, P., 2008. Carbon and nitrogen in forest floor and mineral soil under six common European tree species. For. Ecol. Manage. 255, 35–48.
Vidal Vázquez, E., Miranda, J.G.V., Paz González, A., 2005. Characterizing anisotropy and heterogeneity of soil surface microtopography using fractal models. Ecol. Modell. 182, 337–353.
Vidal Vázquez, E., Vieira, S.R., De Maria, I.C., Paz González, A., 2010. Fractal dimension and geostatistical parameters for soil microrelief as a function of cumulative precipitation. Sci. Agric. 67, 78–83.
Webster, R., Oliver, M.A., 1990. Statistical Methods in Soil and Land Resource Survey. Oxford University Press, Oxford, UK, pp. 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.
Xu, T., Moore, I.D., Gallant, J.C., 1993. Fractals, fractal dimensions and landscapes–a review. Geomorphology 8, 245–262.
Yim, M.H., Joo, S.J., Shutou, K., Nakane, K., 2003. Spatial variability of soil respiration in a larch plantation: estimation of the number of sampling points required. For. Ecol. Manage. 175, 585–588.