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SPATIAL VARIABILITY OF SOIL CO_2 EMISSION IN DIFFERENT TOPOGRAPHIC POSITIONS (1)

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ABSTRACT

The spatial variability of soil CO_2 emission is controlled by several properties related to the production and transport of CO_2 inside the soil. Considering that soil properties are also influenced by topography, the objective of this work was to investigate the spatial variability of soil CO_2 emission in three different topographic positions in an area cultivated with sugarcane, just after mechanical harvest. One location was selected on a concave-shaped form and two others on linear-shaped form (in back-slope and foot-slope). Three grids were installed, one in each location, containing 69 points and measuring 90 x 90 m each. The spatial variability of soil CO_2 emission was characterized by means of semivariance. Spatial variability models derived from soil CO_2 emission were exponential in the concave location while spherical models fitted better in the linear shaped areas. The degree of spatial dependence was moderate in all cases and the range of spatial dependence for the CO_2 emission in the concave area was 44.5 m, higher than the mean value obtained for the linear shaped areas (20.65 m). The spatial distribution maps of soil CO_2 emission indicate a higher discontinuity of emission in the linear form when compared to the concave form.

Key words: sugarcane, carbon dioxide, geostatistics, kriging, soil respiration, topography.

RESUMO

VARIABILIDADE ESPACIAL DA EMISSÃO DE CO_2 DO SOLO EM DIFERENTES POSIÇÕES TOPOGRÁFICAS

A variabilidade espacial da emissão de CO_2 é determinada pela variação de atributos do solo relacionados à produção e ao transporte de CO_2 no interior do solo. Considerando que a distribuição espacial destes atributos ocorre por influência da topografia, o objetivo deste trabalho foi estudar a variabilidade espacial da emissão de CO_2 do solo em três diferentes posições topográficas em área sob cultivo de cana-de-açúcar, após colheita mecanizada da cana crua. Selecionou-se uma área na forma côncava e outras duas em posições contrastantes na forma linear (encosta superior e encosta inferior), nas quais foram instaladas três malhas de amostragem, uma em cada área, contendo 69 pontos e medindo 90 x 90 m cada uma. Caracterizou-se a variabilidade espacial da emissão de CO_2 por meio da semivariância. A estrutura de variabilidade espacial da emissão de CO_2 foi descrita por modelo exponencial na forma côncava e por modelos esféricos nas áreas situadas na forma linear. O grau de dependência espacial foi moderado nas três áreas e o alcance da dependência espacial da emissão na área côncava foi de 44,5 m, superior ao valor médio obtido para as áreas situadas na forma linear (20,65 m). Houve maior descontinuidade da distribuição espacial da emissão de CO_2 do solo na forma linear em relação à forma côncava.

Palavras-chave: cana-de-açúcar, dióxido de carbono, geoestatística, *krigagem*, respiração do solo, topografia.

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1. INTRODUCTION

Soil CO_2 emission is a result of several physical and biochemical processes that affect production and transport of CO_2 inside the soil. The magnitude of soil CO_2 emission varies in time and space depending on the environmental conditions, soil characteristics and agricultural management.

Temperature and soil moisture are the major factors controlling soil CO_2 emission, especially when temporal variability is considered (Kang et al., 2003; Epron et al., 2004). Other properties, related to organic matter and soil porosity, have been cited as also controlling its spatial variability patterns (Fang et al., 1998; La Scala et al., 2000b; Xu and Qi, 2001; Schwendenmann et al., 2003; Epron et al., 2006). Topographical aspects, like surface shape and position in landscape, also influence the spatial distribution of soil properties (Souza et al., 2004a,b,c; Epron et al., 2006) and, consequently, soil CO_2 emission.

Therefore, understanding the spatial variability of soil CO_2 emission is important in order to better understand the dynamics of CO_2 in different ecosystems as the spatial variability characterization helps the interpretation of such phenomena in a given scale. The high degree of variability of soil CO_2 emission observed by Fang et al. (1998) and Rayment and Jarvis (2000), for instance, which found coefficients of variation (CV) from 55% to 87%, justifies the use of geostatistics in order to model the spatial dependence on emission.

According to La Scala et al. (2000b; 2003), the spatial variability structure of a bare soil CO_2 emission can be explained by spherical and, less often, exponential models, and the degree of spatial variability of those studies were classified as strong and moderate, according to the criteria suggested by Cambardella et al. (1994). On the other hand, Ishizuka et al. (2005) observed weak spatial dependence on soil CO_2 emission at a sampling distance of 3 m in natural ecosystems.

The spatial variability patterns obtained by Rayment and Jarvis (2000) and Ohashi and Gyokusen (2007) show considerable changes in variability structure scale of soil CO_2 emission, depending on the experimental condition, as the range of variability on those studies varied from 1 to 80 m.

Understanding the spatial variability of soil CO_2 emission of agricultural areas in Brazil is important in order to conduct a controlled and sustained management to preserve soil carbon, and helping reducing the greenhouse effect. Despite all the efforts there are few studies where spatial variability of soil CO_2 emission is characterized in agricultural areas, especially considering topographic aspects like position and landscape form.

Nowadays, sugarcane is an important agriculture crop in Brazil, and is also recognized that changes in crop residues in this kind of cultivation could produce a positive balance of carbon (Razafimbelo et al., 2006). According to Cerri et al. (2007), the adoption of a rational, mechanized sugarcane harvest without burning (green harvest) can result in a 0.48 Mt C per year sequestered in soil, avoiding a 0.05 Mt C emission in the same period, associated with the methane emission due to harvest and burning processes. New studies are needed in order to clarify the management effect on soil CO_2 emission on those areas.

The objective of this work was to study the spatial variability of soil CO_2 emission in different topographic positions in an area cultivated with sugar cane.

2. MATERIAL AND METHODS

The experiment was conducted in the Santa Isabel farm located from 21° 17′ to 21° 18′ South and 48° 08′ to 48° 10′ West, in Jaboticabal municipal district of São Paulo state, in an area where sugarcane has been cropped for 60 years, with a history of mechanized harvest (green harvest) in the last 10 years. The climate of the area is classified as Aw (tropical with rainy summer and dry winter), according to Köppen, with average temperatures between 24.3 °C in January and 18.8 °C in July. Average annual precipitation is around 1425 mm, with precipitations around 239.5 mm and 25.3 mm for January and July, respectively. Soil was characterized as Rhodic Eutrudox or Latossolo Vermelho Eutroférrico, according to Embrapa (1999).

The topography of the studied area presents two relief forms, one being concave (Conc) and occurring in the highest position of the landscape, and the other linear, towards the hillside, according to the criteria establhished by Troeh (1965). Two locations were defined in the linear form, back-slope (BackS) and foot-slope (FootS) according to a transect criteria proposed by Darlymple et al. (1968), presented in Christofoletti (1980). Samplings were randomly performed in the concave and in the two linear form locations, BackS and FootS, positioned at 612, 621 and 515 m above sea level (Figure 1).

Measurements were performed in the crossing of a grid with 90 x 90 m in dimension, having 49 points regularly distributed in a 15 m distance, with an addition of 20 points inserted in each of the quadrants, totalizing 69 points in sampling area, spaced by distances between 7.5 m and 127.3 m (Figure 2). The additional points in the sampling grid increased the number of studied points in order to obtain more pairs separated by distances smaller than 15 m.

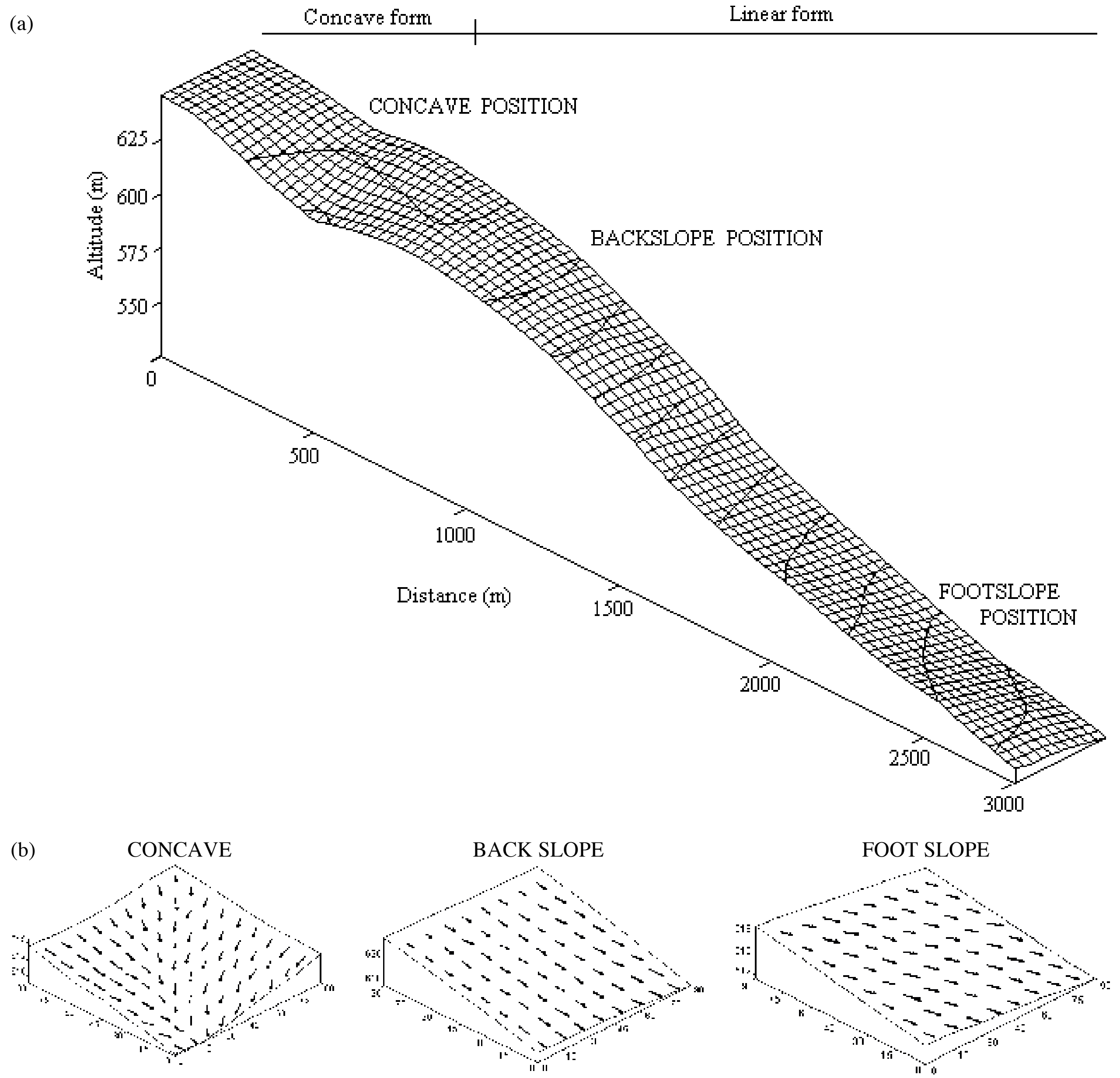

Figure 1. Schematic representation of the experimental site. (a) Study area map: concave and linear shaped areas with view of concave, back-slope and foot-slope positions (Modified from Souza et al., 2003). (b) Elevation model of the three studied positions.

Soil CO_2 emission measurements were conducted close to one month after sugarcane harvest, on August 30 and August 31, 2005 at Conc and BackS locations, respectively, and on September 6, 2005 at FootS position. A precipitation of 12 mm was registered between August 31 and September 6 in the areas. The three areas presented a huge amount of crop residues left after the previous harvest, which occurred between July 29 and August 8, 2005. Measurements of soil CO_2 emission were conducted in each of the studied locations during the afternoon period (between 14 – 16 h), using a portable LI-6400-09 chamber (LI-COR, NE, USA) (Healy et al., 1996). The chamber is a closed system, with an internal volume of 991 cm^3 and a contact area with the soil of 71.6 cm^2 that is able to analyze CO_2 concentration inside by means of optical absorption spectroscopy in infrared. PVC rings were inserted in the soil some days before measurements, in order to eliminate the CO_2 emission

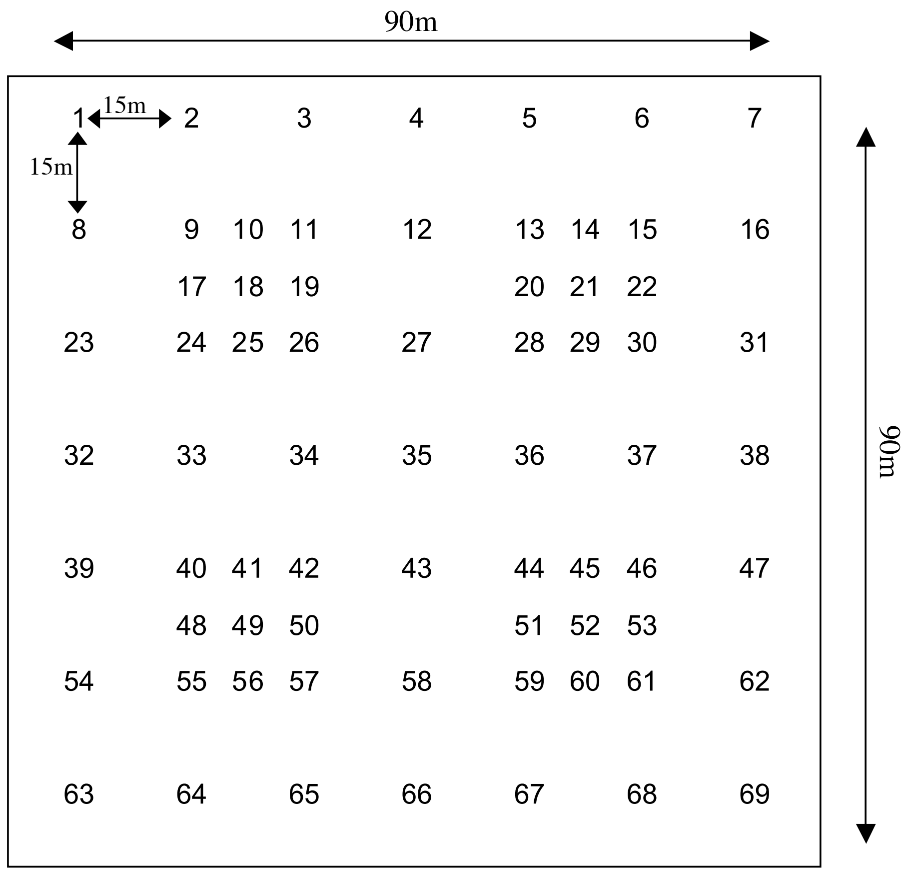

Figure 2. Schematic representation of the experimental grid installed in the three studied locations: 90 x 90 m in dimension, having 49 points regularly distributed in a 15 m distance, with an addition of 20 points inserted in each of the quadrants, totalizing 69 points in sampling area, spaced by distances between 7.5 m and 127.3 m.

caused by the ring insertion in the soil. The measurement chamber was then coupled to rings, at the moment of measurement, in each grid point.

Descriptive statistics (minimum, maximum, mean, median, variance, coefficient of variation, asymmetry and kurtosis) were used in order to show the spread and central tendency of the studied properties (Statsoft, 2001). The normality hypothesis was tested by Kolmogorov-Smirnov method.

The spatial dependence of soil CO_2 emission was obtained by means of geostatistics. Assuming the stationary hypothesis of the data, the semivariogram was applied to quantify the scale and intensity of spatial distribution of studied properties. Semivariance was estimated by the following expression:

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

where $\gamma\,(h)$ is the semivariance of pairs of points separated by h distance; $N\,(h)$ is the number of observations of each pair of points separated by h distance; $Z\,(x_i)$ and $Z\,(x_i+h)$ are the values of Z variable in points x_i and $x_i + h$ (Trangmar et al., 1985).

Experimental semivariograms were created from the calculated values of $\hat{\gamma}\,(h)$ for all pairs of points separated by the distance h, to which the following mathematical models were then fitted: (a) exponential: $\gamma\,(h) = C_o+C\{1\text{-}\exp[-3(h/a)]\}$, ; (b) spherical: $\gamma\,(h) = C_o+C\,[3/2(h/a)-1/2(h/a)^3]$, $0 \leq h \leq a$ e $\gamma\,(h) = C_o+C$, $h > a$ (Vieira, 2000). As in exponential models the sill value never cross the asymptote, in this case the effective range is the difference at which the sill is within 5% of the asymptote.

Models were selected on the basis of the sum of squares of the residues (SSR) and the determination coefficient (R^2). The cross validation procedure, which consists in the removal of each measured value of the data set and the subsequent estimation of it by interpolation, was used in order to verify the reliability of the entire geostatistical model. The model chosen was the one that adjusted the observed and estimated values closer, i.e., the best possible estimate would always match the measured values and would therefore fit in the 45º line on a observed x estimated scatter plot (Isaaks and Srivastava, 1989).

From the theoretical model fitted to the estimated semivariances, $\hat{\gamma}$ *(h)*, the following coefficients are extracted (Trangmar et al., 1985; Isaaks and Srivastava, 1989): nugget effect (C_0), intercept of model in axis of semivariogram, which represents the random variability being an indicative of shorter distance variability; sill ($C + C_0$), which is the semivariance value in which the semivariogram curve stabilizes; range (a), the distance at which the sill is reached which defines the spatial dependence limit. The C value represents the structured spatial variability of the data.

The ratio between nugget effect and sill (C_0/C_0+C), expressed in percent, was used in order to classify the spatial dependence of the studied properties. According to the work of Cambardella et al. (1994), strong, moderate or weak spatial dependence are characterized when (C_0/C_0+C) ≤ 25%; 25 < (C_0/C_0+C) < 75% and (C_0/C_0+C) ³ 75%, respectively.

By using the fitted models estimates of soil CO_2 emission in non-sampled places by means of point kriging was performed (Trangmar et al., 1985). The values obtained were used in the isoline maps for better representation of spatial distribution of soil CO_2 emission in the studied locations.

The GS+ version 7.0 software (Gamma Design Software, 2004) was used to generate the semivariograms, fit and validate the theoretical models and to estimate data in non sampled places. The isoline maps were created by Surfer software (Version 8, Golden Software, Inc., Golden, CO).

3. RESULTS AND DISCUSSION

The observation of extreme values and the frequency distribution confirmed the presence of atypical values in our study. All the extreme values were removed and replaced by the mean values of their closest neighbors, aiming to have a symmetric distribution, defined by asymmetry and kurtosis close to 0.

Mean values of soil CO_2 emission in the Conc, BackS and FootS locations were 0.28, 0.22 and 0.34 g CO_2 m^{-2} h^{-1}, respectively (Table 1). The rainfall of 12 mm, which occurred between August 31 and September 6, 2005, could explain the increased emission in the FootS location that presented mean value higher than the other locations. Emission values found are similar to the ones registered in the same season, at the same location, as in August 2004 that registered values from 0.27 to 0.35 g CO_2 m^{-2} h^{-1} (Brito, 2008). On the other hand, mean values found in this study are higher than the ones reported by Campos (2003) in sugarcane areas, in the same season, even for the traditional burned harvest management (0.13 g CO_2 m^{-2} h^{-1}) or for the mechanized harvest (0.14 g CO_2 m^{-2} h^{-1}).

The values of the coefficient of variation (CV) derived from soil CO_2 emission, in the three topographic positions were between 24.53 and 34.18%, the highest being observed in the BackS location (Table 1). Minimum (0.07 g CO_2 m^{-2} h^{-1}) and maximum (0.54 g CO_2 m^{-2} h^{-1}) values were registered in BackS and FootS locations, respectively. The heterogeneity in CO_2 emission in each location shows the importance of considering the topographical aspects in field studies. Sotta et al. (2006) found CV values between 17.2 and 32.8% depending on topographic position (plateau, upper slope, lower slope and valley). Those values have the same magnitude of the observed temporal changes in soil CO_2 emission, showing the importance of topographical aspects into the definition of its spatial variability pattern.

According to the classification criteria of spatial variability of soil properties, proposed by Warrick and Nielsen (1980), the CV values found for soil CO_2 emission could be considered moderate (Table 1). Other field investigations in which soil CO_2 emission was studied point to even higher CV values (12.7 a 87%), indicating heterogeneity in emissions depending on the experimental condition (Fang et al., 1998; Rayment and Jarvis, 2000; La Scala et al., 2000a, b; La Scala et al., 2003; Ishizuka et al., 2005; Khomik et al., 2006; Sotta et al., 2006; Ohashi and Gyokusen, 2007).

The descriptive statistics indicate a symmetrical distribution of soil CO_2 emission in Conc, BackS and FootS locations (Table 1). Mean and median values are close to all the studied properties with asymmetry and kurtosis near to zero value. Kolmogorov-Smirnov test indicate the normality of data only in Conc location. Despite that, the analysis of mean, median, asymmetry and kurtosis assures the needed conditions for geostatistics application on such data, even in BackS and FootS locations (Isaaks and Srivastava, 1989; Gonçalves, et al., 2001).

The spatial variability structure was defined by an exponential model in the Conc location and spherical models in both linear locations (BackS and FootS) (Table 2 and Figure 3). The choice of a model depends very much on the semivariogram behavior close to the origin

(h close to 0). Exponential models fit better to more erratic phenomena in closer distances than spherical ones (Isaaks and Srivastava, 1989). All the models fitted to the semivariograms were validated by cross validation (Table 2) and the results indicate that the observed and estimated values were close to 1:1 diagonal.

The models fitted to these semivariograms have already described the spatial variability in other experiments. La Scala et al. (2000b), for instance, showed that in a bare soil, CO_2 emission presented spherical models similarly to the findings of our investigation in two out of three studied days. In a tropical forest, Ishizuka et al. (2005) also selected a spherical model to describe the spatial variability structure of soil CO_2 emission. Ohashi and Gyokusen (2007), contrarily, show that spatial variability of soil CO_2 emission in a forest was described by different kinds of models (spherical, exponential, linear), depending on the season.

The degree of spatial dependence (DSD), expressed by the ratio between nugget effect (C_0) and total variance ($C+C_0$) or sill (Cambardella et al., 1994), was classified as moderate for soil CO_2 emission in all topographic positions, as nugget effect represented from 33 to 43% of total data variance (Table 2). Other studies have shown weak degree of spatial dependence (Ishizuka et al., 2005) or also moderate (La Scala et al., 2000b) on soil CO_2 emission, varying also with seasons (strong in summer and winter, moderate in fall and without spatial variability structure in spring) (Ohashi and Gyokusen, 2007).

The range of spatial dependence values can provide information on the heterogeneity of the spatial distribution of the studied properties in each topographic position (Table 2 and Figure 3). For soil CO_2 emission, the range was considerably higher in the concave shaped location (44.5 m) in comparison to those observed in the linear shaped forms (21.1 m for BackS and 20.2 m for FootS). As the range defines the distance from where data could be considered independent (Trangmar et al., 1985), those results show that in order to estimate soil CO_2 emission in the concave shaped form a distance smaller than 44.5 m should be considered. In the case of the linear forms, measurements should have minimum distances of 20.6 m (in average). Therefore, a smaller number of points for sampling would be needed to estimate mean values of soil CO_2 emission in concave forms than in linear shaped ones.

As observed, depending on the topographic position of the experiment, soil CO_2 emission could present differences in range values, which represents the changes in scale of each property. Rayment and Jarvis (2000) found range values of 1 m for soil CO_2 emission in a boreal forest area in Canada, while in a tropical forest Ishizuka et al. (2005) reported ranges of 10 m. According to Ohashi and Gyokusen (2007) the range value in a forest area of Japan varies from 12 to

Table 1. Descriptive statistics of soil CO_2 emission (g CO_2 m^{-2} h^{-1}) in concave, back slope and foot slope locations in area cultivated with sugarcane

Position	Minimum	Maximum	Mean	Median	SD	CV	Asymmetry	Kurtosis	D
Concave	0.11	0.49	0.28	0.27	0.09	30.50	0.37	-0.35	0.11**
Back-Slope	0.07	0.42	0.22	0.22	0.08	34.18	0.23	-0.25	0.06^{NS}
Foot-Slope	0.16	0.54	0.34	0.34	0.08	24.53	0.20	0.13	0.06^{NS}

SD: standard deviation. CV: coefficient of variation. D: Kolmogorov-Smirnov statistical test ^{NS}: non significant at 10%; *: significant at 10%; **: significant at 5%; ***: significant at 1%.

Table 2. Model, estimated parameters and cross validation of experimental semivariograms obtained for soil CO_2 emission in concave, back slope and foot slope locations in area cultivated with sugarcane

Model	Nugget C_0	Sill (C_0+C)	Range (a)	$C_0/(C_0+C)$	DSD*1	R^2	SSR*2	Cross validation*3 a	Cross validation*3 b
Exponential					Concave				
	0.0033	0.0075	44.5	0.43	MO	0.684	$3.54x10^{-6}$	0.03	0.98
Spherical					Back-Slope				
	0.00255	0.00605	21.1	0.42	MO	0.766	$1.426x10^{-6}$	0.60	0.59
Spherical					Foot-Slope				
	0.0022	0.0068	20.2	0.33	MO	0.861	$9.586x10^{-7}$	0.35	0.83

(*1)DSV: degree of spatial dependence: $C_0/(C_0+C)$: Strong (ST) for values smaller than 0.25; moderate (MO) for values between 0.25 and 0.75; weak (WE) for values higher than 0.75 (Cambardella et al., 1994).
(*2)SSR: sum-square residue.
(*3)Linear regression parameters between observed and estimated by model using cross validation procedure: a: linear coefficient; b: angular coefficient and coefficient of determination (R^2).

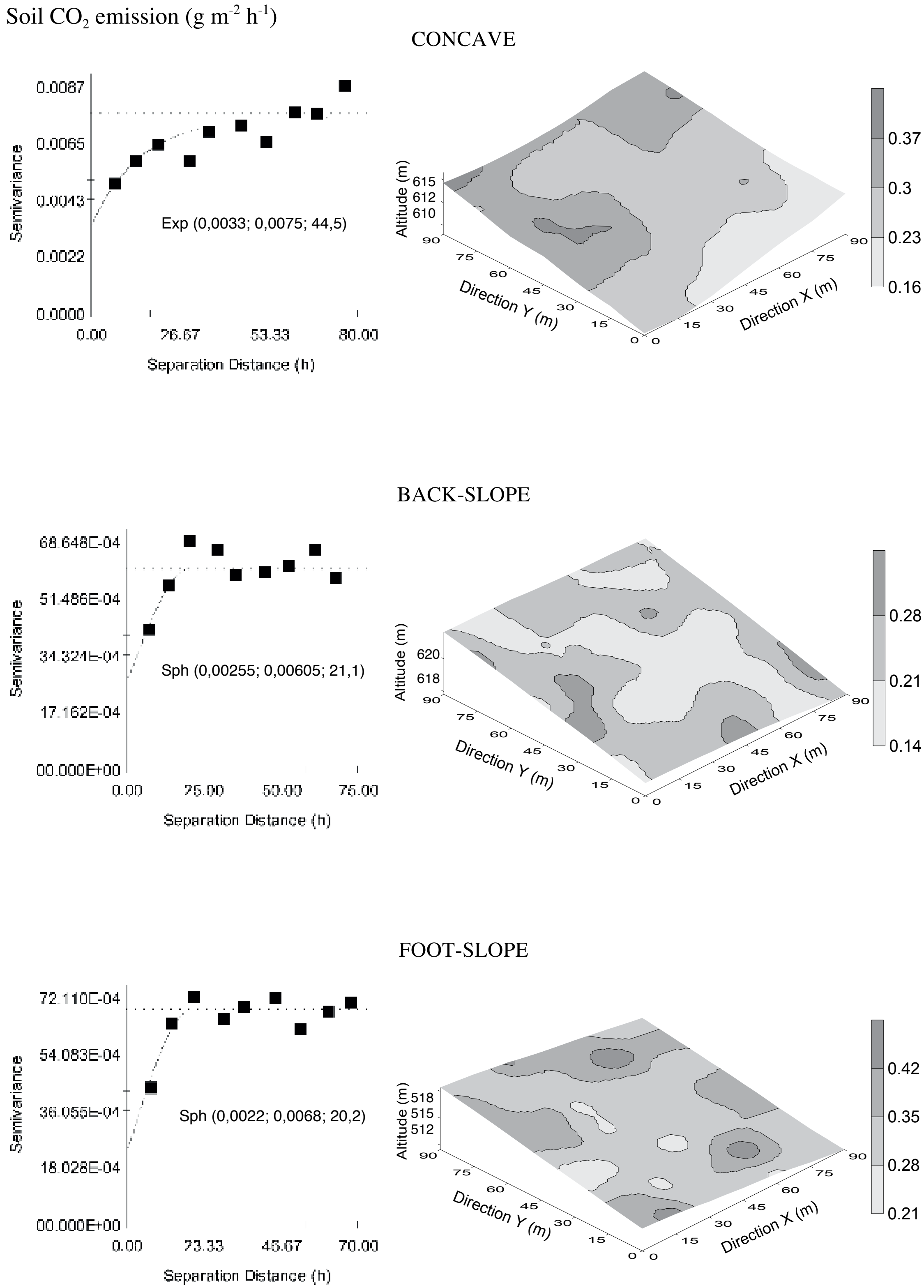

Figure 3. Experimental semivariograms with adjusted models [(Model (C_0; C_0+C; a (m) and maps with estimated values after kriging for soil CO_2 emission (g CO_2 m^{-2} h^{-1})] in concave, back-slope and foot-slope locations.

80 m, depending on the season. In a bare soil, close to the area in this study, soil CO_2 emission range values showed considerable changes (from 29.6 to 58.4 m) in two observations performed along the same week of November (La Scala et al., 2000b).

Surface maps derived from kriging show the distribution of soil CO_2 emission in Conc, BackS and FootS areas (Figure 3). Maps of BackS and FootS areas indicate a higher discontinuity of spatial distribution in soil CO_2 emission, due to the smaller range values of those areas (Table 2). As range in Conc area was twice the value of the linear shaped areas its map presents, consequently, a higher continuity of spatial distribution. Souza et al. (2004a, b, d), otherwise, verified a relationship between small changes of the slope gradient in topographic forms and its soil properties variability, or in other words, their results show a greater fragmentation of spatial distribution of soil properties associated with greater changes in topographic form.

The results obtained in this study show the importance of characterizing the spatial variability models of soil CO_2 emission. The geostatistical analysis of soil CO_2 emission derived different range values and spatial variability models for concave and linear-shaped forms. Those results indicate that a smaller set of points is needed to infer mean soil CO_2 emission in concave forms, in relation to the linear forms. The larger range value in concave form also indicates a larger spatial continuity of soil CO_2 emission in this area when compared to the more discontinuous distribution observed in a more homogeneous topographic form.

4. CONCLUSIONS

1. The structure of the spatial variability of soil CO_2 emission was described by an exponential model in concave-shaped form and spherical models in the linear-shaped locations.

2. The topographic form determines differences in range distance of spatial variability of soil CO_2 emission; higher values were found in concave-shaped form when compared to the linear-shaped ones.

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