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Fractal dimension and anisotropy of soil CO_2 emission in an agricultural field during fallow**

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A b s t r a c t. The study of soil CO_2 emission is a relevant task due to the fact that it is related to many environmental issues, especially the enhanced greenhouse effect. In this work we investigated the spatial variability structure of a bare soil CO_2 emission in an area of 80 x 80 m, during twelve different days. Spatial and temporal variability analyses in the 65-point grid indicate that significant spatial heterogeneity is present in most of the days. Fractal dimension values varying from 2 to 2.88 was determined in a direction of 84.3±22.5^o, which is close to perpendicular of crop lines. This effect seems to be related to the structure of temporal variability of soil CO_2 emission, which presents a complex net of correlation with 83% of grid points connected within the same cluster, also with most of the points aligned perpendicular to crop lines.

K e y w o r d s: soil respiration, soil CO_2 flux, spatial variability, greenhouse gas

INTRODUCTION

Soil CO_2 emission (FCO_2) is result of several physical, chemical and biological processes that affect production of CO_2 and the transport from inside soil to interface soil-atmosphere. FCO_2 varies intensely in time and space depending on environmental conditions, soil characteristics and soil management in studied site. Soil temperature and soil moisture are the main factors controlling its temporal changes (Epron *et al*., 2006; Kang *et al*., 2003) while spatial variability of FCO_2 has been related to other characteristics like soil organic matter and porosity structure (Epron *et al.*, 2006; Schwendenmann *et al*., 2003; Xu and Qi, 2001). Studies concentrate mostly in characterizing the spatial variability patterns by using semivariance (geostatistics) by considering sampled grid as isotropic. But, it is expected that the soil management in agricultural field results in anisotropy affecting properties like soil carbon, porosity and soil water content, among some that are directly related to the production and transport of CO_2 from soil to atmosphere. Therefore it is expected that FCO_2 spatial pattern should evidence also.

High spatial variability has been observed in FCO_2 as Rayment and Jarvis (2000), for instance, found coefficients of variation (CV) from 55% to 87%, justifying the use of geostatistics tools in order to model its spatial dependence. According to La Scala *et al.* (2000, 2003a) the spatial variability structure of FCO_2 in bare soil tropical agrosystem can be explained by spherical and exponential functions, with models that can be characterized as strong and moderate spatial variability dependent (Cambardella *et al*., 1994). Contrarily, Ishizuka *et al* (2005) in a natural ecosystem observed weak spatial variability dependence on FCO_2 in a grid with points spaced at 3 m interval. The spatial variability patterns of FCO_2 obtained by Rayment and Jarvis (2000) and Ohashi and Gyokusen (2007) indicate changes in spatial variability scale and dependence as range of variability varied from 1 to 80 m. The characterization of the spatial variability structure of FCO_2 in agricultural areas is of fundamental importance in order to derive the right and convenient soil management to be used aiming to keep soil carbon instead of emitting it to atmosphere. Despite all effort few studies have characterized FCO_2 spatial variability considering it non-isotropic, especially in agricultural fields.

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The aim of this work was to characterize the anisotropy of FCO_2 in an agricultural field during fallow by using fractal theory.

MATERIALS AND METHODS

The study was conducted on a bare dark Red Latossol (Oxisol) at FCAV-UNESP (21°15'22'' South 48°18'58'' West), São Paulo State, Brazil. The climate of the area is classified as Cwa, according to Köppen, subtropical with average annual temperature of 21°C. The mean annual precipitation is around 1400 mm, with rain distribution concentrated in the period between October and March, and a relatively dry period between April and September.

A grid containing 65 points was established on the experimental site (80x80 m) where the points were spaced at distances ranging from 1 to 10 m. The experimental site had previously been planted with soybean (*Glycine max* L. Merr.) using conventional tillage practices, which was mechanically harvested weeks before the experiment started. Figure 1 presents and schematic of sampled grid over the experimental site, showing the grid directions and points 1 and 3 for reference.

CO_2 emissions from the soil were measured at each grid point during a three week study in twelve different days in mornings (10, 11, 13, 18, 20, and 22) and afternoons (12, 16, 25, 26, 27, and 28) in July 2001, at contrasting soil temperatures and soil moisture conditions. Experiments in the mornings started at around 7 a.m. and afternoons around 3 p.m. Soil temperatures (Tsoil) at 20 cm depth were measured at each grid point using LI-6400 Soil Temperature Probe (built by LI-COR, NE USA) at the same moment that measurements of CO_2 emissions were taken. Soil temperatures were around 21°C, some days mean values were around 17.3°C (July, 13) some other 24.1°C (July, 27).

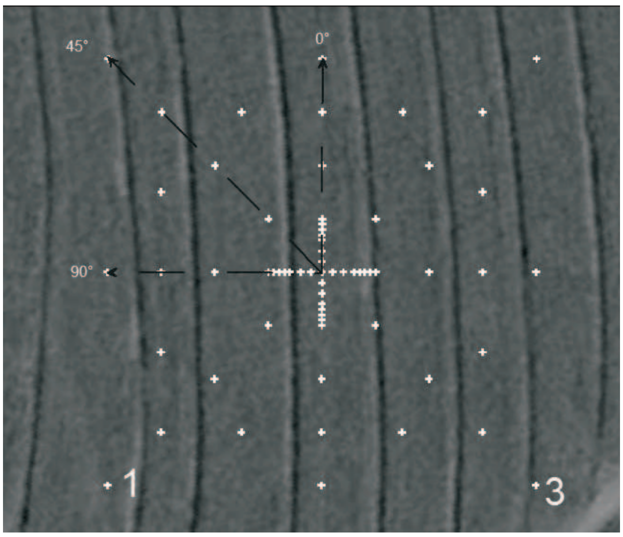

Fig. 1. Schematic show of grid and directions on the experimental area. Dark lines are the crop lines. Photo obtained from Google Earth and mounted over the same site that experiment was conducted.

The CO_2 emissions were measured using a CO_2 flux chamber built by LI-COR (LI-6400-09, LI-COR, NE USA) (Healy *et al.*, 1996). The chamber is a closed system that has an internal volume of 991 cm^3, with an area exposed to the soil of 71.6 cm^2. This was placed on the top of PVC soil collars installed in the field days before the measurements at each grid point. The chamber is coupled to a LI-6400 photosynthesis system that analyzes the CO_2 concentration by infrared gas absorption. Prior to each measurement, the CO_2 concentration inside the chamber was lowered to 370 mol mol^{-1}, by driving the air sampled through soda lime for a few seconds. After that, the increase of CO_2 concentration was measured every 2.5 s, and the soil CO_2 emissions were computed during approximately 90 s, while CO_2 concentration increases up to 390 mol mol^{-1}. In the end of the logging period, a linear regression between the soil CO_2 emissions and CO_2 concentration inside the chamber is computed, and the emission on that point is calculated when the chamber CO_2 concentration is equal to that at the soil surface in the open (380 mol mol^{-1}). Throughout the days of measurement, a short sampling period of 1.5 min at each grid point was used, in order to complete the sampling from the whole 65 points as quickly as possible, to avoid soil temperature variation in the grid during this period. In all days of measurements, the deviation of temperature was smaller than 1°C, when temperatures at different points in the grid were compared.

The fractal dimension was estimated for FCO_2 variability at each day measured. There are many methods to obtain the fractal dimension for spatial variability data (Russ, 1994).We utilized the semivariogram method (Vidal Vázquez *et al.*, 2005). This method consists in estimate the semivariogram defined as:

$$\gamma(h) = \frac{1}{2N}\sum_{i=1}^{N}\left(\mathrm{FCO}_2(x_i) - \mathrm{FCO}_2(x_i+h)\right)^2, \qquad (1)$$

where: $FCO_2(x_i)$ is the emission value in the x_i position and the sum is taken for all points x_i of the grid separated by a distance h.

If the data exhibit a fractal behaviour it scales as:

$$\gamma(h) \propto h^{2H}, \qquad (2)$$

The H coefficient is known as the fractal codimension or Hölder exponent (Huang and Bradford, 1992). Note that if H=0 there would be no spatial dependence of FCO_2 in field. The fractal codimension is defined as:

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

where: D_F is the fractal dimension, d is the Euclidean dimension of the surface which fractal will be determined. For lines, surfaces and volumes, d = 1, 2, 3, respectively. Hence, a property distributed in field (FCO_2) will get its fractal dimension represented as $D_F = 3 - H$.

The H exponent is obtained by linear regression in the log-log plot of Eq. (2) (Perfect and Kay, 1995):

$$H = \lim_{h \to 0} \frac{\log(\gamma(h))}{2\log(h)}. \tag{4}$$

Note that when H=0 fractal dimension assumes a values equal to 3, that represents no spatial variability structure or no relation between the way the property changes in space with h. On the other hand, for instance when $0 < H < 3$, the fractal dimension assumes a value that characterizing the presence of a spatial variability structure and a proper dependence of the studied property (FCO_2) with h.

In addition to this topic, fractal surfaces can present great complexity, for instance fractal dimension can present different values along different directions or scales in field. This anisotropy can be measured by the directional semivariogram (Vidal Vázquez *et al*., 2005). In this work we use fractal theory in order to characterize the anisotropy of FCO_2 in an agricultural field under bare soil condition, where microbial activity in the sole source of CO_2 produced and emitted.

RESULTS AND DISCUSSIONS

Table 1 presents the fractal dimensions (D_F) derived from isotropic and anisotropic semivariograms at 8 and 2 m interval, for all the studied days. As can be seen no significant D_F values were found in the isotropic FCO_2 spatial variability structure at 8/2 m range as regressions between logarithm of semivariance versus logarithm of distance were not significant (p>0.05). On the other hand, anisotropic analysis presents significant D_F values smaller than 3 in days 10, 11, 18 -26 and 28th of July, especially around 84.4± 22.5° direction, while in one day (13th July) this was found in 120.6±22.5° (p<0.05, *marked). Those directions are close to the perpendicular of crop lines indicating a possible influence of soil management into the spatial variability pattern of FCO_2. Spatial variability models have described the complex nature of soil CO_2 emission in agricultural field (Epron *et al*., 2006; Fang *et al*., 1998; La Scala *et al*., 2000; Schwendenmann *et al*., 2003; Xu and Qi, 2001), but few works pay attention to a possible anisotropy caused by management on those areas. Anisotropic semivariograms did not present significant D_F at 8.5± 22.5° and 188.5± 22.5° directions, and it is noticeable that heterogeneity is kept around 84.4° in most of the studied days.

Figure 2 presents two examples of the directional logarithm of FCO_2 semivariance versus logarithm of distance with best linear regression lines inserted. At 84.4±22.5° direction D_F values found were 2.66 and 2.83, for FCO_2 in 18th and 26th of July, respectively, characterizing a significant spatial variability structure in 84.4± 22.5° direction on those days. Changes in fractal dimension from one day to the other are related to the changes in the spatial variability heterogeneity and in the case of FCO_2 are mostly related to the controlling factors like soil moisture and soil temperature (Epron *et al*., 2006).

When temporal variability of FCO_2 is taken in account it is possible to notice that some of the points in grid fluctuate correlated in time with some others. For instance, Fig. 3a

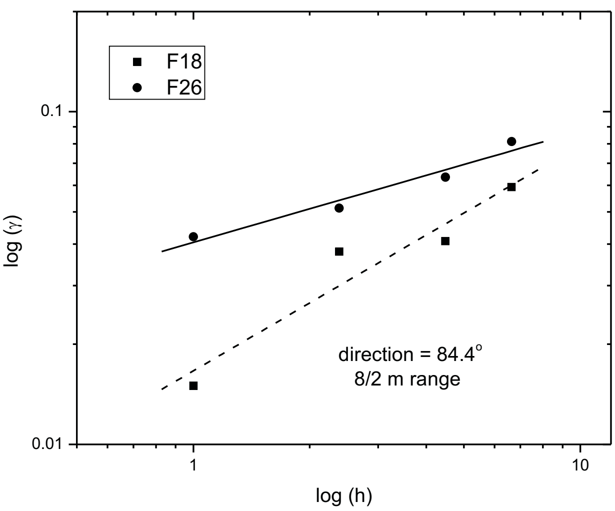

Fig. 2. Logarithm of semivariance versus logarithm of distance in grid points at short (8/2 m) range for days 18 and 26th July. Direction 84.4±22.5°.

T a b l e 1. Isotropic and anisotropic fractal dimension for 8/2 m interval and for the 12 days analyzed

(°)	F10	F11	F12	F13	F16	F18	F20	F22	F25	F26	F27	F28
8.5	3.01	2.96	3.01	3.00	2.96	2.91	2.91	2.92	2.96	2.98	3.25	2.95
84.4	2.60*	2.00*	2.91	2.94	2.93	2.66*	2.67*	2.33*	2.88*	2.83*	2.97	2.79*
120.6	3.47	3.48	3.51	2.68*	3.23	3.70	3.62	3.39	3.35	3.05	3.61	3.40
188.5	3.01	2.96	3.01	3.00	2.96	2.91	2.91	2.92	2.96	2.98	3.25	2.95
Isotropic	2.90	2.76	2.98	3.00	2.98	2.96	2.82	2.81	2.75	2.93	2.92	3.11

*Significant at 5% by F test base on regressions. Angle deviation ± 22.5° around value.

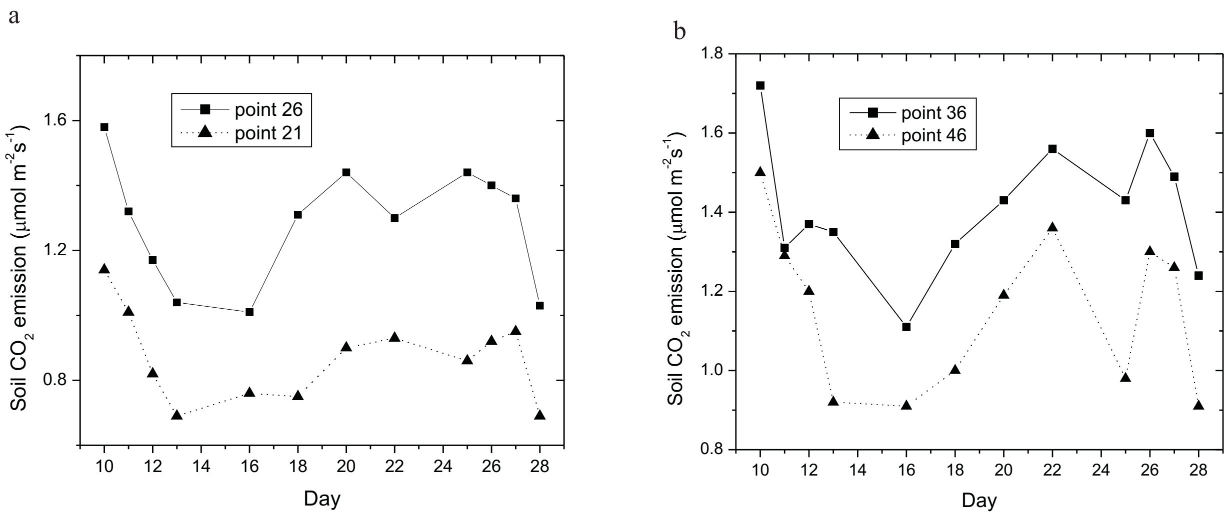

Fig. 3. Temporal variability of FCO_2 in 4 different points in sampled grid: a – points 21 and 26, b – points 36 and 46.

presents the time changes of soil CO_2 emission of two points 21 and 26 that have a linear correlation coefficient of 0.82 ($p<0.01$). Another example can be seen in Fig. 3b where it is presented the time changes in FCO_2 of points 36 and 46 that were also correlated in time, especially after day 13th. The net of correlation in time of emissions of all 65 points in grid is presented in Fig. 4. The graph analysis indicates significant correlation in the temporal variability ($p<0.01$) by connecting points with determination coefficients (R^2) above of 0.50 within straight lines. As can be seen in the Fig. 4a, most of correlated points are aligned in the first quarter of the polar graph pointing to the same directions where a significant spatial variability structure in FCO_2 was determined. That is the case of points 21 and 26 and points 36 and 46 that are aligned along directions close to 84.4±22.5°. We believe this is evidence that temporal variability is governing the anisotropy and spatial variability pattern observed for soil CO_2 emission. As points aligned into directions between 45-90° are mostly correlated in time, differences in FCO_2 during the studied period do not accentuate so much as in points that are not linear correlated in time. Figure 5 presents a typical example of the contrarily, where FCO_2 temporal variability from points 38 and 52 are compared. Difference in FCO_2 of those two points is more unstable in time and dispersive around a fixed value. On the other hand, points having a similar pattern in their temporal variability of FCO_2 are the most probable that keep their emission difference close to a certain value throughout the studied period. So, once spatial variability structure is present in a certain direction the maintenance of this structure is most probable when emission fluctuates in a similar pattern. In a previous work we describe that the mean value of FCO_2 in this experiment was modelled by a multiple regression analysis (backward elimination procedure) in terms of the changes that occurred in solar radiation, air temperature and humidity, evaporation and atmospheric pressure registered during the time period that the experiment was conducted (La Scala *et al.*, 2003b).

When the network visualization is clustering optimized, as show in the Fig. 4b, one can see that almost all points (83%) are connected in a unique cluster. It is important to notice that the points are not necessary direct connected, having a maximum distance between points of 5 steps (diameter of the graph). Also, the points significantly correlated are not necessary spatially close, presenting in some cases, Byzantines correlation path, as in the case of point 1 and 2 (1→47→48→10→2). These results suggest that the complexity of the FCO_2 space-time correlation network can not be completely analyzed by a simple fractal analysis. Nevertheless, it is important to consider spatial variability of FCO_2 and its anisotropy even in bare soil conditions in order to understand better its complex nature.

CONCLUSIONS

1. Spatial variability has shown a complex anisotropic structure, with most of spatial dependence found in the 84.4 ±22.5° direction, close to the perpendicular of crop lines (0°). In one of the days spatial variability structure was observed at 120.6±22.5° direction.

2. Fractal dimension varied between 2 and 2.88. In three of the twelve days studied there were no significant fractal dimension determined.

3. The correlation analysis of soil CO_2 emission from different points in grid indicates that the present of spatial variability structure observed during this 12 day study could be related to the similarities in temporal variability of some points in grid.

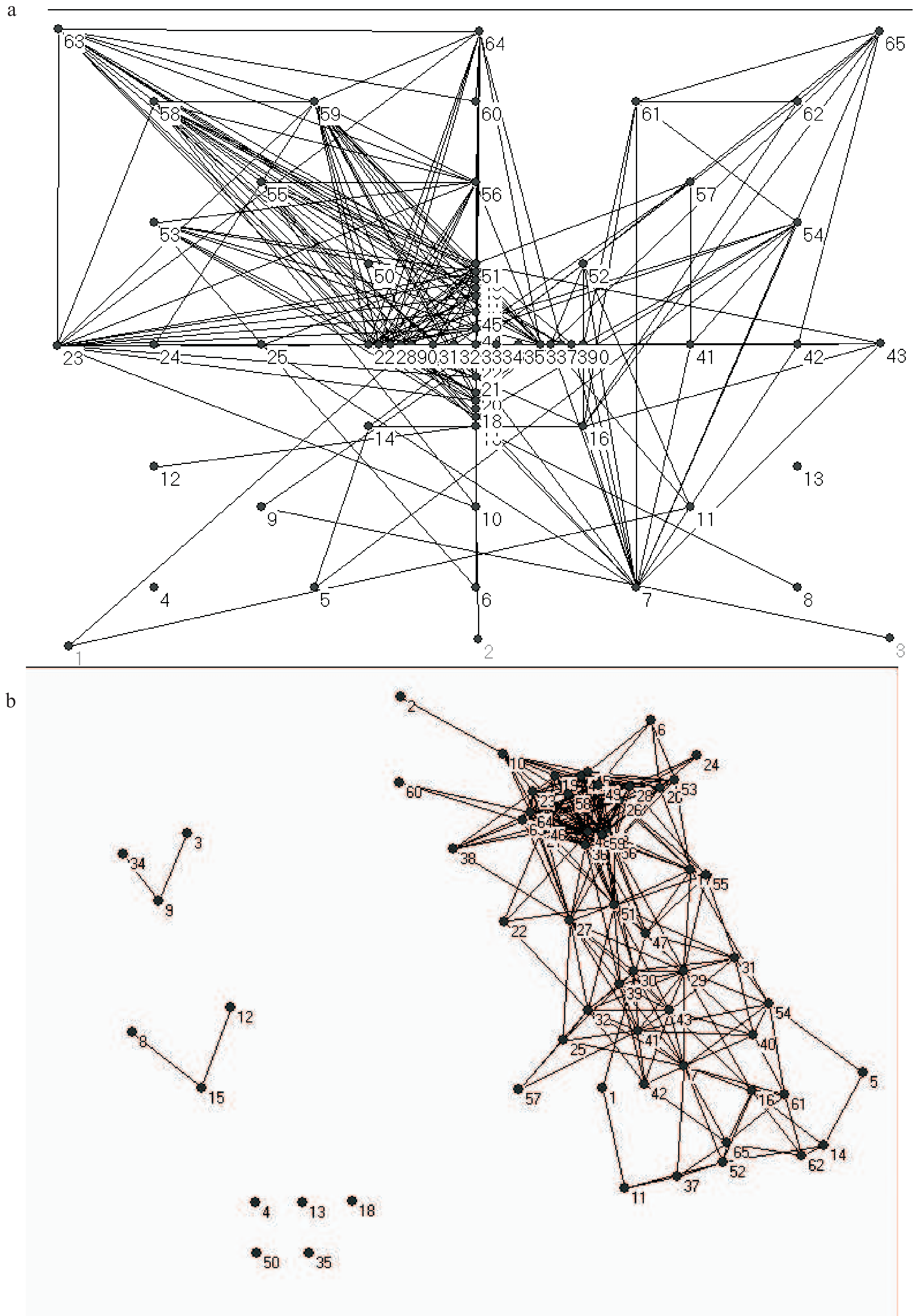

Fig. 4. Graph presenting the net of linear correlation in temporal variability pattern (p<0.01) between: a – points in grid, b – clustering optimized.

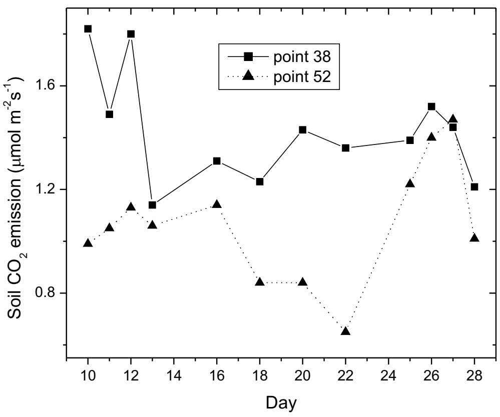

Fig. 5. Temporal variability of FCO_2 in 2 different points in sampled grid: 38 and 52.

REFERENCES

Cambardella C.A., Moorman T.B., Novak J.M., Parkin T.B., Karlen D.L., Turco R.F., and Konopka A.E., 1994. Field-scale variability of soil properties in central Iowa soils. SSSA J., 58(5), 1501-1511.

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

Fang C., Moncrieff J.B., Gholz H.L., and Clark K.L., 1998. Soil CO_2 efflux and its spatial variation in a Florida slash pine plantation. Plant Soil, 205(2), 135-146.

Healy R.W., Striegl R.G., Russel T.F., Hutchinson G.L., and Livingston G.P., 1996. Numerical evaluation of static-chamber measurements of soil-atmosphere gas exchange: identification of physical processes. Soil Sci. Soc. Am. J., 60, 740-747.

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

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

Kang S., Doh S., Lee D., Lee D., Jin V.L., and Kimball J., 2003. Topographic and climatic controls on soil respiration in six temperate mixed-hardwood forest slopes, Korea. Global Change Biol., 9, 1427-1437.

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

La Scala N., Panosso A.R., and Pereira G.T., 2003a. Spatial and temporal variability of CO_2 emission in a bare soil during fallow. Engenharia Agricola, Jaboticabal, 23(1), 88-95.

La Scala N., Panosso A.R., and Pereira G.T., 2003b. Modelling short-term temporal changes of bare soil CO_2 emission in a tropical agrosystem by using meteorological data. Appl. Soil Ecol., 24, 1, 113-116.

Ohashi M. and 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(5), 1130-1138.

Perfect E. and Kay B.D., 1995. Applications of fractals in soil and tillage research: a review. Soil Till. Res., 36, 1-20.

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

Russ J.C., 1994. Fractal Surfaces. Plenum Press, New York, USA.

Schwendenmann L., Veldkamp E., Brenes T., O'Brien J.J., and Mackensen J., 2003. Spatial and temporal variation in soil CO_2 efflux in an old-growth neotropical rain forest, La Selva, Costa Rica. Biogeochem., 64(1), 111-128.

Vidal Vázquez E., Paz González A., and Vivas Miranda J.G., 2005. Characterizing isotropy and heterogeneity of soil surface microtopography using fractal models. Ecological Model., 182, 337–353.

Xu M. and 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(6), 667-677.