SOIL CO_2 EMISSION OF SUGARCANE FIELDS AS AFFECTED BY TOPOGRAPHY

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ABSTRACT: The spatial and temporal variation of soil CO_2 emission is influenced by several soil attributes related to CO_2 production and its diffusion in the soil. However, few studies aiming to understand the effect of topography on the variability of CO_2 emissions exist, especially for cropping areas of tropical regions. The objective of this study was to evaluate the spatial and temporal changes of soil CO_2 emission and its relation to soil attributes in an area currently cropped with sugarcane under different relief forms and slope positions. Mean CO_2 emissions in the studied period (seven months) varied between 0.23 and 0.71, 0.27 and 0.90, and 0.31 and 0.80 g m^{-2} h^{-1} of CO_2 for concave (Conc), backslope (BackS) and footslope (FootS) positions, respectively. The temporal variability of CO_2 emissions in each area was explained by an exponential relation between the CO_2 emission and soil temperature and a linear relation between CO_2 emission and soil water content. The Q_{10} values were 1.98 (± 0.34), 1.81 (± 0.49) and 1.71 (± 0.31) for Conc, BackS and FootS, respectively. Bulk density, macroporosity, penetration resistance, aggregation and oxidizable organic carbon content explain the changes in soil CO_2 emission observed, especially when the Conc position was compared to BackS. The effect of relief form and topographic position on soil CO_2 emission variation was dependent on the time of measurement.

Key words: soil respiration, temporal variation, spatial variation, soil attributes, soil porosity

EMISSÃO DE CO_2 DO SOLO SOB CULTIVO DE CANA-DE-AÇÚCAR EM FUNÇÃO DA TOPOGRAFIA

RESUMO: A variação temporal e espacial da emissão de CO_2 solo-atmosfera é influenciada por inúmeros atributos do solo relacionados à produção de CO_2 e à difusão do gás no solo. Ainda são escassos, entretanto, estudos visando compreender o efeito da topografia na variação da emissão deste gás, especialmente em áreas agrícolas da região tropical. O objetivo deste trabalho foi estudar a variação temporal e espacial da emissão de CO_2 solo-atmosfera e sua relação com atributos do solo em área de cultivo de cana-de-açúcar sob diferentes formas de relevo e posições na encosta. A média da emissão de CO_2 no período de sete meses de estudo variou entre 0,23 e 0,71; 0,27 e 0,90 e 0,31 e 0.80 g CO_2 m^{-2} h^{-1}, nas posições côncava (Conc), encosta superior (BackS) e encosta inferior (FootS), respectivamente. A variação temporal da emissão em cada uma das áreas foi explicada por uma relação exponencial entre emissão de CO_2 e temperatura do solo, e uma relação linear da emissão deste gás com a umidade do solo. O valor de Q_{10} foi 1,98 (± 0,34); 1,81 (± 0,49) e 1,71 (± 0,31) para Conc, BackS e FootS, respectivamente. Densidade do solo, macroporosidade, resistência do solo à penetração, agregação e conteúdo de carbono orgânico oxidável explicaram as variações observadas na emissão de CO_2, especialmente quando se compara a posição côncava com a encosta superior. O efeito do relevo e da posição topográfica sobre a variação da emissão de CO_2 do solo foi dependente da época de amostragem.

Palavras-chave: respiração do solo, variação temporal, variação espacial, atributos do solo, porosidade do solo

INTRODUCTION

Soil CO_2 emission is an important component of the global carbon cycle (Raich & Schlesinger, 1992), which is basically controlled by two processes: CO_2 production within the soil and its transport from the soil into the atmosphere (Fang & Moncrieff, 1999). Microbial activity and root respiration are the major sources of CO_2 production, and the transport of the gas is governed by diffusion. These processes, in turn, are influenced by several attributes that establish the spatial and temporal variations of soil CO_2 emission. Soil temperature and soil water content, or the interaction between both, are the main controlling factors of the variability of soil respiration (Kang et al., 2003; Kang et al., 2000). Besides temperature and water, the spatial variability of soil respiration is also controlled by organic carbon, microbial biomass, root biomass, litter, nutrients (N, Mg, Ca, P), pH, cation exchange capacity, iron oxide content, bulk density and porosity (Epron et al., 2006; Xu & Qi, 2001; La Scala Júnior et al., 2000; Fang et al., 1998).

Changes in CO_2 emissions and soil chemical, physical and biological properties have been reported to be related to land exposition and slope length (Kang et al., 2006; Kang et al., 2003), microtopography (Jia et al., 2003), slope position (Risch & Frank, 2006; Hanson et al., 1993), slope angle (Silva et al., 2004) and relief form (Souza et al., 2006; Souza et al., 2004a,b,c; Souza et al., 2003). Such topographic aspects affect ground and underground water flows, constituting the major cause of spatial variability of soil attributes (Daniels & Hammer, 1992).

Nowadays, in the worldwide scenario, Brazil is the main sugarcane (*Saccharum* spp.) producer, with 6.96 million cropped hectares. This area represents almost 11.5% of the total cropped area with the main Brazilian agricultural products. São Paulo is the major sugarcane producer state, with 3.68 million hectares, corresponding to 52.9% of the total area cropped with sugarcane in Brazil. Considering that the total area cropped with sugarcane increases every year, reaching a 13% increase in 2007/2008 in relation to 2006/2007 (Conab, 2008), studying the spatial and temporal changes of soil CO_2 emission in such agrosystem is of great interest.

The objective of this work was to identify the topographic effect on spatial and temporal variations of soil CO_2 emission in an area currently cropped with sugarcane in the Southeastern region of Brazil, and to determine the soil attributes that control such variations.

MATERIAL AND METHODS

The experiment was carried out on the Santa Isabel Farm located at 21º17' to 21º18' S and 48º08' to 48º10' W, in Jaboticabal, São Paulo state, Brazil, where sugarcane has been cropped for over 60 years and mechanically harvested (green) for over the last ten years. The climate of the region is characterized by tropical rainy summers and dry winters, being classified as Aw by Köepen. The average temperature is 24.3ºC and 18.8ºC for January and July, respectively, while the average year precipitation is around 1425 mm, with total monthly precipitations of 239.5 mm and 25.3 mm for January and July, respectively. The soil is classified as Typic Eutrustox.

The topography of the area presents two relief forms, one concave occurring in the highest position of the landscape, and the other linear, towards the hillside, as described in Souza et al. (2003). The samplings were performed in a 100 × 100 m limited area in the concave form (Conc) and in two positions in the linear form, backslope (BackS) and footslope (FootS) (Figure 1).

Soil CO_2 emission measurements were conducted during 17 days, from April 28 (one month after sugarcane plantation) to November 23, 2004, with ten randomized replicates for each area in each sampling day. The evaluations were conducted in the morning (9–11 h) or in the afternoon (14–16 h), and in some days with measurements conducted in mornings and afternoons, using a flux chamber (LI-6400-09 CO_2, LI-COR, NE, USA) according to Healy et al. (1996). The chamber is a closed system with an internal volume of 991 cm^3 and soil exposed area of 71.6 cm^2, and coupled to a LI-6400 photosynthesis system that analyzes the CO_2 concentration by infrared gas absorption. The chamber was placed on the top of PVC soil collars installed in the field, between rows, some days before the measurements, eliminating the CO_2 flush out effect due to the ring insertion in soil.

Soil temperature (T) was evaluated by a sensor connected to the chamber on each one of the ten evaluation points of CO_2 emission at a depth of 0–0.15

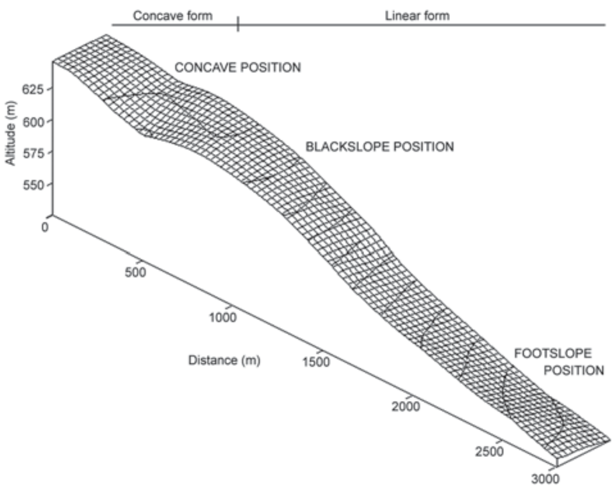

Figure 1 - Altimetric profile covering the concave and linear pedoforms, where the concave backslope and footslope positions were identified. Modified from Souza et al. (2003).

m on the 17 sampling days. Gravimetric soil water content (GM) was determined on 11 of the 17 days of study, in the same replicates and depths (Gardner, 1986).

Soil analysis was made on disturbed and undisturbed soil samples, with five replicates in each area. Soil bulk density was determined on undisturbed soil cores (0.04 m long and 0.05 m diameter) (Embrapa, 1997). Total porosity (TP) was calculated based on soil bulk density. Pore size distribution (macroporosity - Macro; microporosity - Micro) was determined based on soil water retention using a tension table (Embrapa, 1997).

Aggregate stability (Kemper & Rosenau, 1986) was determined by sieving in water, with aggregates that passed through a 7.93-mm sieve and were retained in a 4.76-mm sieve, and then separated in classes using a set of sieves of meshes of 4.76 mm, 2 mm, 1 mm, 0.5 mm and 0.25 mm. Results were expressed in terms of geometric mean diameter (GMD), percentage of aggregates larger than 2 mm ($\varnothing > 2$ mm), percentage of aggregates between 2–1 mm ($\varnothing$ 2-1 mm) and percentage of aggregates smaller than 1 mm ($\varnothing$ <1 mm).

The soil sampled with an auger was passed through a 2-mm sieve to determine particle-size distribution (pipette and sieving method, after the soil samples had been dispersed chemically in a 0.1 M NaOH solution and mechanically in low-rotation agitation for 16 hours, modified by Embrapa (1997)), Fe_2O_3 content (extracted with sulphuric acid) (Embrapa, 1979) and oxidizable organic carbon content (CO) (Raij et al., 1987).

Penetration resistance (PR) was measured using an impact penetrometer (IAA/PLANALSUCAR - STOLF), according to Stolf (1991), with ten replicates in each area, down to the depth of 0.15 m. When performing the penetration resistance tests, soil samples were taken for GM determination, down to the same depth.

All soil attributes were evaluated by the analysis of variance using the following models for each set of response variables: (1st) soil CO_2 emission, soil temperature and soil water content: $Y_{ij} = m + P_i + Error(a) + T_j + P_iT_j + Error(b)$, Y_{ij} being the value of each observation, m the general mean, P_i the effect of the topographic position i, $Error(a)$ the plot error, T_j the effect of time j, P_iT_j the effect of the interaction between topographic position and time, $Error(b)$ the general error; and (2nd) for other evaluated attributes: $Y_{ij} = m + P_i + Error(geral)$, Y_{ij} being the value of each observation, m the general mean, P_i the effect of the topographic position i, $Error(geral)$ the general error. Tukey's test was applied for the multiple comparisons of the means with 10% of probability. All statistical results were obtained by the SAS/Statistical Analysis Systems software package (SAS Institute, 1998).

RESULTS AND DISCUSSION

Soil CO_2 emission variability

Soil CO_2 emission throughout the 7-month period in different landscape positions (Figure 2), had mean values for Conc, BackS and FootS of 0.38, 0.47 and 0.45 g CO_2 m^{-2} h^{-1} (Table 1), respectively, and their variation during this period was above 200%. The BackS area presented mean emissions values between 0.27 and 0.90 g CO_2 m^{-2} h^{-1}. This variation is a consequence of the local climate. The lowest emissions are observed in the winter (June 20 to September 21, 2004, Figure 2), which is characterized by lower precipitation and temperatures. Campos (2003) reports smaller values for annual means of soil CO_2 emission in sugarcane areas in both the traditional slash and burning manual harvesting system (0.13 g CO_2 m^{-2} h^{-1}) and the mechanized harvesting without trash burning (0.14 g CO_2 m^{-2} h^{-1}). Despite these lower values, the author also found a variation of 200% in CO_2 emission (0.07 to 0.21 g CO_2 m^{-2} h^{-1}) throughout the 11-month culture cycle.

The great temporal variability in CO_2 emission presented in our study shows the importance of evaluating emissions in different land conditions and time scales. Since CO_2 emission is affected by a large number of factors, when extrapolating emissions for larger areas it is important to take into account its spatial and temporal controls, like soil temperature, moisture, texture, litter stocks and topographical position (Sotta et al., 2006). Indirect estimates based on the difference in soil organic carbon stocks are

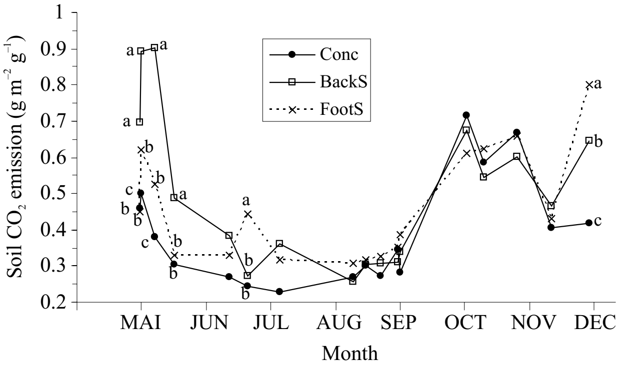

Figure 2 - Soil-atmosphere CO_2 emission in the concave (Conc), backslope (BackS) and footslope (FootS) positions. Evaluations performed from April 28 to November 23, 2004. The letters indicate the evaluations where differences in CO_2 emission were observed between the positions on the same day (Tukey, $p < 0.1$).

Table 1 - CO_2 emission and soil attributes evaluated in the concave, backslope and footslope positions at a depth of 0–0.15m on a sugarcane culture area.

Attribute[1]	Concave	Backslope	Footslope	CV (%)[2]
CO_2m (g CO_2 m^{-2} h^{-1})	0.38 (0.21)	0.47 (0.26)	0.45 (0.24)	55.21
T (ºC)	22.47 (3.85)	23.01 (3.61)	23.62 (3.82)	16.43
M (%)	21.35 (6.18)	21.21 (5.96)	20.15 (5.82)	28.68
Clay (g kg^{-1})	610.00 a	576.67 a	606.33 a	4.79
Silt (g kg^{-1})	255.00 a	256.67 a	233.67 a	10.73
Sand (g kg^{-1})	135.00 b	166.67 a	160.00 a	3.26
BD (kg dm^{-3})	1.43 a	1.22 b	1.37 a	2.91
TP (m^3 m^{-3})	0.477 a	0.491 a	0.445 a	11.08
Micro (m^3 m^{-3})	0.434 a	0.399 a	0.343 a	15.76
Macro (m^3 m^{-3})	0.043 b	0.092 a	0.102 a	18.41
PR (MPa)	2.25 a	1.50 b	1.62 ab	28.24
GMD (mm)	1.33 b	2.05 a	1.75 ab	23.92
∅>2 mm (%)	50.96 b	74.77 a	66.17 ab	22.49
∅2-1 mm (%)	9.94 a	3.44 b	6.17 ab	62.21
∅<1 mm (%)	39.10 a	21.80 b	27.66 ab	37.11
CO (g dm^{-3})	16.47 b	20.48 a	18.15 ab	12.10
Fe_2O_3 (%)	15.35	19.25	21.00	-

[1] CO_2m, T and M (mean soil CO_2 emission, temperature and moisture over the studied period and their respective standard errors in brackets; BD (bulk density), TP (total porosity), Micro (microporosity), Macro (macroporosity), PR (penetration resistance), GMD (geometric mean diameter), ∅>2 mm (% of aggregates with diameter larger than 2 mm), ∅2-1 mm (% of aggregates with diameter between 2 and 1 mm); ∅<1 mm (% of aggregates with diameter smaller than 1 mm), CO (oxidizable organic carbon), Fe_2O_3 (obtained from sulphuric attack). [2] CV: coefficient of variation. (Tukey, $p < 0.05$).

also used for predictions of soil carbon losses. Changes in soil organic carbon stocks due to land use in Brazil were estimated using a map of different soil-vegetation associations combined with results from a soil database (Bernoux et al., 2001, 2002).

Differences ($p < 0.1$) found in mean soil CO_2 emissions on a same day, when topographic positions were compared, indicate seasonallity dependence (Figure 2). Hanson et al. (1993) also found differences in CO_2 emission in some evaluations, but not for the whole period of study, when comparing emissions from areas in different topographic positions (top, slope or valley). The topography effect on soil CO_2 emission was observed especially in the first days of the experiment, when the soil was found almost bare with no vegetation. The fact that the differences in the emissions between the positions were not maintained during the whole experiment is probably related to other factors, such as the contribution of root respiration with the development of the root system of the sugarcane, in agreement with Parkin et al. (2005). According to these authors, root respiration masked the effect of topography on soil CO_2 emission, since such effect is greater on maize crops, a grassy crop like sugarcane, than on soybean crops.

During the first days of the experiment, the BackS area presented the highest emissions in relation to those observed in the Conc and FootS areas ($p < 0.10$) (Figure 2), indicating that soil CO_2 emission is different in relation to topographic positions. Other authors report a significant increase in soil CO_2 emission in the descending direction of the hillside, with higher emissions in the lower positions of the hillslope when compared to top positions. This is related to the contribution of erosion, since, in the lowered parts, an increase in soil surface biomass (Risch & Frank, 2006), thickness and organic matter content of the A horizons and crop productivity (DeJong, 1981) is observed. However, the increase in CO_2 emission in our study did not occur in this direction along the hillside. The soil cover from crop residues has probably provided greater protection against erosion processes, preventing soil loss and reduction in surface organic carbon, since the area in the higher positions presented higher soil CO_2 emission and organic carbon content (Table 1). On the other hand, when comparing Conc with linear relief forms (BackS and FootS), it was observed that the relief form did not always determine differences in CO_2 emission at the beginning of the experiment, since on some days no difference was observed between Conc and FootS emissions.

Variation in soil attributes

BackS had the lowest soil bulk density, highest macroporosity, highest geometric mean particle diameter, highest percentage of aggregates with diameter larger than 2 mm, the smallest percentage of aggregates with diameter between 2 and 1 mm, smallest percentage of aggregates with diameter smaller that 1 mm, smallest soil penetration resistance and highest oxidizable organic carbon content when compared with Conc ($p < 0.1$) (Table 1). Considering the same soil attributes, the values for FootS were between those found for the Conc and BackS areas, differing from BackS in relation to bulk density and from Conc in relation to macroporosity only. These results reinforce the influence of topographic position and/or relief form on soil attributes.

The area presenting the smallest bulk density and penetration resistance and the highest macroporosity was the one that presented the highest CO_2 emission (BackS) (Table 1 and Figure 2). This result shows the importance of the soil porous space for gaseous transport and, consequently, for microbial activity, which is in aggreement with the results found by Xu & Qi (2001). Higher total porosity facilitates oxygen entrance into the soil, favoring respiration and, consequently, increasing CO_2 emissions (Fang et al., 1998). Although total porosity values for Conc, BackS and FootS were similar, the highest emissions were observed on the sites with higher macroporosity. This indicates the influence of pore size distribution on emissions, since soil gas diffusion, according to Fick's law: $E_{CO_2} = -D^{ar}_{CO_2}(TP-M)(L/Le)^2 dC/dx$ (where ECO_2 is the soil CO_2 emission, $-D^{ar}_{CO_2}$ the diffusion coefficient of the gas in the air, $(TP - M)$ the water free porosity, and $(L / Le)^2$ the tortuosity factor) (Alvenäs & Jansson, 1997), is not only dependent on total porosity (TP), but also on tortuosity. Thus, macro and micropore distribution determines the possible trajectories of gases in the soil, affecting both the entrance of O_2 and the release of CO_2.

Differences observed in Fe_2O_3 and oxidizable organic carbon content between topographic positions are coherent with the results obtained for aggregate stability indexes (GMD, <∅2 mm, ∅2-1 mm and <1 mm, Table 1), confirming the positive relation between these attributes and aggregation (Oades, 1984; Schwertmann & Taylor, 1989). Despite the physical protection by the organic matter associated with aggregation, the highest CO_2 emissions were observed in BackS, which was probably due to the higher oxidizable organic carbon content of this area. A positive association between CO_2 emissions and soil organic carbon was also found by Xu & Qi (2001) and La Scala Júnior et al. (2000). Yoo et al. (2006) reported higher emissions in relation to higher soil organic carbon content available for microbial activity.

CO_2 temporal emission and its relationship with soil temperature and moisture

Soil temperature throughout the period varied between 17.8 and 30.6ºC, the lowest value being observed in Conc and the highest in FootS. Mean values for each day varied between 17.9 to 30.2ºC, 18.8 to 29.1ºC and 18.9 to 30.6ºC for Conc, BackS and FootS, respectively. Comparing the areas, the major differences of daily mean temperature were observed between Conc and FootS, being higher in FootS in 9 of the 17 sampled days (Tukey, $p < 0.1$). The temperatures for BackS did not differ from the other areas in most of the observations. Considering the data from the 17 evaluations, the coefficient of variation (CV) for temperature was 16.43%. Analyzing the data from each day, this variation is lower, with CV values between 1.39 and 8.25%, except for one observation where CV was 13.15%.

The temporal variability of soil CO_2 emission in the different positions was explained by an exponential relation of emission to soil temperature (Fang & Moncrieff, 2001; Xu & Qi, 2001; Lloyd & Taylor, 1994). Model $ECO_2 = ae^{-bT_{SOIL}}$ (Equation 1) was fitted to a linear relationship, thus obtaining a model of the type $Ln\ (ECO_2) = a + b\ T_{SOIL}$ (Equation 2), which presented the best adjustment based on the coefficient of determination of the model (R^2) for Conc in relation to other linearly located areas (Table 2). Temperature accounted for 24 to 51% of the CO_2 emission changes, which is related to the smaller variation in soil temperature (CV of 1.39 to 13.15%) in relation to the variation of CO_2 emission (CV of 19.3 to 61.3%).

The estimation of Q_{10}, which represents the sensitivity of CO_2 emission to a 10-degree-celsius increase in soil temperature was calculated by the equation $Q_{10} = e^{10b}$ (Equation 3) for each topographic position, where b stems from Equation 2 previously presented. The results obtained for Conc, BackS and FootS were 1.98 (± 0.34), 1.81 (± 0.49) and 1.71 (± 0.31), respectively, being close to values previously reported in the literature (Lloyd & Taylor, 1994; Raich & Schlesinger, 1992). By comparing topographic positions Conc and BackS, it was observed that Conc presented a lower Q_{10} value and better aggregate stability (Table 1). This result, according to Davidson & Janssens (2006), may stem from greater physical protection from soil organic matter and, consequently, from a reduction in emission sensitivity in relation to soil temperature in these areas. Nevertheless, when considering the three topographic positions, it was not

Table 2 - Relation between CO_2 emission and soil, temperature (ºC) and gravimetric moisture (%) attributes in the studied topographic positions

Topographic position	Estimated Parameters				
	$Ln_{(ECO2)} = a + b\ T_{SOIL}$ (Equation 2)				
	a	b	R^2	p	$Q_{10} = e^{10b}$
Concave	-2.556 ± 0.399	0.068 ± 0.017	0.51	0.001	1.98 (±0.34)
Backslope	-2.166 ± 0.636	0.059 ± 0.027	0.24	0.044	1.81 (±0.49)
Footslope	-2.100 ± 0.438	0.054 ± 0.018	0.39	0.010	1.71 (±0.31)
	$E_{(CO2)} = a + b\ M_{SOIL}$ (Equation 4)				
	a	b	R^2	p	
Concave	0.170 ± 0.142	0.012 ± 0.006	0.31	0.100	
Backslope	0.027 ± 0.230	0.025 ± 0.010	0.43	0.039	
Footslope	0.386 ± 0.208	0.006 ± 0.010	0.04	0.563^{NS}	

$E(CO_2)$: soil CO_2 emission; T_{SOIL}: soil temperature; M_{SOIL}: soil moisture; Q_{10}: sensitivity of CO_2 emission to a 10ºC increase in soil temperature for each topographic position, where b stems from Equation 2. ^{NS}: not significative ($p < 0.10$). There is no difference for CO_2 emission sensitivity in relation to soil temperature and moisture for the three topographic positions according to the T test for parallelism and the F test for coincidence ($p < 0.05$) (Zar, 1999).

possible to draw any conclusions concerning this relationship between aggregation and Q_{10}, since FootS presented the lowest Q_{10} value, and did not differ from the other areas in relation to aggregation.

Considering the studied period the mean soil water content varied from 13.2 to 29.7%, 14.6 to 30.5% and 12.6 to 28.5% for Conc, BackS and FootS, respectively. Soil water contents were affected by the position in the slope, since the major differences were observed between BackS and FootS (Tukey, $p < 0.1$). The CV value for the total period was 28.68%, and analyzing the variation during each day, the CV varied from 5.72 to 24.37%.

The temporal variability of CO_2 emission could be explained by a linear relation with soil water content ($E(CO_2) = a + b\ M_{SOIL}$) (Equation 4) in Conc and BackS only ($p < 0.1$) (Table 2). Soil water content accounted for 31 and 43% of the emission variation for those areas, respectively. The lack of relationship between soil water content and emissions in FootS suggests that the effect of the soil water content is dependent on the topographic position.

In summary, soil temperature affected the temporal changes in soil CO_2 emission in all areas while the effect of soil water content was evident only in Conc and BackS. Other researchers report the effect of these factors on emission changes. Soil respiration was dominantly controlled by temperature in a mountain area in China, since the influence of moisture was observed only when it was a limiting factor (Li et al., 2007). Reth et al. (2005) also related a relation between soil moisture and CO_2 emission only in the dry period of the year. Results obtained in the eastern Amazonian area (Brazil) (Sotta et al., 2006) and in a tropical rainforest (Asia) (Kosugi et al., 2007) show that the temporal variability of soil CO_2 efflux was depended mainly on soil water content. Strong effects of soil temperature and soil water content on CO_2 were observed in managed forests in Canada (Peng & Thomas, 2006).

ACKNOWLEDGMENTS

To FCAV-UNESP Graduated Program in Plant Production; to CAPES, CNPq and FAPESP for financial support; and to Santa Isabel Farm for providing the study area and technical support.

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Received October 10, 2007
Accepted June 27, 2008