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Spatial variation of soil carbon stability in sugarcane crops, central-south of Brazil

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ABSTRACT

The decay constant (k) of soil organic carbon can be used in the decision making of soil management practices and it is an indicative of the spatial variability of soil carbon stability, which depends on the interactions of physical, chemical and biological factors within agroecossystem. The aim of this work was to determine the spatial variability structure of soil carbon losses, expressed by the factor k, and its relationship with the soil attributes in sugarcane crops, in the central-south region of Brazil. The experiments were carried out in areas of commercial sugarcane plantations, in the cities of Motuca (MOT), Guariba (GUA) and Pradópolis - SP (PAD), in the State of São Paulo, and Aparecida do Taboado (APT), in Mato Grosso do Sul. The measurements of soil CO_2 emission (FCO2) were recorded in the areas of study by the LI-COR system (LI-8100). The multivariate approach indicated that the two principal components (PC1 and PC2) explained around 55% to 68% of the total variability contained in the dataset in the areas studied, respectively. The soil physical attributes showed discriminatory power within PC1 and indicated a contrast between air-filled pore space and soil water content. In PC2, the chemical attributes indicated a joint action of the cations exchange capacity and available phosphorous content. PAD and APT areas presented negative and significant spatial patterns between factor k and PC1. For the spatial patterns between k and PC2 in GUA and APT, values with negative and significant correlations occurred. The results indicate that the soil carbon accumulation potential presented high spatial variability on a small scale; thus, in the same area, there were changes in the spatial patterns of factor k, presenting regions with potential accumulations or sources of carbon in the system of cultivation of raw cane, being able to be carried out the specific management in the same productive area.

1. Introduction

In recent years there has been a significant increase in the levels of CO_2 concentration in the atmosphere. The intensification of this process has been increasing since the pre-industrial era. CO_2 can store thermal energy coming from solar radiation, which causes the temperature of the planet as a whole to increase indirectly, this results in the increase in microbial activity and the intensity of the respiration of the roots, thus causing greater production of CO_2 in agricultural soils (Xie et al., 2015). Many soil attributes influence on the process of CO_2 production and transfer in the soil, for example: the soil bulk density, soil texture, air-filled pore space, soil temperature and soil water content (Moitinho et al., 2015).

The CO_2 emission process from the soil can be measured by a mathematical model, through the production of CO_2 in the soil, at intervals of time, right after or soil preparation (La Scala et al., 2008). The model assumes that the Decay of C in readily decomposed organic matter is an equation of the first order, which is influenced by cultivation and the types of soil preparation, because soil preparation accelerates the organic oxidation process of C, resulting in the release of large amounts of CO_2 into the atmosphere in a short period of weeks (La Scala et al., 2006). This factor holds information about the potential of CO_2 emission at a specific point in the area of study, determined by the stability of carbon, and can be used for decision-making in relation to the use and management of the soil. The decay constant k is determined by the following equation: k = FCO2 / Cstock, where k = decay constant (day^{-1}); FCO2 = soil CO_2 emission (Mg ha^{-1} day^{-1}); Cstock = carbon stock (Mg ha^{-1}); therefore, depending on the practices and

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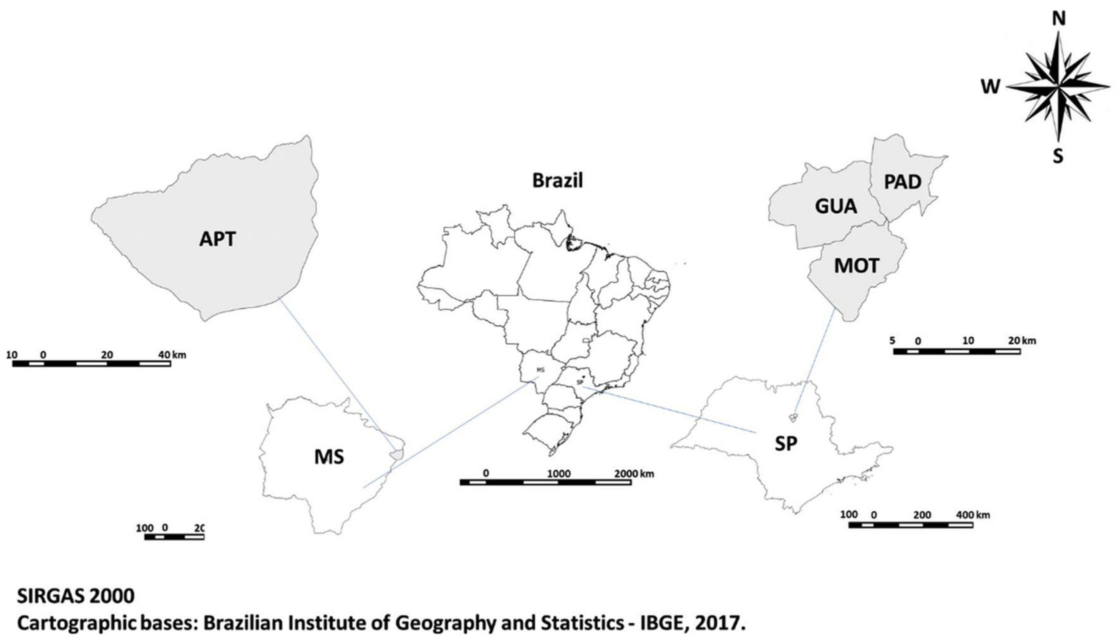

Fig. 1. Maps of the cities of experimental areas of the State of São Paulo - SP (Pradópolis - PAD, Guariba - GUA and Motuca - MOT) and Mato Grosso do Sul - MS (Aparecida do Taboado - APT).
(PAD – Pradópolis, GUA – Guariba, MOT – Motuca, APT – Aparecida do Taboado, SP – São Paulo, MS – Mato Grosso do Sul, km – kilometers, N – north, S – south, E – east, W – west, SIRGAS - Geocentric Reference System for the Americas and IBGE – Brazilian Institute of Geography and Statistics)

managements related to the soil, different potentials of CO_2 emission or sequestration can be observed. In the present context, the precise determination of carbon loss in agricultural areas is key for Brazil to achieve its goals regarding the reduction of GHG emissions. Thus, k can be used as an indicator of the CO_2 balance as a consequence of different land-use and management decisions. De Figueiredo et al. (2015) observed the interferences of different soil tillage, harvesting systems, straw management around the harvest, changes in the sugarcane areas, FCO2 and Cstock, before the replanting of crops in Brazil, in the short term, through k, measuring the flow of CO_2 from the soil. The results were that the additional FCO2 was induced by tillage. The change from harvesting systems to burned cane to green can improve Cstock soil, especially when straw was maintained on the surface soil.

Brazil is a major food producer and the world's largest producer of sugar cane (*Saccharum spp.*) in the world. According to data from the National Supply Company - CONAB (2019), in the 2018-2019 harvest the planted area was around 8.59 million hectares and production of 620.44 million tons. The State of São Paulo was the largest producer in the country, with 4.43 million hectares and production of 332.88 million tons, comprising 53.65% of the processed sugarcane. Already the state of Mato Grosso do Sul is the fourth largest producer in the country, with 647.4 thousand hectares and production of 49.50 million tons, where it was responsible for 7,54% of Brazilian production.

The practices ratoon elimination by soil tillage in sugarcane areas can lead expressive losses of soil carbon by soil CO_2 emission especially in short periods, by the changes in the factors as: soil water content, soil temperature, soil chemical-physical and biological attributes (Moitinho et al., 2015). Besides that, the environmental performance of this Brazilian biofuel has been recognized by the Environmental Protection Agency - EPA, as it is an advanced renewable fuel that has a great capacity to reduce greenhouse gas emissions when compared to gasoline by up to 61 % (EPA, 2010). Therefore, the study of soil management practices related to this crop is of great importance to mitigate greenhouse gas (GHG) emissions.

Besides, when sugarcane fields are burned, results in the loss of all the straw and releasing a large amount of gases are aerosols into the atmosphere (De Figueiredo et al., 2015). On the other hand, in green management the mechanical harvesting provides the return of crop residues to the soil surface favoring soil organic matter accumulation and gas emission reduction, when compared to the burned system. Awe et al. (2015) investigated the residual effect of tillage and introduction of straw mulching on the temporal variability and covariance structures of soil temperature of a sugarcane field in southern Brazil during the 2011/2012 growing season and observed that the straw cover significantly influenced the thermal regime of the soil, during the critical phases of winter and summer. They also observed that the SWC was higher in the plots that had straw, when compared to the other treatments without the surface layer.

Geostatistics estimates the spatial dependencies of the mean values and the unsampled points. Through kriging, maps are generated for zoning and specific management of areas, helping in agricultural work. There is also georeferencing optimization for the physical, chemical (Corrêa et al., 2015) and biological properties of the soil, which have a large spatiotemporal variation, correlating with the productive potential of the soil. Bicalho et al. (2014) investigated the spatial variability and soil attributes in a cane zone mechanically harvested using fractal dimension (DF) derived from isotropic variograms at different scales (fractograms) and observed that the spatial variability structure indicated a significant relationship with the spatial variability structure for the most soil attributes, which can be used to describe the spatial dependence of variables along the scale.

With the purpose of studying the spatial variability of factor k in commercial areas of sugarcane, multivariate structures of carbon losses were determined, through the emissions of CO_2, in agricultural soils cultivated with sugarcane, as well as their relationship with the physical and chemical attributes of the soil.

2. MATERIAL AND METHODS

2.1. Characterization of the Study Area

The present study was conducted in commercial areas of sugarcane crops based on the raw sugarcane system, in the cities of Motuca (MOT), Guariba (GUA) and Pradópolis (PAD), in the state of São Paulo, and Aparecida do Taboado (APT), in Mato Grosso do Sul (MS) (Fig. 1). In São Paulo, the soils were classified as eutroferric Red Latosol. In

Motuca, the texture of the soil was defined as very clayey (clay > 600 g kg^{-1}). In Guariba and Pradópolis, the soil was classified as clayey (350 g kg^{-1} < clay < 600 g kg^{-1}). As for Aparecida do Taboado (MS), the soil was classified as distroferric Red Latosol with clayey texture, according to the Brazilian System of Soil Classification -SIBCS (Santos et al., 2013).

The climate in all areas was classified as Aw, according to the Köppen methodology. The average annual temperatures for the cities of the state of São Paulo were 22.2 °C and the annual rainfall was 1400 mm with rainfall concentrated from November to February. The elevation of the municipalities in relation to the sea level were 550 (MOT), 620 (GUA) and 515 (PAD) meters. For the ATP, mean annual temperatures were 23.7 °C and annual rainfall was 1,300 mm with concentrated rainfall from November to February. The elevation from sea level was 370 meters.

2.2. Measurements of FCO2, SWC and Ts

The CO_2 emission (FCO2) were recorded in the portable LI-COR system (LI-8100, Lincoln, NE, USA), during the initial growth phase of the crop. In the measurement mode the LI-8100 system captures the changes in CO_2 concentration inside the chamber using an infrared gas analyzer (IRGA). The soil chamber disposes an internal volume of 854.2 cm^3, with a circular contact area to soil of 83.7 cm^2 and was installed on PVC soil collars, previously placed at a depth of 3 cm at soil grid points. The duration time for the determination of CO_2 concentration within the chamber is 1.5 minutes to perform the interpolation of the concentration of CO_2 concentration in the soil (account for each 2.5 s). Percentage in volume the soil water content (SWC) was measured with a portable hydrosense system. Soil temperature (Ts) was registered by a 20 cm depth probe (thermistor based) inserted into the soil close to the collars (TDR model, Campbell, USA). Measurements of FCO2, Ts, and SWC were performed simultaneously in both grid points, in the morning (7:00–9:00 AM).

2.3. Analysis of Soil Physical and Chemical Attributes

After finishing these field measurements, soil samples were collected from 0 to 0.10 m and sieved with a 2 mm mesh to determine the base saturation (BS), sum of bases (SB), hydrogen potential (pH), calcium (Ca), magnesium (Mg), potassium (K), phosphorus (P), cation exchange capacity (CEC) and potential acidity (H Al), following the methodology suggested by EMBRAPA (1997). In addition, available phosphorous measured was according to the ion exchange resin method (Raij et al., 2001). The analysis of the total organic carbon (TOC) in the soil samples was achieved with a total organic carbon analyzer (TOC-V, Shimadzu Labs) with a solid sample module (model SSM-5000, Shimadzu Labs). The TOC values were multiplied by 1.72 to transform them into the soil organic matter content (SOM) (EMBRAPA, 1997).

The determination soil bulk density (Ds) was made in non-deformed core samples collected by a suitable sampler adapted to cylinders with an average size of 5.0 cm internal diameter and 4.0 cm in height (EMBRAPA, 1997). Total pore volume (TPV) was calculated with base soil bulk density values, microporosity and microporosity, using a porous plate under 60 cm saturated water tension column (EMBRAPA, 1997). The air-filled pore space (AFPS) fraction was mensuramented by means of difference between the total pore volume (TPV) and the fraction of porosity filled by water (WFPS), which is equivalent to the soil water content (SWC).

2.4. Decay constant (k) and principal component analysis (PCA)

The stock of carbon was calculated for a depth of 0.10 m and, based on the equivalent soil mass to account for soil density variations, at the different areas of study, using equation 1 (Bayer et al., 2000):

$$Cstock = \frac{(OC\ .\ Ds\ .\ h)}{10} \tag{1}$$

Where Cstock = carbon stock (Mg ha^{-1}); OC = is the concentration found by analysis of soil samples (g kg^{-1} = SOM/1.724); Ds = soil bulk density (kg dm^{-3}); h = thickness of the soil in the sampled depth interval (0.10 m).

To determine the decay constant k (day^{-1}), was performed the calculation, given by equation 2:

$$k = \frac{\text{FCO2}}{\text{Cstock}} \tag{2}$$

Where k = decay constant (day^{-1}); FCO2 = soil CO_2 emission (Mg ha^{-1} day^{-1}); Cstock is carbon stock of the soil (Mg ha^{-1}). For the principal component analysis (PCA), the following set of soil attributes: soil water content (SWC), air-filled pore space (AFPS), macroporosity (Macro), available phosphorous (P) and cations exchange capacity (CEC).

For the analysis of PCA, the attributes were chosen to maximize the variability of the data for the main components 1 (PC1) and 2 (PC2), so that each evaluated area presented a cumulative variability greater than 50% (Kaiser, 1958). In order to minimize the significant data in eigenvectors (smaller set of orthogonal variables) the analysis of the main components was used in the studied characteristics, formed by the linear combination between the studied soil attributes. Multiple regression analysis was performed for variable selection. Principal component analysis was performed using STATISTICA 7.0. For these analyzes, the variables k, CO_2 emission and carbon stock were not selected.

To provide a better interpretation of the correlations between k and the study sites, the map regions were divided into quadrants. The alignment was done in a counterclockwise direction, with quadrant one at the top left and quadrant two at the right. At the bottom we have two more quadrants, on the left we have quadrant three and the right quadrant four.

3. RESULTS

3.1. Multivariate Analysis of Soil Attributes in the Cultivation of Sugarcane

In all the cases studied, PCA explained a large part of the variability related to k. For the MOT area, PC1 explained 43.4% of the total data variability, while PC2 explained 21.0%, adding up to 64.4% (Fig. 2). The variables that most contributed to PC1 were AFPS, with a positive correlation (r = 0.98), and SWC, with a negative correlation (r =

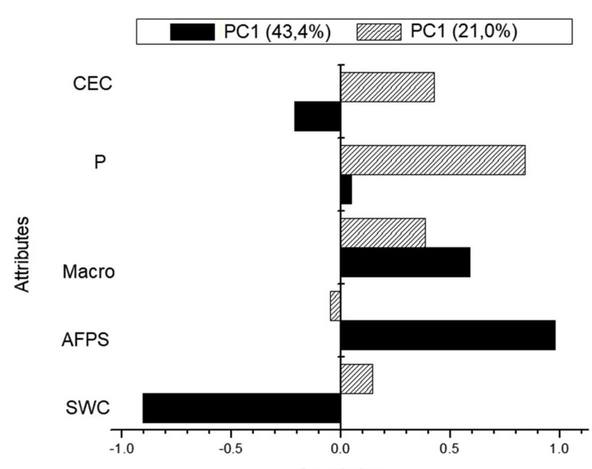

Fig. 2. Principal component analysis indicating the correlation coefficient between the principal components and the variables for Motuca, SP, Brazil. (PC1 – principal components 1, PC2 – principal components 2, CEC – cations exchange capacity, P – available phosphorous, Macro – macroporosity, AFPS – air–filled pore space, SWC – soil water content)

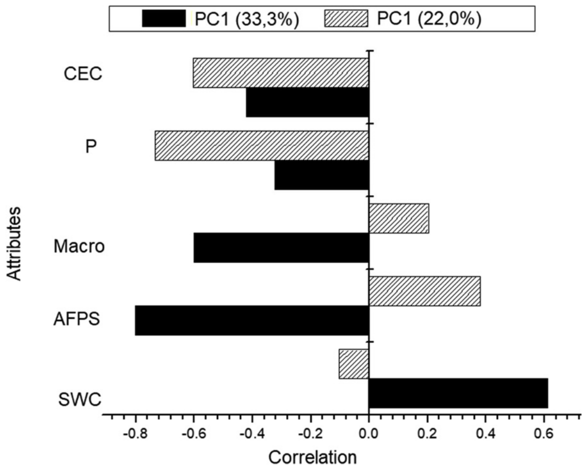

Fig. 3. Principal component analysis indicating the correlation coefficient between the principal components and the variables for Guariba, SP, Brazil.
(PC1 – principal components 1, PC2 – principal components 2, CEC – cations exchange capacity, P – available phosphorous, Macro – macroporosity, AFPS – air–filled pore space, SWC – soil water content)

-0.90). In turn, PC2 presented a positive correlation for the following variables: P (r = 0.84) and CEC (r = 0.42).

In GUA, PC1 explained 33.3% of the total variance of the data, whereas PC2 explained 22.0%, adding up to 55.3% (Fig. 3). The variables that most contributed to PC1 were SWC, with a positive correlation (r = 0.61), and AFPS, with a negative correlation (r = -0.80|). PC2 showed a negative and significant correlation for the variables CEC (r = -0.60) and P (r = -0.73).

In PAD, PC1 explained 42.7% of the total variance of the data, whereas PC2 explained 26.6%, adding up to 69.3% (Fig. 4). The variables with the highest discriminant power were macroporosity (Macro) and AFPS, with negative correlations equal to r = -0.96 and r = -0.92. PC2 showed positive significant correlations for the variables CEC (r = 0.76) and P (r = 0.71).

In APT, PC1 explained 40.6% of the total variance of the data, whereas PC2 explained 23.7%, adding up to 64.3% (Fig. 5). The variables with the highest discriminant power for PC1 were SWC, with a negative correlation (r = -0.98), and AFPS, with a positive correlation (r = 0.97). PC2 showed negative correlations for the variables CEC (r = -0.70) and P (r = -0.69).

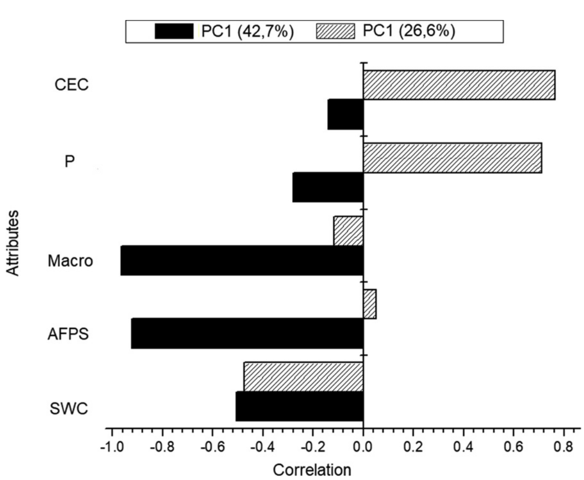

Fig. 4. Principal component analysis indicating the correlation coefficient between the principal components and the variables for Pradópolis, SP, Brazil.
(PC1 – principal components 1, PC2 – principal components 2, CEC – cations exchange capacity, P – available phosphorous, Macro – macroporosity, AFPS – air–filled pore space, SWC – soil water content)

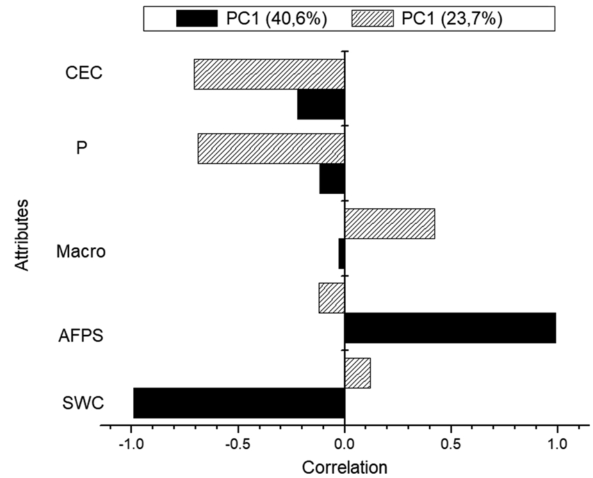

Fig. 5. Principal component analysis indicating the correlation coefficient between the principal components and the variables for Aparecida do Taboado, MS, Brazil.
(PC1 – principal components 1, PC2 – principal components 2, CEC – cations exchange capacity, P – available phosphorous, Macro – macroporosity, AFPS – air–filled pore space, SWC – soil water content)

4. DISCUSSIONS

In Fig. 6, it can be observed that in the regions with the highest values of k there are lower values of Cstock and higher values of FCO2, forming potential regions of higher carbon sources. Whereas at the points where lowers values of k are observed, there are lower values of FCO2 and higher stocks of carbon, which characterize regions of potential carbon accumulation, directly influenced by soil moisture, management and porosity. With the same purpose of determining the relationship between FCO2, Cstock and soil attributes, Figueiredo et al. (2017) evaluated and characterized FCO2 and Cstock in areas of degraded (DP) and managed (MP) pastures located close to each other, describing their spatio-temporal variability and any correlation with possible control factors and they observed that management influenced directly on the soil attributes. MP showed lower FCO2 and higher Cstock, indicating a stability of C in the soil when compared to the area of DP. The PCA analysis explained about 60% of the original variance of data, showing existence of spatial dependence between the soil attributes and the FCO2 and Cstock processes of the CO_2 in the soil, these similar values found in the works of Carvalho et al. (2018) and Moitinho et al (2018), 67% and 58%, respectively. In the analyzes the areas MOT, GUA and APT, PC1 is formed by the contrast between soil water content and air-filled pore space, whereas in PAD a joint relationship between macroporosity and AFPS is observed, both of which related to the process of soil gas transfer. Similar to the results observed here, Almeida et al. (2018) realized that the transport of soil gases are dependent on the soil porosity, which control with the processes of oxygen input and CO_2 emission for the aerobic activity of microorganisms.

The results showed a significant correlation between PC1 and k, associated with the lower values of SWC and higher values of AFPS. Also, a similarity between the spatial continuity of the isolines of the maps of k and PC1 was observed, thus indicating a simple linear correlation between the spatial patterns k and PC1, as seen in Table 1. Thus, PCA can identify the attributes responsible for the patterns of variability of carbon loss in the soil, where AFPS and SWC were the limiting factors in MOT, GUA and PAD. Thereby, in PAD, the highest values of PC1 were related to the lowest values of AFPS and Macro, where these variables controlled the spatial variability of FCO2 in this area of study. As for PC2, no significant correlation values were observed between the quadrants (Table 1). Similar results were observed

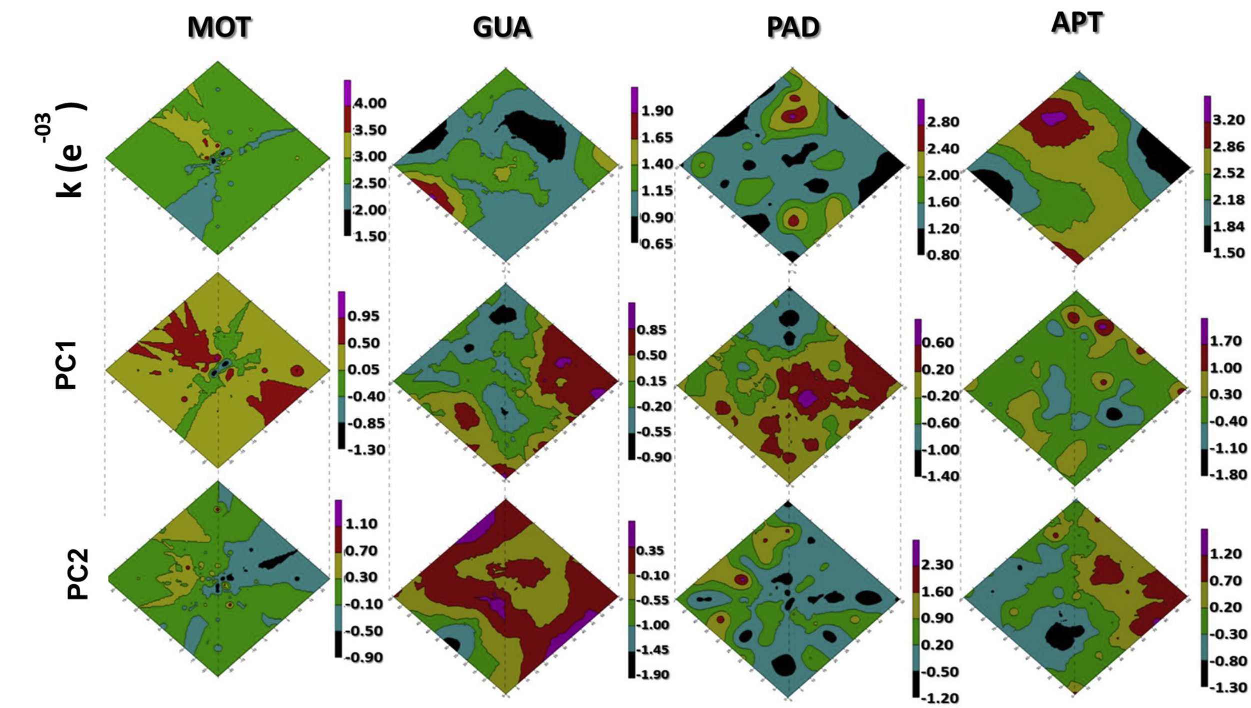

Fig. 6. Determination of the spatial patterns of the decay constant of carbon k and principal components (CP1 and CP2) by means of ordinary kriging for the MOT, PAD, GUA and APT areas.
(PC1 – principal components 1, PC2 – principal components 2, k – decay constant, (PAD – Pradópolis, GUA – Guariba, MOT – Motuca, APT – Aparecida do Taboado)

in which the SWC directly influenced the FCO2 processes, impacting in the emission of CO_2 from the soil to the atmosphere, in production and CO_2 transport in the soil (De Souza et al. 2019). In addition, Dossou-Yovo et al. (2016) noted that the dynamics of CO_2 emission from the soil into the atmosphere is related to the diffusion of CO_2, which is directly influenced by the interaction between the porous space of the soil and the moisture content. Thus, the diffusion of gases, conditions for the entire soil biota and the movement and retention of water are related to the soil pore system (Pires et al., 2017). The PC2 component was formed by soil fertility due to the strong relationship between cation exchange capacity and available phosphorus (Fig. 6), both attributes related to CO_2 formation and correlations of soil carbon stability patterns. For the spatial patterns of ATP, PC2 had positive correlation with k, showing that for the higher values of PC2 and k, regions of greater soil fertility were observed, represented by high P and CEC values, resulting in the low soil carbon stability. Already in the regions with lower PC2 scores, lower soil fertility and lower k values were observed, thus forming regions with greater soil carbon accumulation. Panosso et al. (2011) performing PCA, also observed that the joint action between CEC and P, showing a high correlation with CP1. Carvalho et al. (2018) showed that under natural soil conditions in southern Brazilian Amazonia the attributes of soil chemistry were the ones that most interfered in the CO_2 emission process.

5. CONCLUSIONS

Significant correlation coefficients were observed between the principal components and the maps of the k factor in all areas of study, where soil physical attributes were the main drivers for CO_2 emission, in areas of raw sugarcane, in the state of São Paulo. As for the city of Aparecida do Taboado – MS, soil chemical properties were the main drivers for changing the spatial patterns of soil carbon stability.

The results showed that within a same area, there were changes in the spatial patterns of k, thus leading to the occurrence of regions with potential for carbon accumulation or sequestration in the soil in areas of sugarcane crops. That information which may be used to enhance the performance of agricultural practices, mainly those that are related to soil preparation, the use of agricultural inputs, accumulation of OM in the form of straw, water management, soil water content and specially the mitigation global climate changes.

Declaration of Competing Interest

None.

Table 1
Linear correlation coefficients between the quadrants (Q1, Q2, Q3 and Q4) of spatial patterns maps of factor k and principal components 1 and 2, in the areas studied for sugarcane in the raw sugarcane system, Brazil.

Quadrants	Motuca		Guariba		Pradópolis		Aparecida do Taboado	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
Factor k								
Q1	0.69*	0.67*	−0.47	0.59*	−0.37	0.06	−0.52*	−0.63*
Q2	0.67*	0.24	0.66*	−0.60*	0.11	−0.42	−0.51*	0.14
Q3	0.69*	0.30	−0.07	−0.07	−0.24	−0.25	0.06	0.83*
Q4	0.81*	0.70*	0.15	0.48	−0.06	−0.36	−0.62*	−0.57*

* Highlighted values indicate significant correlation coefficients by the t-Student test at a 5% level.

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