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Temporal variability of the CO_2 emission and the O_2 influx in a tropical soil in contrasting coverage conditions

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ABSTRACT

Aim: The proposal was to investigate the temporal variability of CO_2 emission (FCO2), the influx of O_2 in the soil (FO2), soil moisture (SM) and soil temperature (ST), as well as, understand the process of oxygen entry into the soil.
Methods: Soil and its relationship with land cover and local climatic conditions. FCO2, FO2, soil moisture and temperature, and other meteorological data (e.g., atmospheric pressure, average air temperature and precipitation).
Results: There was a positive linear correlation between the soil's CO_2 emission and O_2 capture and these correlations occurred in areas of mulch and vegetated cover, respectively, $r = 0.45$ ($p < 0.05$) and $r = 0.44$ ($p < 0.05$). The analysis of variance of temporal variability was significant, which demonstrates that the time and soil cover factors interfere with the dynamics of FCO2 ($F = 2.1379$; $p < 0.0001$), FO2 ($F = 1.9124$; $p = 0.003$), SM ($F = 5.30$; $p < 0.0001$), ST ($F = 10.51$; $p < 0.0001$).
Conclusion: It is concluded that the temporal variability of the soil's CO_2 emission and O_2 capture is associated with the coverage, soil moisture and atmospheric conditions of the region. Thus, the soil cover provided thermal control and the maintenance of soil moisture. It is hoped that these contributions will serve as an interest in the formation of public policies for the mitigation of greenhouse gases, talking with the objective for sustainable development number 13.

1. Introduction

The energy balance in the Earth-atmosphere system has been altered over the past centuries causing an increase in the planet's average temperature, which results, among other consequences, in global climate change. Such climate change is directly related to the increase in greenhouse gases in the atmosphere, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Solomon et al., 2007).

The agricultural activities are responsible for the emission of significant amounts of CO_2, CH_4 and N_2O into the atmosphere, contributing with approximately 11, 47 and 58% of the total anthropogenic emissions of these gases, respectively (Intergovernmental Panel on Climate Change - IPCC, 2007). In Brazil, in turn, the emission of CO_2, CH_4 and N_2O from agriculture and land use change, correspond to 75, 78 and 91% (Cerri et al., 2007). Increase in deforestation, conventional management and methods of soil preparation, liming, and burning of forests and agricultural residues are sources of CO_2 emissions. Use of nitrogen fertilizers and animal wastes contribute toward N_2O emissions; CH_4 emissions are generated from agriculture and rearing of livestock, chiefly from the enteric fermentation of cattle (Alencar et al., 2022).

Soil is one of the richest carbon (C) reservoirs in the Earth's crust (Jensen et al., 2018). The inadequate management of soil has altered carbon stocks in diverse environments; and as a consequence, it increases the loss of C in the form of CO_2 emission. According to the special report of the Intergovernmental Panel on Climate Change, in 2018, the global average temperature rose 1.5 °C in relation to the pre-industrial levels (Intergovernmental Panel on Climate Change – IPCC, 2018). This indicates the importance of studies on the understanding of the

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effects of the management, cover condition and soil attributes on the soil CO_2 emission (Jensen et al., 2018; Lopera, 2019).

In a review of agricultural areas in Brazil, many authors have indicated the potential of soil management, such as no-till, and conversion, such as agro-ecological systems or crop-livestock-forest integration, towards soil carbon sequestration and mitigation of the greenhouse gases effect (GHG) (Lal, 2009; La Scala Jr. et al., 2012; Moitinho et al., 2013). However, it is necessary to consider how the soil properties influence the CO_2 emissions; i.e., according to Luo and Zhou (2006) the soil moisture and temperature are related to the temporal variability, while, soil organic matter (SOM), soil porosity and mineralogical attributes are more associated with the spatial variability of the CO_2 emission (Brady and Weil, 2013; Bahia et al., 2014; Silva et al., 2018).

The aerobic microbial activity and the cellular respiration of the plant roots are the main sources of the soil's CO_2 emission (Luo and Zhuo, 2006), as both biogeochemical processes are oxygen dependent (Bini et al., 2016). Thus, it is important to consider the dynamics of oxygen in the soil-plant-atmosphere system, because the activities of the soil microorganisms, the main driver of soil organic matter decay, require certain levels of oxygen (O_2) in the soil atmosphere (Reichardt, 1975, 1996). Despite the fundamental role O_2 plays in the soil, still little is known about its relation with the emission of GHG from the soil (Song et al., 2019). Few studies have assessed the effect of O_2 on CO_2 emission from soil; for example, Almeida et al. (2018) and Vicentini et al. (2019) have done so in areas of sugar cane cultivation and forests, respectively. To summarize, soil metabolism is attributed to the sum of all chemical reactions within a living organism. When this process is aerobic, it could be reduced to O_2 input being the terminal electron acceptor of the respiratory chain and, consequently, CO_2 emission into the atmosphere and surrounding ecosystem. Soil redox potential is used as an indicator of oxygenation and to control the state and consumption of CH_4 and N_2O (Yasin and Andreasen, 2016). It is linked with microbial metabolism and production transformation in the environment (Rubol et al., 2012). Soil subjected to prolonged flooding delays the decomposition of organic matter, lowering CO_2 production while favoring methanogenesis or nitrification and denitrification (Yasin and Andreasen, 2016).

The effect of the properties or the conditions of the soil are determinant to the gas transport.

(Thorbjørn et al., 2008), as CO_2 emission or O_2 capture. Soil aeration, water movement, the potassium content in the soil, the heat transfer through the soil-atmosphere system and soil cover conditions increase the biological activity and consequently the O_2 capture (Quastel, 1965; Moreira and Siqueira, 2006). Furthermore, the soil cover could act as a physical barrier that would hinder the gas diffusion process resulting in non-significant oxygen inflow (Neira et al., 2015).

Several studies evaluated the temporal variation of CO_2 emissions associated with soil moisture and soil temperature (La Scala Jr et al., 2012; Moitinho et al., 2013; Iamaguti et al., 2015; Silva et al., 2018; Santos et al., 2019). However, only a few studies have proposed to assess the relation between the soil's CO_2 emission and O_2 absorption, with the soil temperature and soil moisture (Angert et al., 2015; Almeida et al., 2019; Vicentini et al., 2019). Additionally, the condition of the cover, fertilization inputs and the soil management impose physical, chemical and biological disturbances on the soil, altering the biogeochemical cycles of the elements in the soil and the cycling of nutrients (Moreira and Siqueira, 2006; Lisboa et al., 2012). The management that prioritizes straw (e.g., no-till) or vegetation cover has been an effective strategy to reduce CO_2 emissions from the soil (Moitinho et al., 2013). Another work carried out in Latin America confirmed that CO_2 emissions from the soil can be associated with different types of soil cover (e.g., live or dead cover) (Lopera, 2019).

This study advances in understanding the different uses of land cover (e.g. bare soil, soil with straw or soil with vegetation) and their effects on gas dynamics, thus making associations with root respiration (Angert et al., 2015), favoring microbial life (Bini et al., 2016) and bare soils with little increase in organic matter (La Scala et al., 2000). This study is focused on the different types of soil cover in a red oxisol (Santos et al., 2019) and relates the dynamics of CO_2 emission and O_2 influx with the temporal variability of soil temperature and soil moisture, associated with climatic data. Other authors try to explain this soil gas dynamics exclusively with the soil attributes and local microbiota (Moitinho et al., 2021) or exclusively with the structure within soil aggregates on the soil's limited ability to dissolve and transport oxygen (Zhu et al., 2019).

The effects of different types of soil cover on O_2 influx are poorly understood, especially in dry soils due to soil structure (Zhu et al., 2019). Even in soils with vegetation cover, the partially saturated rhizosphere, with an increase in microbial oxygen consumption, could make the rhizosphere less and less oxygenated (Keiluweit et al., 2015; Zhu et al., 2019). But, when the soil becomes aerobic, this carbon can be rapidly oxidized microbially, which can result in increased gas emissions (Chen et al., 2020; Zhu et al., 2019). These questions impelled the accomplishment of this study to verify this hypothesis.

The hypothesis is that the type of cover (e.g., live or dead cover) or its absence (bare soil) changes the dynamics of the soil's CO_2 emission and O_2 capture, by influencing the maintenance of soil moisture and temperature. This study aims to investigate the temporal variability of CO_2 emissions, the rates of soil O_2 influx, soil moisture and temperature; to understand the relationship between soil O_2 capture and climatic variables (e.g., atmospheric pressure, average air temperature and precipitation), under different soil cover conditions, in a tropical climate.

2. Material and methods

2.1. Study area

The study was conducted at the agroclimatological station of the São Paulo State University.

"Júlio de Mesquita Filho" (UNESP), in the municipality of Jaboticabal (21° 14′ 05″ S and 48° 17′ 09″ W), at an altitude of 615 m, located in the west of the state of São Paulo, Brazil. The regional climate was classified as B1rB'4a ', humid mesothermal, with little water deficiency (Thornthwaite, 1948). Thus, this study is based on tropical climate conditions.

The soil of the experimental area is classified by Brazilian System of Soil Classification (SiBCS) as eutrophic red latosol typical clayey texture (Santos et al., 2019). and as clayey Oxisol by Soil Taxonomy (Awale, 2014). The chemical and physical attributes of the soil for the studied layer (0–0.20 m) are shown in Table 1. The analyses of the soil were carried out following the recommendations of the Manual of Methods of Soil Analysis (Teixeira et al., 2017).

Table 1
Chemical and physical attributes of the soil in the A horizon (0–0.20 m) for the treatments. Where: BS is bare soil, SwM is soil with mulch and SwLV is soil with live vegetation cover.

		BS	SwM	SwLV
Power of Hydrogen (pH)	$CaCl_2$	4.1	4.1	4.6
Organic Matter (OM)	g dm^{-3}	12.0	18.0	21.0
Phosphorus (P)	mg dm^{-3}	8.0	16.0	32.0
Sulfur (S)	mg dm^{-3}	15.0	8.0	11.0
Calcium (Ca)	$mmol_c$ dm^{-3}	5.0	10.0	13.0
Magnesium (Mg)	$mmol_c$ dm^{-3}	4.0	9.0	7.0
Potassium (K)	$mmol_c$ dm^{-3}	0.6	0.6	1.6
Aluminum (Al)	$mmol_c$ dm^{-3}	11.0	7.0	3.0
Potential Acidity (H + Al)	$mmol_c$ dm^{-3}	32.0	35.0	27.0
Sum of Bases (SB)	$mmol_c$ dm^{-3}	10.2	20.9	21.1
Cation Exchange Capacity (CEC)	$mmol_c$ dm^{-3}	42.3	56.1	48.4
Base Saturation (V)	%	24.0	37.0	44.0
Aluminum Saturation (m)	%	52.0	25.0	13.0
Sand	g kg^{-1}	580	600	660
Silt	g kg^{-1}	50	50	40
Clay	g kg^{-1}	370	350	300

2.2. Experimental design and treatments

The experimental sites were arranged in three adjacent plots of 2 × 3 m (6 m^2 of area). Each plot had three treatments: bare soil (BS), exposed soil without any type of soil cover, soil with live vegetation cover (SwLV), where the species used to cover was potato grass (*Paspalum notatum* Flüggé); and soil with mulch (SwM), in which case the soil has a 0.10-m layer of grass mulch. The experimental plots have been conserved in the same place, and more detailed information on the soil management can be found in Table 2.

Seven points were allocated per plot. Each point was delimited by a PVC (Polyvinyl Chloride) ring with a diameter of 0.10 m and height of 0.08 m. The ring was inserted into the soil surface at a depth of 0.03 m. From August to October 2019 17 evaluations were conducted (n = 357 observations). During that period, the soil CO_2 flow (FCO_2), soil temperature (ST), soil moisture (SM) and the influx of O_2 in the soil (FO_2) were measured.

In this paper, the dates August 09, 10, 11, 12, 15, 19, 22, 24 and 26; September 05, 09, 13, 19, 23 and 27; and October 7 and 10 were identified as day of year (DOY), and correspond to the days: 221, 222, 223, 224, 227, 231, 234, 236, 238, 248, 252, 256, 262, 266, 270, 280, 283, respectively.

The climatological data of maximum, minimum and average temperatures (°C) and precipitation events (mm) during the study period are shown in Fig. 1a, while atmospheric pressure (hPa) and average wind speed (m s^{-1}) are in Fig. 1b. All data were collected from the UNESP agroclimatological station for the period studied.

2.3. CO_2 flux, soil temperature and soil moisture assessments

Assessments of CO_2 emissions from the soil were conducted from 7 a.m. to 9 a.m.) and they were registered using a portable Soil Gas Flux System of the LI-COR Environmental series LI-8100 by Biosciences (Nebraska USA).

The Li-8100 system consists of a closed chamber, attached over the rings previously inserted in the soil, at the points to be assessed. In its measurement mode, the system monitors changes in the concentration of CO_2 inside the chamber, by means of optical absorption spectroscopy in the infrared spectral region (IRGA - Infrared Gas Analyzer). The assessment time in each ring was 1 min and 30 s, when the growth of CO_2 concentration inside the chamber was registered and a linear regression was conducted at the end, resulting in the flow of CO_2 from the soil into the atmosphere.

Together with the CO_2 emission assessments, the soil moisture (SM) was evaluated at all sampling points, using a portable TDR-Campbell® system (Hydrosense TM, Campbell Scientific, Australia), consisting of a probe with two 20 cm rods, which were inserted into the ground, perpendicular to the surface. The soil moisture value is obtained from the time it takes an electric current to travel the distance of 32 mm from one rod to another. The measured value is given as a percentage. The soil temperature (ST) was measured using Incoterm® glass mercury geothermometers at the depths of 0.02, 0.05, 0.10, 0.20 and 0.30 m, in two different readings (at 7 a.m. and 9 a.m.). The average of the temperatures measured was used as the soil temperature.

Table 2
History of land use in the experimental area. Source: FCAV/Unesp Agroclimatological Station.

Treatments	Description
Bare Soil (BS)	Maintained as bare soil. Before it was vegetated with grass
Soil with Mulch (SwM)	The mulch is renewed about three times a year with vegetable remains of the grass trimmed from the mulch. The mulch layer is about 0.10 m thick.
Live Vegetation Cover (SwLV) (*Paspalum notatum* Flüggé)	Grass is trimmed about three times a year using a brush cutter. Vegetable remains are used in SwM.

Source: Agroclimatological Station - Unesp/FCAV.

2.4. Determination of O_2 influx

For the determination of O_2 capture by the soil, we used the same seven points and plots where FCO_2 was determined. The determination of FO_2 was performed using a portable Flux UV sensor in the environment within the scope of Flux 0–25%. (CO2Meter, Inc.).

This system consists of a portable sensor that uses the principle of fluorescence with ultraviolet light (UV) to determine the concentration of oxygen in the environment. This sensor is linked to the computer and uses the GasLab® software for setting, calibration and recording of reading data in real time.

The PVC ring served as a chamber to calculate the influx of $^{O}2^{\cdot\ \mathrm{The\ O2\ concentration\ reading\ time}}$ was 5 min. The concentration of the gas inside the chamber decreases over time, indicating the O_2 capture curve by the ground. The rate of soil O_2 capture (equation (1)) was calculated by linear interpolation of the gas concentration values inside the chamber during the first 5 min of sampling. The UV Flux sensor (CO2Meter, Inc.) has already been used efficiently to measure the soil's O_2 capture in the studies by Angert et al. (2015); Almeida et al. (2018); Almeida et al. (2019) and Vicentini et al. (2019).

$$FO_2\ (t) = \frac{dO_2}{A.dt} \tag{1}$$

where, FO_2 (t) is the amount of O_2 measured over time; dO_2 is the change in concentration in relation to the time unit (dt) in the internal volume of the ring whose area in contact with the ground is A (Jassal et al., 2012; Giacomo et al., 2014).

The O_2 influx was calculated by equation (2) considering the atmospheric pressure, air temperature and the volume of the evaluation chamber. The initial concentration of the reading, in part per million (ppm) was converted into grams of O_2 absorbed using the molar ratio. The volume of the PVC camera was 0.00066 m^3 with an area of 0.0078 m^2. The volume measured by the UV Flux sensor (ppm) was converted into mol of O_2 using the ideal gas law equation:

$$P(\Delta V) = \Delta n(RT) \tag{2}$$

where, V is the O_2 capture volume given in (ppm); P corresponds to atmospheric pressure (Pa), T, the temperature of atmospheric air (K) and R the constant of perfect gases (J mol^{-1} K^{-1}).

2.5. Data analysis

For better understanding the FCO_2 variation depending on the type of soil cover and climate, three types of analysis were performed: temporal variation, Pearson's linear correlation matrix and hierarchical analysis.

All data was processed using the statistical software R Core Team (2022) with the aid of the packages: MASS (Venables and Ripley, 2002), hier. part (Nally and Walsh, 2004), ExpDes.pt (Ferreira et al., 2018), corrplot (Wei and Simko, 2017) and tidyverse (Wickham et al., 2019).

2.6. Temporal variation

This analysis was performed for FCO2, FO2, SM and ST. The data in use consists of the means of each sample point for these variables. The means underwent repeated measures analysis of variance over time (F test) to yield the values for standard error. An analysis of Pearson's correlation matrix was also performed to understand the relations of FCO2 as a function of FO2, SM and ST.

Simultaneously, statistical analyses, basic assumptions of analysis of variance, error normality and homogeneity of variances were tested for

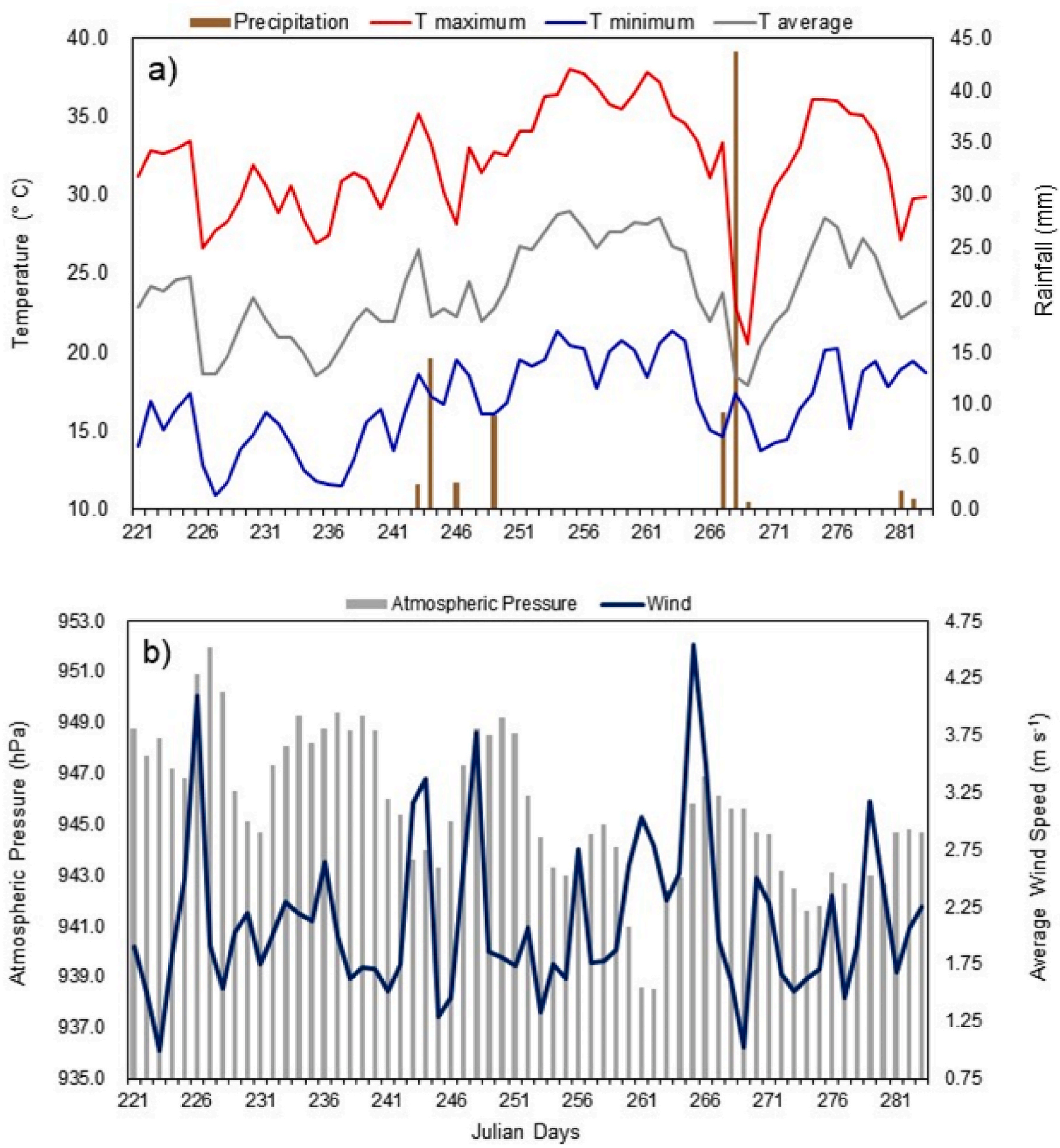

Fig. 1. Climatic data of the study area. a) Values for air temperature (average, maximum and minimum) (° C) and rainfall (mm) in the assessment period (July and August), indicated by the arrows. b) Values for the Wind Speed (m s^{-1}) and Atmospheric Pressure (hPa).

all evaluated attributes. The comparison of means was performed using the LSD test at 5% probability.

2.7. Pearson's correlation

The correlation matrix was performed for all temporal variables (CO_2 emission, O_2 influx, Soil moisture and Soil Temperature) including all climatic variables collected in the agroclimatological station. Was applied Pearson's correlation for each treatment with the help of the Corrplot package (Wei and Simko, 2017). The level of significance was $p < 0.05$ with a 95% confidence level.

2.8. Hierarchical partitioning analysis

Hierarchical partitioning was performed to estimate the independent explanatory capacity of each variable about the soil's CO_2 emission and O_2 influx. Thus, hierarchical partitioning estimates the independent and joint contributions of each explanatory factor with all other factors separately (Doi et al., 2014). This approach has been successfully used to deal with the multicollinearity between explanatory variables, especially in ecological data (Olea et al., 2010).

3. Results

3.1. Temporal variation of CO_2 emission, O_2 influx, soil moisture and temperature

The analysis of variance replicated over time for CO_2 emission (FCO_2) was statistically significant ($F = 2.1379$; $p < 0.0001$) to the interaction between the types of cover (bare soil, mulch and vegetation) and the time (assessment days). On the first day, there was no statistically significant effect of the soil cover on the FCO_2 emission (Fig. 2)

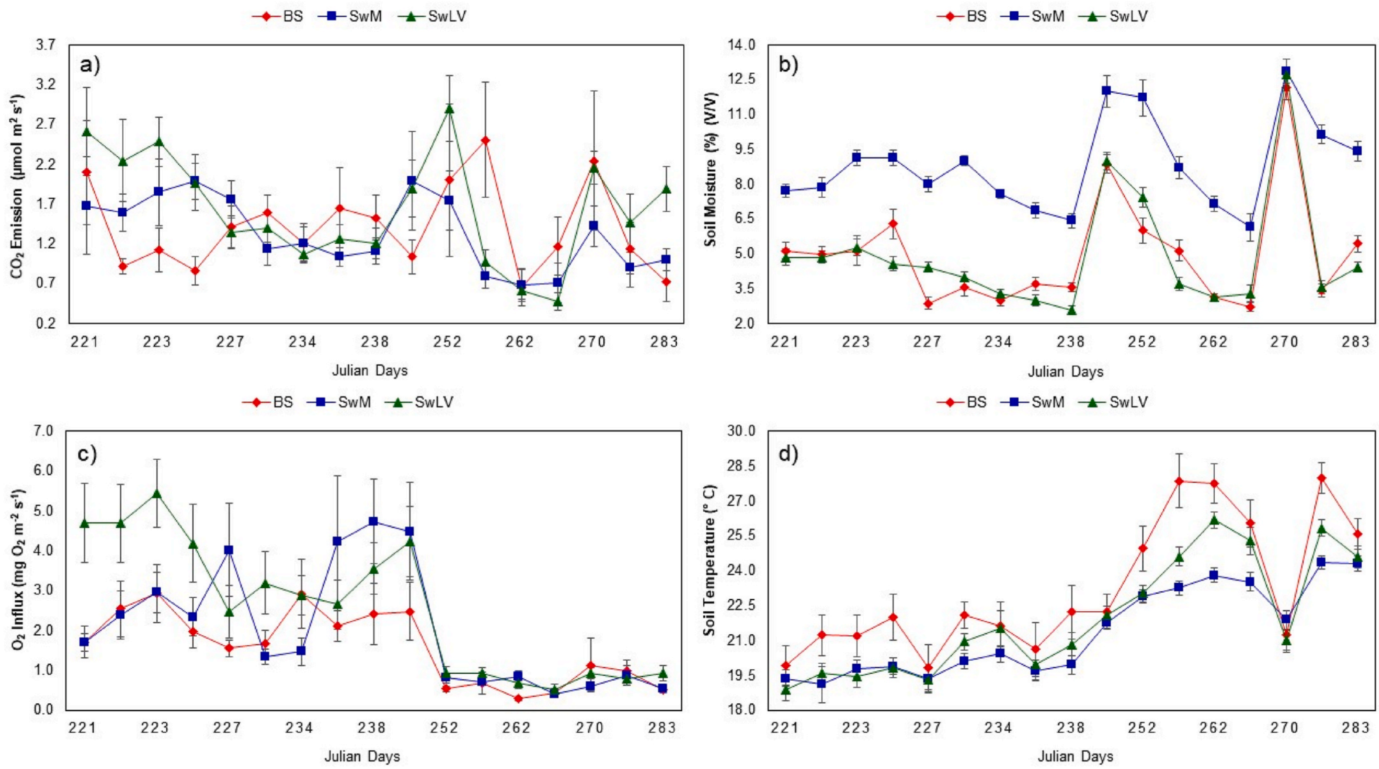

Fig. 2. Temporal variability for Bare Soil (BS), Soil with Mulch (SwM) and Vegetated Soil (SwLV). Respectively, a) CO_2 emission (FCO_2) (μmolm^{-2} s^{1}); b) Soil moisture (%) (v/v); c) O_2 influx (FO_2) (mg O_2 m^{-2} s^{-1}); d) Soil temperature (° C). Error Bar - Indicates the standard error of the mean for the day of the year.

when comparing the bare soil (BS) (2.10 μmol m^{-2} s^{-1}), the mulch (SwM) (1.68 μmol m^{-2} s^{-1}) and the vegetated cover (SwLV) (2.61 μmol m^{-2} s^{-1}) using the LSD ($p < 0.05$).

The CO_2 emission from the soil was significant according to the LSD test ($p < 0.05$) on days 222, 223, 224 and 256. Between days 222 and 223, the highest CO_2 emission patterns occurred in the SwLV, respectively, 2.24 and 2.28 μmol m^{-2} s^{-1}. On day 224, there were no significant differences between SwLV and SwM ($p < 0.05$), respectively, 1.97 and 1.99 μmol m^{-2} s^{-1}. On day 256, the BS had a higher CO_2 emission pattern (2.51 μmol m^{-2} s^{-1}) ($p < 0.05$) when compared to the other treatments (Fig. 2a). The highest values of FCO_2 on days 222 and 223 were observed in the SwLV treatment, with the highest rates of O_2 absorption by the soil (Fig. 2a and c) and lowest values of soil moisture (Fig. 2b).

As for the capture of O_2 by the soil (FO_2) there was also a significant interaction between time (days of assessments) and treatments (types of cover) assessed ($F = 1.9124$; $p = 0.003026$). The highest rate of soil O_2 absorption was observed in SwLV on days 221, 222, 223, 224 and 234, respectively, 4.70; 4.69; 5.43; 4.18; 3.19 mg O_2 m^{-2} s^{-1}, significant according to the LSD test ($p < 0.05$). With the decrease in soil moisture, over the same period, in the SwLV treatment (Fig. 2b), the gas diffusion increases, increasing the entry of oxygen into the soil.

Once again, the effect of soil moisture on the flow of soil gases is observed. Whereas, on days 252, 256, 262, 266, 270, 280 and 283 there were no significant differences in O_2 absorption between treatments according to the LSD test ($p < 0.05$).

It was observed a significant interaction between time and treatments ($F = 5.30$; $p < 0.0001$) for soil moisture (SM). It was found that the SwM treatment had higher soil moisture (LSD test $p < 0.05$) throughout the experiment (Fig. 2b), except for day 270, which did not present significant differences between the treatments. This could be a result of the increasing water content in the soil due to an accumulated precipitation of 54 mm in the two days before day 270 (Fig. 1a). SM, SwLV and BS treatments did not differ from each other according to the LSD test ($p < 0.05$), except for days 224, 227, 252 and 256 (Fig. 2b). This can be attributed to the effect of environment temperature variability (Fig. 1a), and can be the result of the evapotranspiration that occurs in the SwLV.

For soil temperature (ST), there was also a significant interaction between treatments and days of assessment ($F = 10.51$; $p < 0.0001$). As expected, due to the higher level of soil moisture in.

SwM, lower soil temperatures occurred in this treatment, unlike BS, which without plant protection or mulch is more susceptible to solar radiation and consequently to an increase in temperature (Fig. 2d).

3.2. *Pearson's correlation matrix*

There is a positive linear correlation between FCO2 and FO2. This correlation was observed in the SwM ($r = 0.45$; $p < 0.05$) (Fig. 3b) and SwLV ($r = 0.44$; $p < 0.05$) treatments (Fig. 3c). In the BS treatment, there is a negative and significant linear correlation between FO_2 and soil temperature ($r = -0.74$; $p < 0.05$) (Fig. 3a).

The same was observed between FO_2 and average air temperature ($r = -0.44$; $p < 0.05$) (Fig. 3a). In BS, a positive and significant linear correlation was observed between FO_2 and atmospheric pressure ($r = 0.69$; $p < 0.05$) (Fig. 3a).

The SM correlates with positive and significant linear FCO_2 only in SwLV treatment ($r = 0.56$; $p < 0.05$) (Fig. 3c). In this paper, significant and negative linear correlations were observed in the SwM and SwLV treatments, respectively, $r = -0.58$, $p < 0.05$; $r = -0.50$, $p < 0.05$ (Fig. 3b and c).

3.3. *Hierarchical partitioning*

The results show that the most important variable for O_2 influx is the atmospheric pressure (AP) followed by the soil temperature (ST) (Fig. 4a). But if we consider the effect of the soil management, there is a change in the importance of the climatic variables; i.e., for bare soil the

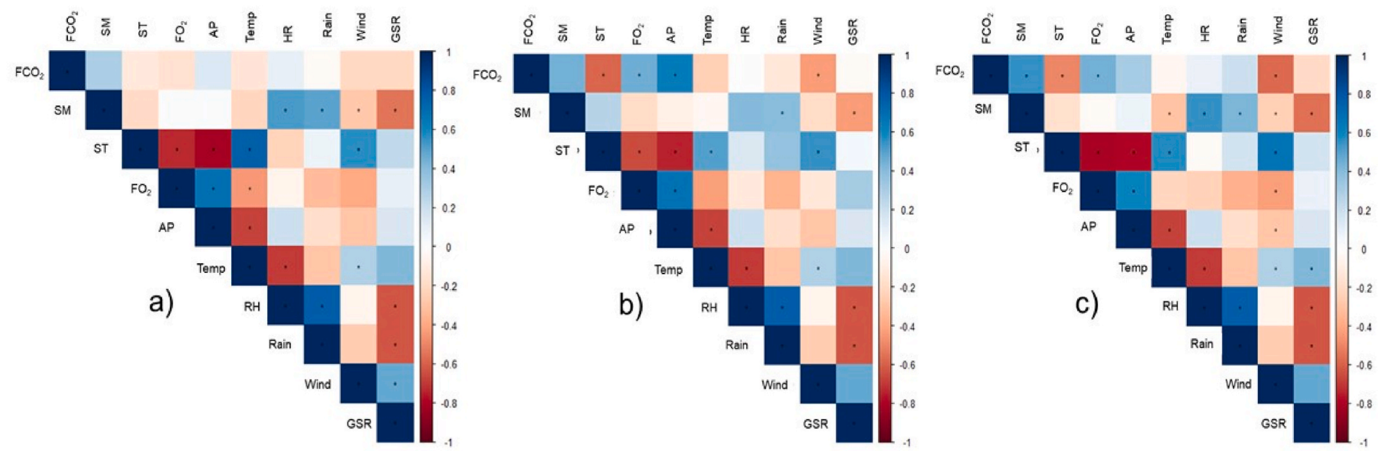

Fig. 3. Pearson's linear correlation for treatments: a) Bare soil (BS), b) Soil with Mulch (SwM) and c) Vegetated soil (SwLV). The confidence interval was 95%, the level of significance adopted was ($p < 0.05$). Where, FCO_2 is the CO_2 emission (μmol m^{-2} s^{-1}), SM is the soil moisture (%) (vol/vol), ST is the soil temperature (° C), FO_2 is the O_2 influx (mg O2 m^{-2} s^{-1}), AP is the atmospheric pressure (hPa), Temp is the average air temperature (° C), RH is the average relative humidity (%), Rain is the rainfall (mm); Wind is the average wind speed (m s^{-1}); GSR is the global solar radiation (MJ m^{-2}). * Indicates statistical significance ($p < 0.05$).

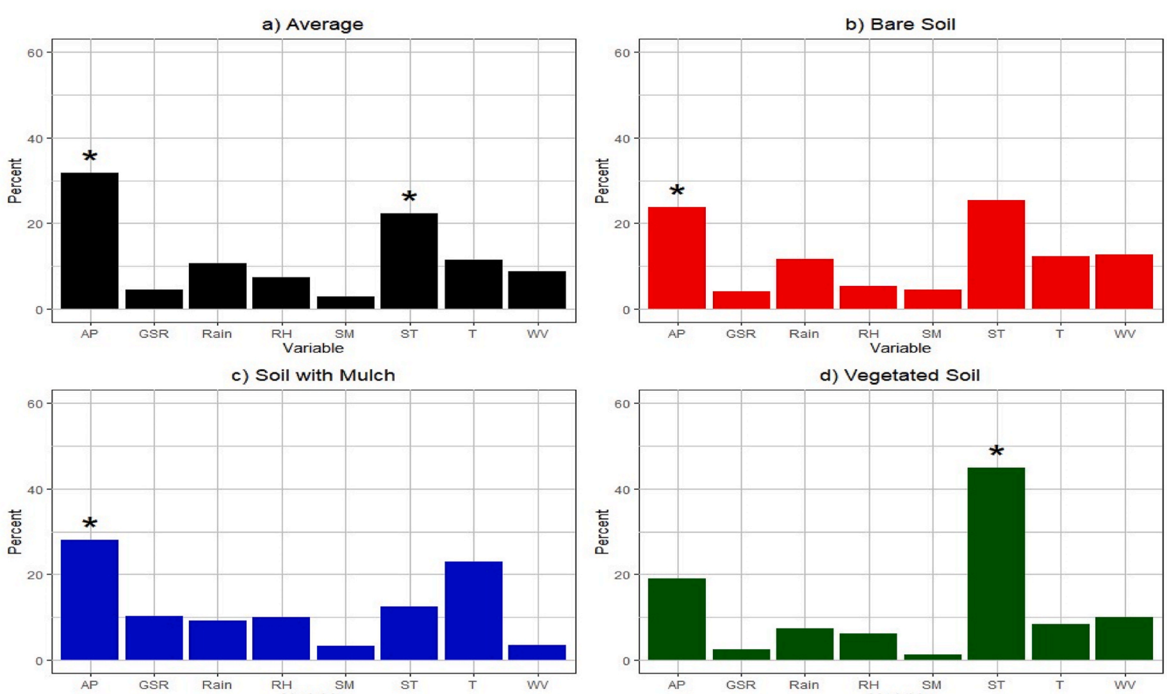

Fig. 4. Hierarchical analysis of the O_2 influx under the different soil management and climatic variables: a) all data, b) bare soil, c) Soil with Mulch and d) Vegetated Soil. Where: AP: atmospheric pressure, GSR: global solar radiation, Rain: rainfall, RH: relative humidity, SM: soil moisture, ST: soil temperature, T: air temperature, WV: wind velocity. * Indicates statistical significance (p-value < 0.05).

most important variables are ST and then AP (Fig. 4b), for the soil with straw the most important is AP, and then the air temperature (T) (Fig. 4c), and finally the vegetated soil show that the ST (Fig. 4d) is the most important variable (see Fig. 5).

In the hierarchical analysis for CO_2 emissions without considering the effects of treatments, we have the following climatic variables that describe the process of CO_2 emission from the soil: AP, ST, T and WV. However, when considering the soil cover, the bare soil did not observe significant effects.

4. Discussion

4.1. *Temporal variation of CO_2 emission, O_2 influx, soil moisture and temperature*

In some studied days, the non-significant difference in FCO_2 may reflect the low values of soil temperature observed between treatments (Fig. 2d). Although these non-significant differences in FCO_2 could be related to the low consumption of O_2 in the soil (Fig. 2c). The CO_2 emissions depend on the aerobic microbial activity, root respiration and the oxidation process of soil organic matter (Lal, 2009). Also, this biological process depends on the influx of O_2 in the soil and the condition of soil water content and temperature (Campbell, 1985; Cook, 1995;

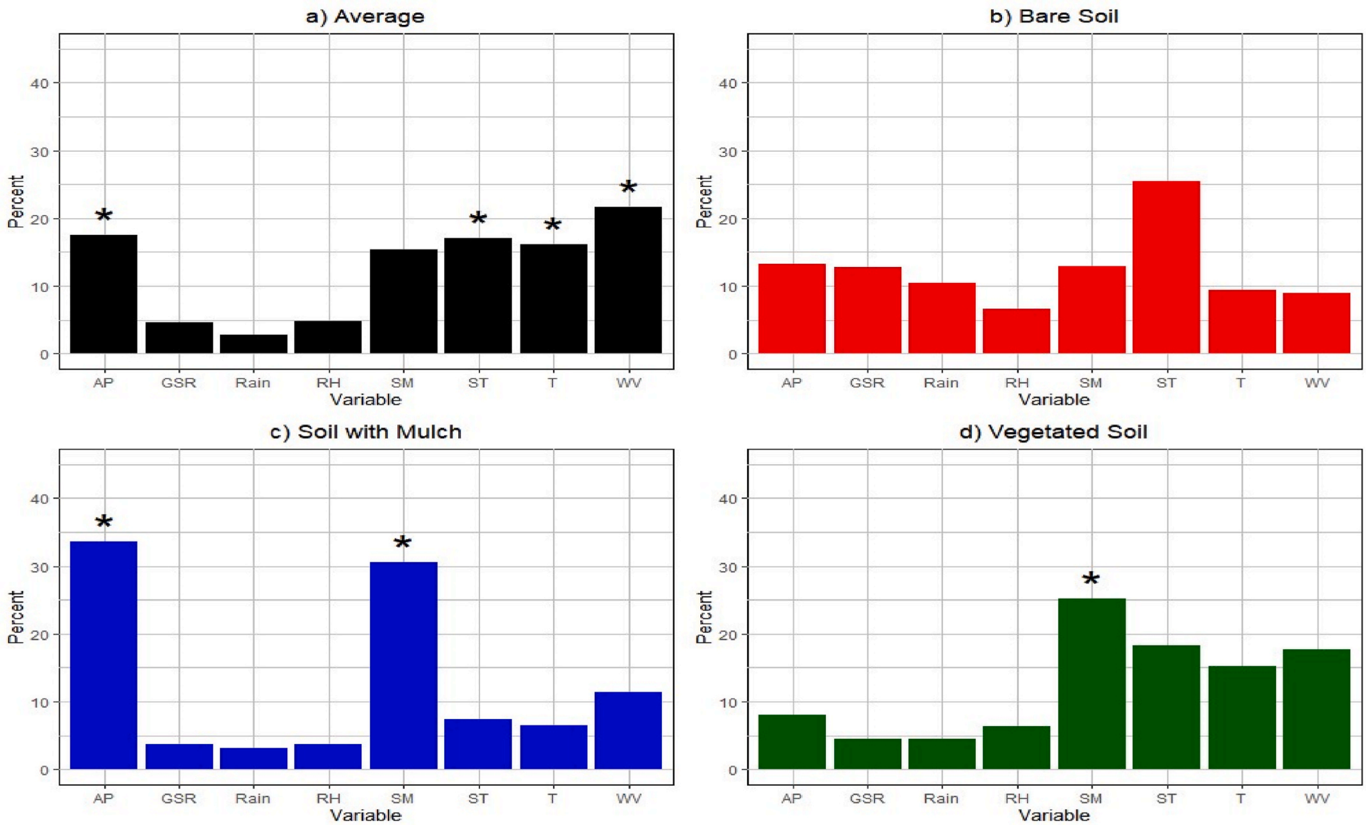

Fig. 5. Hierarchical analysis of the CO_2 emission under the different soil management and climatic variables. a) all data, b) bare soil, c) Soil with Mulch and d) Vegetated Soil. Where: AP: atmospheric pressure, GSR: global solar radiation, Rain: rainfall, RH: relative humidity, SM: soil moisture, ST: soil temperature, T: air temperature, WV: wind velocity. * indicates statistical significance (p-value < 0.05).

Bartholomeus et al., 2008).

This effect may be related to the stimulation of the roots, increasing the consumption of O_2 and releasing more CO_2 (Franco and Inforzato, 1946). However, on day 224, the SwLV and SwM treatments did not show significant differences between them ($p < 0.05$); the decrease in soil moisture and less O_2 absorption could be the main factors to explain this behavior (Fig. 2b and c). In general, the treatment with the lowest CO_2 emission is BS, except for day 256 (Fig. 2a), which may be a reflex effect of the increase in soil moisture and temperature, and, as a consequence, an increase in microbial activity (Schwartz et al., 2010).

Thus, this higher rate of O_2 capture by the soil may be related to root respiration due to increased availability of O_2 in the soil (Araújo Neto et al., 2014). This can be a joint effect of the decrease in atmospheric pressure and the increase in the air and soil temperature, which negatively influenced the soil moisture and, consequently, the soil O_2 influx.

Neira et al. (2015) stated that the breathing processes of roots and microorganisms are dependent on soil moisture and temperature, which influence the soil O_2 consumption rate. Another important factor, is that the process of entry of O_2 into the soil is given by diffusion, a process of mass transfer mathematically described by Fick's laws, which is dependent on the atmospheric pressure (Reichardt, 1975, 1996; Neira et al., 2015).

Higher temperature linked to lack of thermal protection of the soil cover causes lower levels of soil moisture (Fig. 2b) and an increase in the soil organic matter consumption by the microorganism. The lower content of organic matter in the BS can be seen in Table 1. In tropical environments, where the soil temperature remains around 25 °C, thus, soil moisture and its oscillations occupying soil pore spaces play a more important role in explaining variations in CO_2 emissions and O_2 influx (Luo and Zhuo, 2006; Thorbjørn et al., 2008).

4.2. *Pearson's correlation matrix*

Almeida et al. (2019) correlated higher CO_2 production rates with higher soil O_2 consumption rates, due to the response of microorganisms in the soil. The deposition of material on the soil surface, as well as the vegetation cover and soil organic matter, has a great influence on organisms resulting in greater biological activity of the soil (Moreira and Siqueira, 2006).

The result of this interaction explains the positive correlation between the soil's CO_2 emission and O_2 absorption, that is, it is the oxygen consumption by the soil microbiota. In the case of soil with mulch, there is maintenance of humidity and thermal control. In the vegetated cover, there are the conditions offered by the rhizosphere to microorganisms.

These correlations can be explained, since these factors directly influence the transport of oxygen in the soil (Neira et al., 2015). On the surface of the soil, factors of the soil-atmosphere system directly imply gas exchange processes. This was observed in the bare soil, due to the difficulty in maintaining biological activity linked to direct exposure to sunlight and other meteorological conditions that are inhibitors of the microbial community (Moreira and Siqueira, 2006).

When assessing soil CO_2 emission, an important aspect is soil moisture. It has a direct action on the biogeochemical processes and dynamics of soil organic matter. It contributes to the diffusion of nutrients, one of the regulating factors of the decomposition activity of microorganisms (Six et al., 2006), and acts on microbial mobility (Moreira and Siqueira, 2006) and autotrophic activities (Tsai et al., 1992), are also subject to water restriction (Davidson and Janssens, 2006). Soil moisture content is closely associated with soil aeration conditions and can be a determining factor in the intensity of microbiological activity. (La Scala et al., 2006). However, under conditions higher than 60% water-filled pores diffusion of O_2 gases and CO_2 transport is impaired.

(Linn and Doran, 1948). These effects are mainly due to the interaction between the moisture content and the porous space of the soil (Ordóñez-Fernández et al., 2008), resulting in a lower availability of oxygen for the metabolism of aerobic microorganisms (Lal, 2009).

Lopera (2019) in his study with different vegetation coverings, showed a negative correlation between soil moisture and CO_2 emissions ($r = -0.16$; $p < 0.05$). Thus, this divergence can be explained because in the study by Lopera (2019) there were very low temperature values that work as an inhibitor of microbial activity.

In this study, it was observed that the edaphic biota may have been favored due to SM, significantly increasing the CO_2 emission from the soil, explaining the positive correlation. In studies that assess the correlations between FCO_2 and soil temperature, a negative correlation is usually observed, because the edaphic fauna is limited by positive or negative extreme temperatures (Iamaguti et al., 2015).

In agreement with Iamaguti et al. (2015) who also observed a significant negative linear correlation between FCO_2 emission and soil temperature ($r = -0.71$; $p < 0.05$) in Oxisol soils in a tropical region. When trying to correlate the temperature to the CO_2 emission, two things must be considered: assessment times, season. Thus, cold and dry seasons, such as the winter, imply the dynamics of living soil activity.

This implication is due to the drop in the temperature connected with little water availability (Moreira and Siqueira, 2006). The soil cover is a controller of soil moisture, providing relative thermal control (Ussiri and Lal, 2009). Thus, these interactions cause the correlation between FCO_2 and FO_2 with soil temperature to have a negative linear behavior. In tropical soils soil temperature is not a limiting factor, because it presents favorable conditions for microbial development and is relatively constant (Schwendenmann et al., 2003; Adachi et al., 2006; Davidson and Janssens, 2006). In this context, Davidson and Janssens (2006) state that the influence of temperature on the temporal variability of soil CO_2 emission may be hidden by the effect of soil water. Soil temperature and soil moisture can covary, resulting in a complex interaction to separate their effects (Schwendenmann et al., 2003; Savva et al., 2013).

4.3. Hierarchical partitioning

The effect of temperature on the O_2 influx in the soil was already observed by Vicentini et al. (2019), Thus, while the increase in pressure positively impacts the diffusion of O_2 in the soil, the temperature of the soil has an inverse relationship to the process of diffusion of gases in the soil, this physical process is described by Fick's law (Neira et al., 2015).

Soil pressure and soil moisture were the variables that exerted the strongest influence on the temporal variability of CO2 flux. Soil with mulch (SwM), moisture is more associated with soil microorganisms; the emission is associated with biological factors favored by soil moisture in this treatment (Luo and Zhuo, 2006; Bini et al., 2016), resulting patterns in heterotrophic soil respiration.

And finally, in the vegetative treatment (SwLV), the strong association between soil moisture and CO_2 flux is probably related to heterotrophic and autotrophic respiration. The moisture is often conceptualized as a crucial control on microbial growth-moist conditions favor growth, whereas dry conditions constrain it (Homyak et al., 2018). I addition, sufficient soil moisture levels exerts influence on root respiration and favors nutrient uptake (Burton et al., 1998).

5. Conclusions

The temporal variability of the variables as CO_2 emissions or O_2 influx, showed that in treatments with vegetation or mulch cover the effect of climatic variables can be reduced. In bare soil, the lack of physical protection affects attributes such as soil moisture and temperature, which are linked to variation in time.

The correlation matrix showed that with soil coverage (protection), there is a significant dependence between the oxygen inflow and the carbon dioxide emission. The partitioning analysis showed that there are factors that collaborate more with the CO_2 emission than the entry of oxygen into the soil, making it clear that at certain moments the emission can be linked to other atmospheric factors such as pressure.

Understanding the entry of O_2 into the soil and CO_2 emissions can help to determine the best type of soil cover management that should be used to reduce CO_2, the main greenhouse gas, and to collaborate as a long-term climate change mitigation technique.

In this paper, the carbon stock was not verified over time, but, hypothetically, as the soil cover influences the emission, it is expected that over time this factor may impact the carbon stock in the soil, remaining as a future study perspective.

The results of this study can facilitate understanding the dynamics of gases in the soil and the dynamics of soil oxygen with other greenhouse gases, such as nitrous oxide.

From this study it is possible to work on a model to predict the standard of temporal variability of soils' CO_2 emission and O_2 influx; as an alternative, this may be useful to recommend which type of cover is most advantageous to the soil ecosystem.

As a perspective for future work, it is expected that these data will support the understanding of soil oxygen dynamics and its relationship with greenhouse gas emissions, so it will be possible to use models with machine learning techniques that are possibly the most accurate estimate of emissions, such data will help shape global public policies to mitigate these emissions, thus meeting the sustainable development objective number 13.

CRediT authorship contribution statement

Wanderson Benerval De Lucena: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria Elisa Vicentini:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Gustavo André De Araújo Santos:** Methodology, Investigation, Data curation. **Bruna De Oliveira Silva:** Resources, Investigation. **Daniel Vítor Mesquita Da Costa:** Investigation, Data curation. **Kleve Freddy Ferreira Canteral:** Resources, Investigation. **José A. Neira Román:** Writing – review & editing, Supervision, Software, Formal analysis. **Glauco De Souza Rolim:** Writing – review & editing. **Alan Rodrigo Panosso:** Supervision, Conceptualization. **Newton La Scala:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

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References

Adachi, M., Bekku, Y.S., Rashidah, W., Okuda, T., Koizumi, H., 2006. Differences in soil respiration between different tropical ecosystems. Appl. Soil Ecol. 34, 258–265. https://doi.org/10.1016/j.apsoil.2006.01.006.

Alencar, A., Zimbres, B., Silva, C., Tsai, D., Silva, F.B., Quintana, G.O., Graces, I., Coluna, I., Shimbo, J.Z., Carvalho, K., Potenza, R.F., Azevedo, T., 2022. Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa (SEEG). Desafios e oportunidades para redução ds emissões de metano no Brasil. Observatório do Clima, Brasil.

Almeida, R.F., Teixeira, D. de B., Montanari, R., Bolonhezi, A.C., Teixeira, E.B., Moitinho, M.R., Panosso, A.R., Spokas, K.A., La Scala Jr., N., 2018. The ratio of CO_2 and O_2 as index for categorizing soil biological activity in sugarcane areas under contrasting straw management regimes. Soil Res. https://doi.org/10.1071/SR16344. SR16344.

Almeida, R.F., Spokas, K.A., Teixeira, D. de B., La Scala Jr., N., 2019. Biochar insights from laboratory incubations monitoring O_2 consumption and CO_2 production. Biochar 1, 249–258. https://doi.org/10.1007/s42773-019-00021-6.

Angert, A., Yaki, D., Rodeghiero, M., Preisler, Y., Davidson, E.A., Weiner, T., 2015. Using O_2 to study the relationships between soil CO_2 efflux and soil respiration. Biogeosciences 12, 2089–2099. https://doi.org/10.5194/bg-12-2089-2015.

Awale, Rakesh, et al., Soil Survey Staff, 2014. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys, 12 edition Natural Resources Conservation Service. U.S. Department of Agriculture Handbook 436.

Bahia, A. S. R. de S., Marques Jr., J., Panosso, A.R., Camargo, L.A., Siqueira, D.S., La Scala Jr., N., 2014. Iron oxides as proxies for characterizing anisotropy in soil CO_2 emission in sugarcane areas under green harvest. Agric. Ecosyst. Environ. 192, 152–162. https://doi.org/10.1016/j.agee.2014.04.017.

Bartholomeus, R.P., Witte, J.-P.M., van Bodegom, P.M., van Dam, J.C., Aerts, R., 2008. Critical soil conditions for oxygen stress to plant roots: Substituting the Feddes-function by a processbased model. J. Hydrol. 360, 147–165. https://doi.org/10.1016/j.jhydrol.2008.07.029.

Burton, A.J., Pregitzer, K.S., Zogg, G.P., Zak, D.R., 1998. Drought reduces root respiration in sugar maple forests. Ecol. Appl. 8 (3), 771–778.

Brady, N.C., Weil, R.R., 2013. Elementos da natureza e propriedades dos solos, 3[a] ed. Bookman, Porto Alegre, p. 704.

Campbell, G., 1985. Soil Physics with BASIC - Transport Models for Soil-Plant Systems. Elsevier, New York, USA.Centurion. J. F. 1998.

Cerri, C.E.P., Sparovek, G., Bernoux, M., Easterling, W.E., Melillo, J.M., Cerri, C.C., 2007. Tropical agriculture and global warming: impacts and mitigation options. Sci. Agric. 64, 83–99.

Chen, S., Wang, J., Zhang, T., Hu, Z., 2020. Climatic, soil, and vegetation controls of the temperature sensitivity (Q10) of soil respiration across terrestrial biomes. Global Ecology and Conservation (22), e00955. https://doi.org/10.1016/j.gecco.2020.e00955.

Cook, F.J., 1995. One-dimensional oxygen diffusion into soil with exponential respiration: analytical and numerical solutions. Ecol. Model. 78, 277–283. https://doi.org/10.1016/0304-3800(94)00179-L.

Davidson, E., Janssens, I., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440, 165–173. https://doi.org/10.1038/nature04514.

Doi, H., Heeren, A., Maurage, P., 2014. Scientific activity is a better predictor of Nobel Award chances than dietary habits and economic factors. PLoS One 9 (3), e92612. https://doi.org/10.1371/journal.pone.0092612.

Ferreira, E.B., Cavalcanti, P.P., Nogueira, D.A., 2018. In: ExpDes.pt: Pacote Experimental Designs (Portuguese). R Package Version 1.2.0. https://CRAN.Rproject.org/package=ExpDes.pt.

Franco, C.M., Inforzato, R., 1946. O sistema radicular do cafeeiro nos principais tipos de solo do estadode Sao Paulo. Bragantia 6 (9), 443–478.

Giacomo, G., Angelo, F., Fabio, B., Stefano, B., Riccardo, M., 2014. Measurements of soil carbon dioxide emissions from two maize agroecosystems at harvest under different tillage conditions. Sci. World J. 1–12. https://doi.org/10.1155/2014/141345.

Homyak, P.M., Blankinship, J.C., Slessarev, E.W., Schaeffer, S.M., Manzoni, S., Schimel, J.P., 2018. Effects of altered dry season length and plant inputs on soluble soil carbon. Ecology 99, 2348–2362. https://doi.org/10.1002/ecy.2473.

Iamaguti, J.L., Moitinho, M.R., Teixeira, D. de B., Bicalho, E. de S., Panosso, A.R., La Scala Jr., N., 2015. Preparo do solo e emissão de CO_2, temperaturae umidade do solo em área canavieira. R. Bras. Eng. Agríc. Ambiental 19, 497–504. https://doi.org/10.1590/18071929/agriambi.v19n5p497-504.

Intergovernmental Panel on Climate Change - IPCC, 2007. Climate Change 2007: Mitigation. Contribution of Working Group III. Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, United Kingdom and New York, p. 863.

Intergovernmental Panel on Climate Change - IPCC, 2018. Climate change 2018: mitigation. Geneva: [s.n.]. In: Contribution of Working Group III. Fourth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_SPM_version_report_LR.pdf. June, 18 2019.

Jassal, R.S., Blacka, T.A., Nesic, Z., Gaumont, Guayd, 2012. Using automated non-steady state chamber systems for making continuous long-term measurements of soil CO_2 efflux in forest ecosystems. Agric. For. Meteorol. 161, 57–65. https://doi.org/10.1016/j.agrformet.2012.03.009.

Jensen, J.L., Schjønning, P., Watts, C.W., Christensen, B.T., Peltre, C., Munkholm, L.J., 2018. Relating soil C and organic matter fractions to soil structural stability. Geoderma 337, 834–843. https://doi.org/10.1016/j.geoderma.2018.10.034.

La Scala Jr., N., Marques Jr., J., Pereira, G.T., Corá, J.E., 2000. Carbon dioxide emission related to chemical properties of a tropical bare soil. Soil Biol. Biochem. 32, 1469–1473.

La Scala Jr., N., Bolonhezi, D., Pereira, G.T., 2006. Short-term soil CO_2 emission after conventional and reduced tillage of a no-till sugar cane area in southern Brazil. Soil Tillage Res. 91 (1–2), 244–248. https://doi.org/10.1016/j.still.2005.11.012. Amsterdam.

La Scala Jr., N., De Figueiredo, E.B., Panosso, A.R., 2012. On the mitigation potential associated with atmospheric CO_2 sequestration and soil carbon accumulation in major Brazilian agricultural activities. Braz. J. Biol. 72, 775–785. https://doi.org/10.1590/S1519-69842012000400012.

Lal, R., 2009. Challenges and opportunities in soil organic matter research. Eur. J. Soil Sci. 60, 158–169. https://doi.org/10.1111/j.1365-2389.2008.01114.x.

Linn, D.M., Doran, J.W., 1948. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and non tilled soils. Soil Sci. Soc. Am. J. 48, 1267–1272. https://doi.org/10.2136/sssaj1984.03615995004800060013x.

Lisboa, B.B., Vargas, L.K., Silveira, A.O.D., Martins, A.F., Selbach, P.A., 2012. Indicadores microbianos de qualidade do solo em diferentes sistemas de manejo. Rev. Bras. Ciência do Solo 36, 33–43. https://doi.org/10.1590/S0100-06832012000100004.

Lopera, M.C., 2019. Flujo de CO_2 del suelo bajo diferentes coberturas de la Reserva Forestal Protectora Bosque Oriental de Bogotá. Rev. Acad. Colomb. Cienc. Ex. Fis. Nat. 43, 234–240. https://doi.org/10.18257/raccefyn.823.

Luo, Y., Zhou, X., 2006. Soil Respiration and the Environment. Academic Press, San Diego, p. 316.

Moitinho, M.R., Padovan, M.P., Panosso, A.R., La Scala Jr., N., 2013. Efeito do preparo do solo e resíduos da colheita de cana-de-açúcar sobre a emissão de CO_2. Rev. Bras. Cienc. Solo. 37, 1720–1728. https://doi.org/10.1590/S0100-06832013000600028.

Moreira, F.M. de S., Siqueira, J.O., 2006. Microbiologia e bioquímica do solo, vol. 2. Editora da UFLA, Lavras, p. 729.

Nally, R.M., Walsh, C.J., 2004. Hierarchical partitioning public-domain software. Biodivers. Conserv. 13, 659–660. https://search.proquest.com/openview/6f19c4d612b6cf75b106e479e7084a58/1.

Neira, J., Ortiz, M., Morales, L., Acevedo, E., 2015. Oxygen diffusion in soils: understanding the factors and processes needed for modeling. Chil. J. Agric. Res. 75, 35–44. https://doi.org/10.4067/S0718-58392015000300005.

Olea, P.P., Mateo-Tomas, P., De Frutos, A., 2010. Estimating and modelling bias of the hierarchical partitioning public-domain software: Implications in environmental management and conservation. PLoS One 5, e11698.

Ordóñez-Fernández, R., Carbonell Bojollo, R., González-Fernández, P., Perea Torres, F., 2008. Influencia de la climatología y el manejo del suelo en las emisiones de CO_2 en un suelo arcilloso de la vega de Carmona. What Car? 6, 2339–2354.

R Core Team, 2020. In: R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Reichardt, K., 1975, 3. Processos de transferência no sistema solo-planta-atmosfera. Piracicaba: Centro de Energia Nuclear na Agricultura/USP e Fundação Cargill, p. 286.

Reichardt, K., 1996. Dinâmica da matéria e da energia em ecossistemas, vol. 2. Piracicaba: USP/Esalq., p. 505

Santos, G.A.A., Moitinho, M.R., Silva, B. de O., Xavier, C.V., Teixeira, D. de B., Corá, J.E., La Scala Jr., N., 2019. Effects of long-term no-tillage systems with different succession cropping strategies on the variation of soil CO_2 emission. Sci. Total Environ. 686, 413–424. https://doi.org/10.1016/j.scitotenv.2019.05.398.

Savva, Y., Szlavecz, K., Carlson, D., Gupchup, J., Szalay, A., Terzis, A., 2013. Spatial Patterns of Soil Moisture under Forest and Grass Land Cover in a Suburban Area, in Maryland, vol. 192. USA. Geoderma, Amsterdam, pp. 202–210.

Schwartz, R.C., Baumhardt, R.L., Evett, S.R., 2010. Tillage effects on soil water redistribution and bare soil evaporation throughout a season. Soil Till. Res. 110, 221–229.

Schwendenmann, L., Veldkamp, E., Brenes, T., O'Brien, J.J., Mackensen, J., 2003. Spatial and temporal variation in soil CO2 efflux in an old-growth neotropical rain forest. La Selva, Costa Rica. Biogeochemistry 64 (1), 111–128. Dordrecht.

Silva, B. de O., Moitinho, M.R., Santos, G.A.A., Teixeira, D. de B., Fernandes, C., La Scala Jr., N., 2018. Soil CO_2 emission and short-term soil pore class distribution after tillage operations. Soil Tillage Res. 186, 224–232.

Solomon, S., Qin, D., Manning, M., 2007. In: Climate Change 2007: the Physical Science Basis. Cambridge University Press, Cambridge, 996pp. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. http://www.ipcc.ch/pdf/assessment_report/ar4/wg1/ar4_wg1_full_report.pdf.

Song, X., Ju, X., Topp, C.F.E., Rees, R.M., 2019. Oxygen regulates nitrous oxide production directly in agricultural soils. Environ. Sci. Technol. 53, 12539–12547.

Teixeira, P.C., Donagemma, G.K., Fontana, A., Teixeira, W.G. (Eds.), 2017. Manual de Métodos de Análise de Solo, vol. 3, p. 574. Brasília, DF: Embrapa.

Thorbjørn, A., Moldrup, P., Blendstrup, H., Komatsu, T., Rolston, D., 2008. A gas diffusivity model based on air-, solid-, and water-phase resistance in variably saturated soil. Vadose Zone J. 7, 1276.

Tsai, S.M., et al., 1992. Microbiologia Do Solo. Sociedade Brasileira de Ciência do Solo: Campinas, p. 360.

Ussiri, A.N., Lal, R., 2009. Long-term tillage effects on soil carbon storage and carbon dioxide emissions in continuous corn cropping system from an Alfisol in Ohio. Soil Till. Res. 104, 39–47. https://doi.org/10.1016/j.still.2008.11.008.

Venables, W.N., Ripley, B.D., 2002. In: Modern Applied Statistics with S, fourth ed. Springer, New York. ISBN 0-387-95457-0. http://www.stats.ox.ac.uk/pub/MASS4/.

Vicentini, M.E., Pinotti, C.R., Hirai, W.Y., Moraes, M.L.T., Montanari, R., Teixeira Filho, M.C.M., Milori, D.M.B.P., La Scala Jr., N., Panosso, A.R., 2019. CO_2 emission and its relation to soil temperature, moisture, and O_2 absorption in the reforested areas of Cerrado biome Central Brazil. Plant Soil 444, 193–211.

Wei, T., Simko, V., 2017. In: R Package "corrplot": Visualization of a Correlation Matrix (Version 0.84). Available from: https://github.com/taiyun/corrplot.

Wickham, et al., 2019. Welcome to the tidyverse. Journal of Open Source Software 4 (43), 1686. https://doi.org/10.21105/joss.01686.

Yasin, M., Andreasen, C., 2016. Effect of reduced oxygen concentration on the germination behavior of vegetable seeds. Hortic. Environ. Biotechnol. 57, 453–461.

Zhu, Y., Dyck, M., Cai, H.J., Song, L.B., Chen, H., 2019. The effects of aerated irrigation on soil respiration, oxygen, and porosity. J. Integr. Agric. 18, 2854–2868.