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REGULAR ARTICLE

CO_2 emission and its relation to soil temperature, moisture, and O_2 absorption in the reforested areas of Cerrado biome, Central Brazil

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Abstract
Aims To characterise the temporal variability in soil CO_2 emissions (FCO_2), soil O_2 influx (FO_2), soil water content (SWC), and soil temperature (Ts) and their relations in long-term reforested areas (30 years of conversion) in an Oxisol, Cerrado biome, Brazil. Methods The following land-use changes (Luces) were evaluated: pine (PI), eucalyptus (EU), and native species (NS) reforested areas. The molar ratio between FCO_2 and FO_2 (respiratory quotient, RQ) was calculated to better understand the process of soil metabolism.
Results Soil CO_2 emission was 28% less in PI than in the other LUCs. A model including Ts, SWC, and FO_2 could explain 91 and 62% of the FCO_2 temporal variability in NS and PI, respectively. The total FCO_2 (November 2015 to May 2016) were 11.26, 10.99, and 7.97 Mg ha-1 for EU, NS, and PI areas, respectively ($p < 0.05$). The SWC, but not Ts, influenced the

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temporal variation of FCO_2. The first two principal components accounted for 69.32% of the total variability, and two groups distinguished mainly on the basis of soil chemical attributes.

Conclusions Temporal variations of FCO_2 in reforested areas in the Cerrado were influenced by edaphoclimatic conditions. Soil carbon stock was influenced by the type of forest and litter on the ground. FO_2 was similar in all LUCs studied. The results indicate that RQ of >1 is associated with the effect of root system-mediated soil respiration. Our results suggest that LUCs influence soil carbon input and output—soil carbon dynamics—by changing soil attributes.

Keywords Soil respiration · Soil metabolism · Brazilian savanna · Carbon loss

Introduction

Over the past 50 years, half of the native forests of the Brazilian Cerrado biome have been converted to agriculture and pasture. Among the environmentally damaging changes related to deforestation, soil degradation is particularly serious. Land Use and Land-Use Change and Forest directly affect both the input and output of soil carbon to the atmosphere. This is crucial for tropical regions (Roitman et al. 2018), as higher temperature and soil water content enhance the rate of decomposition of soil organic matter (SOM), thereby accelerating soil organic carbon (SOC) losses to the atmosphere. In addition, carbon stock changes after reforestation strongly depend on climate conditions, soil type, and tree species (Don et al. 2011; Li et al. 2012).

High SOM has been suggested to be a key indicator of soil quality (Doran and Parkin 1994), owing to its sensitivity to changes arising from different forms of land use. The SOM plays a key role in agroecosystem sustainability and influences the physical, chemical, and biological attributes of soil. Notably, soil degradation decreases SOM and SOC, thereby reducing soil productivity and thus contributing to increased soil CO_2 emission with direct impacts on the climate (Lal 2009; Caride et al. 2012).

The production of CO_2 is a result of soil biochemical processes and is directly related to root respiration and SOM decomposition via microbial activity (Lal 2009). Soil respiration (SR) can be defined as the consumption of oxygen (FO_2) and production of CO_2 and its emission (FCO_2) because of the metabolic processes of soil organisms. Kursar (1989) reported that SR includes microbial decomposition of litter, root exudates, and dead roots as well as respiration by roots and root symbionts. However, many factors influence these processes, including soil water content and temperature; physical and chemical soil attributes such as humification index (H_{LIFS}) of SOM, the C:N ratio of organic material, and solar radiation; topography; and FO_2 (La Scala et al. 2000; Panosso et al. 2008; de Brito et al. 2009; Panosso et al. 2011; Bicalho et al. 2014; Moitinho et al. 2015; Almeida et al. 2018). On a global scale, SR rates change seasonally and are positively correlated with mean annual precipitation and annual air temperatures (Raich and Schlesinger 1992). SR also varies with the type of vegetation, amount and quality of litter supplied to the soil, and decomposition rate of fine roots (Raich and Tufekciogul 2000; Ohashi et al. 2019).

Management practices such as rehabilitation of degraded pastures and reforestation could maintain or even increase SOM content and have been considered efficient in promoting carbon absorption (C), especially in the aboveground biomass, and soil protection (Pulrolnik et al. 2009; Fialho and Zinn 2014). Soil CO_2 emission can be used as a bioindicator of soil C dynamics; the ratio between FCO_2 and FO_2 (respiration quotient, RQ) is another means of describing and categorising microbial activities (Angert et al. 2014). The RQ can be used as an index to categorise soil biological activity: RQ values close to 1 reveal aerobic activity, with a balance between CO_2 production and O_2 consumption (Almeida et al. 2018). Thus, the determination of FO_2, which is driven by aerobic microbial activity, is imperative to understand the relationships of CO_2 emissions in tropical environments (Stern et al. 1999).

Further information is lacking on greenhouse gas emissions from the soils of reforested areas in the Cerrado biome, Brazil. Hence, this study tested the hypothesis that land use can alter the physicochemical and biological attributes of soil, resulting in changes in soil metabolism. The forest type influences the dynamics of SOC decomposition depending on temperature, soil water content, and leaf litter quality. All these factors cause temporal variation in soil CO_2 emissions. Based on this context, this study aimed to characterise the temporal variability in soil CO_2 emissions, soil O_2 influx, soil water content, and soil temperature, as well as their relations in long-term reforested areas (30 years of conversion) in Oxisol, Cerrado biome, Brazil.

Materials and methods

Characterisation of the areas

The study was conducted from November 2015 to May 2016 in three planted forests— pine, eucalyptus, and native species reforest areas—located on an experimental farm of the Faculty of Engineering (UNESP), Selvíria City, Mato Grosso do Sul, central Brazil (20° 20′ 53.41″ S and 51° 23′ 55.50″ W at 354 m above sea level). The soil was classified as Oxisol (Haplic Acrustox). The topography of the region is characterised as moderately flat, originating from basaltic soils, according to Soil Taxonomy (Soil Survey Staff 2014).

The climate in the region is classified as C1dAa′ by the Thornthwaite system (Rolim et al. 2007), indicating a dry subhumid region without a water surplus. It is megathermal, with summer evapotranspiration of less than 48% of the annual potential evapotranspiration; an annual mean temperature of 23.5 °C, and mean annual rainfall of 1300 mm. The climate data throughout the study period (Table 1) were obtained from the weather station located on the experimental farm. The study sites were adjacent to areas represented by land use typical of the region where processes associated with changes in soil use occurred in nearby areas; the conditions of soil type, temperature, pressure, and rainfall regime were the same across the study sites. The areas studied had soil covered by native vegetation of the Cerrado until the 1970s; they were deforested in 1978 for annual crop production until 1986. In 1986, the areas were converted to different uses as follows: *Eucalyptus* forest, *Pinus* forest, or reforested native species.

The experimental areas were named as follows: (PI) A population formed by 3 hec of pine (*Pinus caribaea* var. *hondurensis*) planted in June 1986 by using 3 × 3 m spacing; (EU) An area of 3 hec containing a basic population of eucalyptus (*Eucalyptus camaldulensis*) planted in April 1986 by using 4 × 4 m spacing; and (NS) A forest of mixed native species established in March 1986, containing 21 species randomly distributed using 3 × 2 m spacing. The native species area included the following arboreal species of the Cerrado biome: *Albizia lebbeck*, *Chorisia speciosa*, *Cydonia oblonga*, *Enterolobium contortisiliquum*, *Eugenia jambolana*, *Ficus clusiifolia*, *Holocalyx glaziovii*, *Hovenia dulcis*,

Table 1 Pluvial precipitation (mm) and maximum, mean, and minimum temperatures (°C) for the measurement of soil CO_2 emission (FCO_2) and O_2 absorption (FO_2) in the areas of eucalyptus, pines, and reforested native species

Date	Day	Precipitation (mm)	Accumulated rainfall (mm)	Air temperature (°C)		
				Minimum	Mean	Maximum
07/11/2015	1	0.0	0.00	22.10	25.30	28.70
12/11/2015	6	0.0	13.20	24.40	30.50	37.00
19/11/2015	13	0.5	92.50	22.60	27.70	34.70
27/11/2015	21	0.0	187.80	22.00	28.90	36.60
02/12/2015	26	0.0	248.50	23.60	26.60	30.00
11/12/2015	35	2.3	282.40	22.40	26.20	32.40
18/12/2015	42	36.0	326.10	21.80	27.50	35.60
21/01/2016	75	0.0	586.90	22.00	27.50	32.90
30/01/2016	85	0.0	654.00	24.30	27.30	32.80
03/02/2016	89	0.0	654.00	22.50	28.60	36.20
16/02/2016	102	0.0	686.50	24.60	28.70	33.70
25/02/2016	111	0.0	762.10	23.20	25.90	31.40
08/03/2016	123	0.0	895.30	24.30	28.80	34.80
18/03/2016	133	0.0	939.50	21.70	28.30	34.90
22/03/2016	137	0.8	940.50	21.90	28.20	37.60
01/04/2016	147	0.0	1014.10	23.00	28.80	36.50
07/04/2016	153	0.0	1014.10	20.70	28.00	36.00
05/05/2016	161	0.0	1108.90	17.50	23.80	32.20
11/05/2016	182	0.0	1162.30	18.70	22.40	30.00
17/05/2016	193	0.0	1178.00	17.70	20.40	25.00

Jacaranda semisenata, *Koelreuteria paniculata*, *Moquilea tomentosa*, *Morus nigra*, *Myroxylon balsamum*, *Peltophorum dubium*, *Psidium guajava*, *Pterocarpus quercinus*, *Peltophorum vogelianum*, *Spondias venulosa*, *Tabebuia chrysotricha*, *Tabebuia impetiginosa*, and *Tabebuia odontodiscus*.

Soil CO_2 emission, O_2 absorption, temperature, and water content

In each experimental plot, measurements were performed for 20 days across the 193 days of study, between November 2015 and May 2016. The evaluations were always performed during the morning (7 to 12 h), and all areas were evaluated on the same day. Soil CO_2 emissions were recorded using a soil flux system (LI-8100; LI-COR Bioscience, Nebraska, USA). The flow camera is a closed system with an internal volume of 991 cm^3 and internal contact area of 78.5 cm^2; it determines the CO_2 concentration via optical absorption spectroscopy in the infrared region. In each area, 25 sampling points (replicates) were established using polyvinyl chloride (PVC) collars having a diameter of 0.10 m and height of 0.085 m; the collars remained fixed during the entire experiment. The flow camera was attached to these collars; for each sample point, soil CO_2 emissions were recorded for 120 s. Soil temperature was determined for all points studied by using a digital thermometer, and soil water content was determined using a time domain reflectometry equipment (Hydrosense™; Campbell Scientific, Australia) containing two metallic stems of 0.12 m, which were inserted perpendicularly to the soil during the experiment near the points where CO_2 emission was measured.

The soil O_2 absorption was measured by selecting 10 points from each area. The O_2 influx was measured using a portable UV flux sensor at 0–25% CO_2 (CO_2 Meter, Inc., Ormond Beach, FL, USA). This system contains a portable sensor that uses the principle of fluorescence with UV light to determine the oxygen concentration in the environment. The sensor was connected to a computer, and GasLab® software package was used to set, calibrate, and record the data in real time.

The rate of soil O_2 absorption (dO_2/dt) was calculated via linear interpolation of the values of gas concentration inside the camera during the first 300 s of sampling. The O_2 absorption rate was calculated using eq. (1), taking into account the atmospheric pressure, air temperature, and chamber volume.

$$FO_2(t) = {}^{dO_2}/_{dt.A} \tag{1}$$

where $FO_2(t)$ is the amount of O_2 measured in time, and dO_2 is the change in concentration in relation to the unit of time (dt) on the surface area of the collar (A) (Jassal et al. 2012; Giacomo et al. 2014). The initial concentrations of the readings were obtained in parts per million (ppm). The volume of the PVC camera was equal to 0.00066 m^3, with an area equal to 0.008 m^2. The volume measured using the sensor (ppm) was converted to mol of O_2 by using the ideal gas equation as follows:

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

The soil FO_2 rate (dO_2/dt) was calculated via linear interpolation of the concentration values as a function of time, taking into account the atmospheric pressure, temperature, and volume of the gas trapped in the chamber by using FO_2 (Smagin et al. 2016; Almeida et al. 2018) as follows:

$$FO_2\left(g.m^{-2}s^{-1}\right) = \frac{dO_2\ 10^{-6}PM}{dt\ RT}\ H \tag{3}$$

where dO_2/dt is the amount of O_2 (ppm) measured at time t (s), P is the atmospheric pressure (Pa); M is the O_2 molar mass (g m^{-3}), R is the universal gas constant (8.31 J mol^{-1} K^{-1}), T is the absolute temperature (K), and H = V/A is the ratio of the volume (V) = 0.00066 m^3 to cross-sectional area (A) = 0.008 m^2 of the camera above the ground (soil surface).

The respiratory quotient (RQ) is the ratio between the volume of CO_2 produced and that of O_2 absorbed during respiration over a period of time. Its value may be one, zero, or higher or lower than one. The results of CO_2 emissions and values of O_2 absorbed were used to calculate RQ in the units of (mol mol^{-1}).

$$RQ = \frac{FCO2}{FO2} \tag{4}$$

Determination of the chemical and physical attributes of the soil

In each area, all 25 points where FCO_2 was measured were selected. Soil samples were collected from a depth of 0.0 to 0.10 m after 193 evaluation days of soil CO_2

emission, O_2 absorption, soil temperature, and soil water content. The samples were air dried, homogenised, and sieved using a 2 mm mesh. For chemical analysis, the following parameters were measured: soil organic matter (SOM); available phosphorus (P); content of calcium (Ca), magnesium (Mg), potassium (K), and aluminium (Al); and potential acidity H + Al. The concentrations of exchangeable Ca, Mg, and K and P available were measured using the ion exchange resin method (Raij 2001). The cation exchange capacity, sum of bases, and base saturation were calculated. For the soil physical attribute analyses, soil samples were collected from the depths of 00–0.10; 0.10–0.20; 0.20–0.30; and 0.30–0.40 m at all sampling points after the evaluations. The soil bulk density (BD) was determined using undeformed core samples of 5.0 cm in internal diameter and 4.0 cm in height (Embrapa 1997). The total pore volume was calculated on the basis of the value of bulk density, and the distribution of pores by size was determined using a porous plate funnel under a tension of 0.60 m of water column in previously saturated samples. The volume of pores retained in the sample corresponded to the micropores, and the calculated difference between the total volume of pores and micropores corresponded to the volume of macropores (Embrapa 1997).

The carbon stock was calculated on the basis of the equivalent soil mass (Carvalho et al. 2009). The authors reported that, when samples are collected from fixed layers, C stock calculation needs to be corrected for variations in soil BD after land-use changes. The correction proposed by Ellert and Bettany (1995) and Moraes et al. (1996) was used, in which an equivalent mass of cultivated area soil that contains the same mass of soil as the corresponding layer (0.0–0.40 m) in native Cerrado is calculated using the following equation:

$$\text{equivalent soil layer (m)} = \frac{Mce}{Marea} \times 0.40, \qquad (5)$$

where *Mce* is the weighted mean of BD in the respective soil layers in native Cerrado, *Marea* is the weighted mean of BD in the respective soil layers in each reforest area, and the value 40 is related to the 0–0.40 m soil depth in the reference area (native Cerrado vegetation). The carbon stock ($Mg \cdot ha^{-1}$) was calculated by multiplying the element concentration (%) by soil bulk density ($g \cdot cm^{-3}$) and the equivalent soil layer thickness (m). Nitrogen stocks were calculated in a similar manner.

Granulometric analysis (sand, silt, and clay) was performed using the method proposed by Embrapa (1997).

Determination of C/N ratio of litter

The carbon and nitrogen content in the litter was determined by collecting 15 representative samples of 1 m^2 of accumulated plant residues from each reforested area. All samples from each area studied were collected on the same day. The litter samples were collected in May 2016. The organic carbon and nitrogen contents were determined using the methods described by Tedesco et al. (1995) and Bataglia et al. (1983), respectively.

Humification index assessed using laser-induced fluorescence spectroscopy

The humification index of SOM (H_{LIFS}) was determined using laser-induced fluorescence spectroscopy (LIFS; Milori et al. 2006). The portable LIFS system is a laboratory equipment developed by the Brazilian Agricultural Research Corporation—Embrapa Instrumentation (Bordonal et al. 2017). The soil sample preparation and analysis procedures were according to the methods described by Santos et al. (2015).

Statistical analysis

The data were first analysed using descriptive statistics (mean; standard error of the mean; standard deviation; maximum, minimum, and coefficients of variation; skewness; and kurtosis). The Shapiro–Wilk test was performed at the 5% probability level to verify the hypothesis of data normality. Time variability was described using variance analysis of repeated measures in time and mixed models by using time and its interaction as random effects. The means were compared using the Tukey test at a significance level of 5% probability. Principal component analysis was used to describe a large part of data variability by using principal components. Principal component analysis condenses relevant information into a smaller set of orthogonal (uncorrelated) variables, referred to as eigenvectors (Johnson and Wichern 2002), corresponding to linear combinations of the original soil properties studied. Stepwise regression was used to select the most effective set of predictors for soil CO_2 emissions in each area. In multiple linear regression, the significance levels for

F-test were used to judge the entry of a variable into an existing model and the removal of a variable from a model, where $p = 0.10$. All analyses were performed using R software package (agricolae_1.3–1.tar.gz; nortest_1.0–4.tar.gz; lawstat_3.3.tar.gz; ExpDes; HH_3.1–35.tar.gz; pastecs_1.3.21.tar.gz; stepwise_0.3.tar.gz; BiplotGUI_0.0–7.tar.gz; vegan), which is in the public domain (R: A Language and Environment for Statistical Computing 2019).

Results

Temporal variability analysis

The FCO_2 varied throughout the 193 days. In pine, the variation reached a minimum value of 2.654 μmol m^{-2} s^{-1} on the 85th day and a maximum value of 5.065 μmol m^{-2} s^{-1} on the 123rd day. In general, the mean values in eucalyptus varied from 4.407 μmol m^{-2} s^{-1} on the first day to the peak of 7.106 μmol m^{-2} s^{-1} on the 102nd day. For native species, the minimum and maximum values were 3.525 μmol m^{-2} s^{-1} on the 161st day and 6.850 μmol m^{-2} s^{-1} on the 102nd day, respectively, with the accumulated rainfall for this period being 685.50 mm (Table 1 and Fig. 1a).

The average FCO_2 in the areas of pine, eucalyptus, and native species were 4.059, 5.606, and 5.526 μmol m^{-2} s^{-1}, respectively. The FCO_2 in the pine forest was significantly lower ($p < 0.05$) than that in the eucalyptus and native species forests (Table 2 and Fig. 1a). According to the classification for the coefficient of variation proposed by Warrick and Nielsen (1980), the temporal measurement values had high variability (CV > 24). For all variables analysed in the three areas, the data

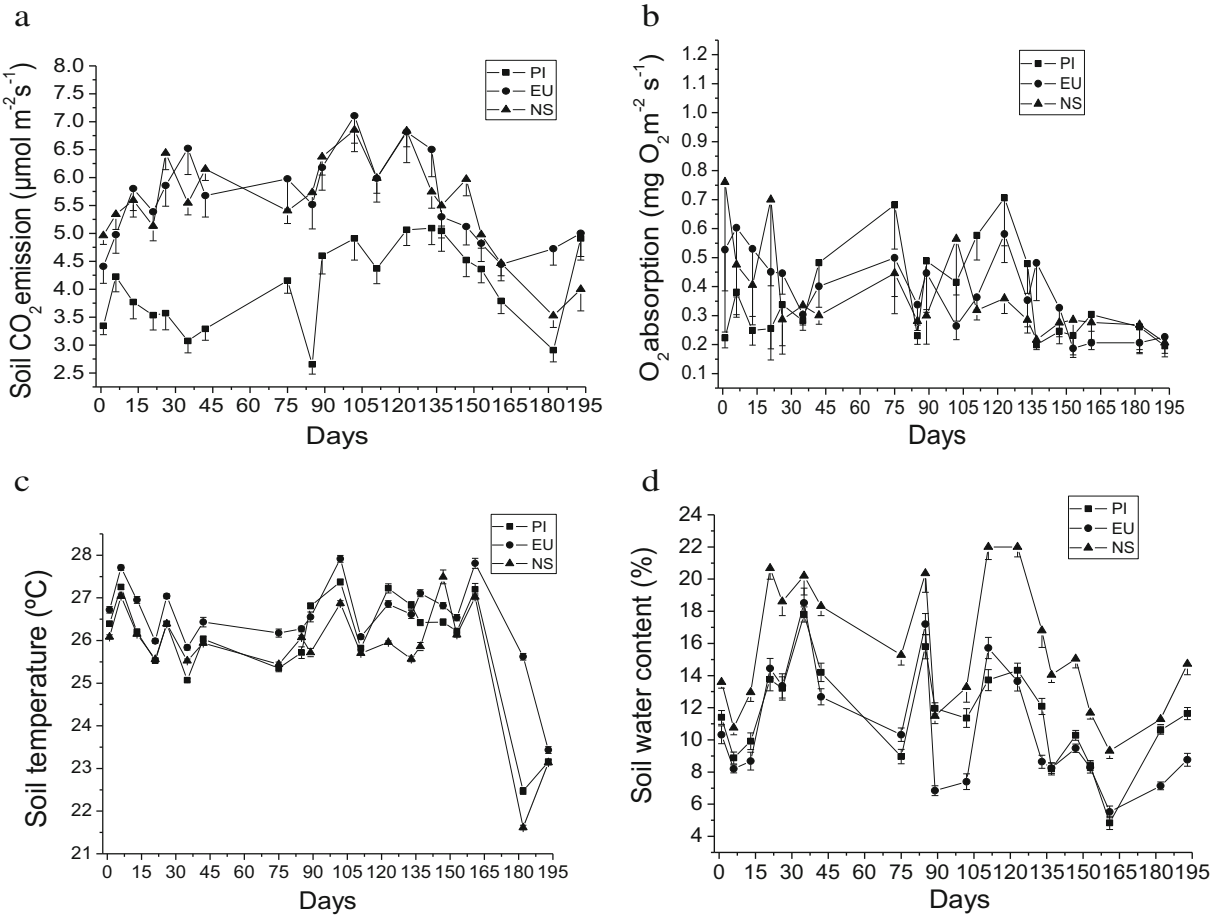

Fig. 1 Time variation of (**a**) soil CO_2 emission (μmol m^{-2} s^{-1}); (**b**) O_2 absorption (mg O_2 m^{-2} s^{-1}); (**c**) soil temperature (°C); and (**d**) soil water content (%) in the studied reforested areas. PI, pine; EU, eucalyptus; and NS, native species

Table 2 Descriptive statistics of soil CO_2 emission (FCO_2), O_2 absorption (FO_2), temperature (Ts), and soil water content (SWC) in the areas of pine, eucalyptus, and native species reforest areas, from November 2015 to May 2016

Area	Mean	CI (95%)	Median	Maximum	Minimum	SD	CV (%)	Skewness	Kurtosis
Soil CO_2 emission (μmol m^{-2} s^{-1})									
Pine	4.059 b	3.698–4.419	3.850	5.065	2.654	1.553	38.255	0.837	0.90
Eucalyptus	5.606 a	5.243–5.968	5.365	7.106	4.407	2.12	37.809	0.71	0.42
Native species	5.526 a	5.121–5.930	5.140	6.439	3.525	1.848	33.438	0.876	1
Soil O_2 absorption (mg m^{-2} s^{-1})									
Pine	0.371 a	0.285–0.435	0.293	0.705669	0.178691	0.324	87.312	0.731	4.304
Eucalyptus	0.369 a	0.321–0.442	0.268	0.60299	0.186429	0.314	85.093	0.834	6.033
Native species	0.366 a	0.294–0.437	0.300	0.760678	0.206608	0.32	92.722	1.055	10.51
Soil Temperature (°C)									
Pine	25.995 a	25.400–26.588	26.300	27.372	22.472	1.297	4.988	−1.321	1.712
Eucalyptus	26.523 a	26.073–26.973	26.500	27.916	23.432	1.018	3.839	−1.073	2.645
Native species	25.765 a	25.150–26.378	25.900	27.492	21.616	1.322	5.13	−1.628	3.457
Soil Water Content (%)									
Pine	11.566 a	10.166–12.965	11.000	17.800	4.840	3.811	32.949	0.231	0.069
Eucalyptus	10.669 a	8.939–12.398	10.000	18.520	5.520	4.397	41.216	0.993	1.063
Native species	15.620 b	13.750–17.489	15.000	20.200	9.320	5.221	33.427	0.416	−0.676

CI (95%), 95% confident intervals; SD, standard deviation; CV, coefficient of variation (%); Skewness, coefficient of asymmetry; Kurtosis, coefficient of kurtosis. Means followed by the same letter (lowercase) in the columns do not differ between each other by the Tukey test ($p < 0.05$)

distribution was symmetric, as asymmetry was close to zero.

The CO_2 emissions on the 193rd day of the study were calculated using the trapezoidal rule (Whittaker and Robinson 1967), and the result was converted to megagrams. Among the three evaluated areas, the pine forest soil emitted 27.48% (7.97 Mg ha^{-1}) less CO_2 than the native species soil (10.99 Mg ha^{-1}) and 29.23% less CO_2 than the eucalyptus forest soil (11.26 Mg ha^{-1}).

No statistically significant difference in FO_2 was observed between the study areas ($p < 0.05$) owing to the high variability of the data (Table 2). However, throughout the 193 days, FO_2 varied from 0.17869 to 0.7056 mg m^{-2} s^{-1} (on the 137th and 123rd days, respectively) in pine; from 0.1864 to 0.6029 mg m^{-2} s^{-1} (on the 153rd and 6th days, respectively) in eucalyptus; and from 0.2066 to 0.7606 mg m^{-2} s^{-1} (on the 193rd and 1st days, respectively) in the native species forest (Fig. 1b). Accumulated FO_2 in the three areas was 189.028 8 mg m^{-2} s^{-1}.

The temporal variations in FO_2 and FCO_2 tended to remain the same in the three areas studied, with a decline in emissions starting from the 123rd and 147th days, respectively. The rainy season in the region started in October and lasted until March. The highest accumulated precipitation of 248.5 mm was noted in November (the start of evaluations), followed by that in March, with 244.1 mm. The largest CO_2 flows were observed in the period with the highest rainfall. Rainfall in the region was higher between the 13th and 137th days of study.

In May, i.e. during the dry season or the first 153 days of the study, the region received very little rain (69.4 mm), and the lowest FCO_2 values and FO_2 absorption were observed in the three areas (Table 1 and Fig. 1a, b).

The time variations related to soil water content were associated with variations in precipitation that occurred in the areas during the study period. In pine, the soil water content values varied from 4.84 to 17.8% (on the 161st and 35th days, respectively). On the 35th day, around the time when measurements were obtained, rain of 2.3 mm occurred. This event influenced the maximum soil water content, which varied from 5.52 to 18.52% (on the 161st and 35th days, respectively) in the eucalyptus forest and from 9.32 to 22.00%, (on the 161st and 123rd days, respectively) in the native species forest (Fig. 1d).

All throughout the experiment, the emission standards (CO_2) changed over the short term after the occurrence of rain. On the 13th day, after rainfall of

0.5 mm, emissions increased in the eucalyptus and native species forests. However, the soil in the pine forest area was not sensitive to this low rainfall event, which did not influence the soil water content. This is possibly due to factors such as interception of rain by the vegetation canopy, as well as the thick layer of litter (10.74 Mg ha^{-1}) relative to the native species area.

However, the rainfall of 2.3 mm on the 35th day influenced the soil water content in the area of pines, but did not cause variation in CO_2 emissions. However, on the 42nd day after a rainfall event of 36 mm, FCO_2 increased in all areas.

The soil water content was significantly higher in the native species (soil water content of 15.62%; $p < 0.05$) than in the pine (11.57%) and eucalyptus (10.67%) forest soil (Table 2). The soil temperature was less variable during this study, which possibly contributed to the lack of correlation between the variables. The mean temperatures were similar in the three forests—approximately 26 °C ($p > 0.05$). After 193 days, we observed the lowest mean soil temperature of 23 °C for the three areas. On that day, we also recorded the lowest air temperature (Table 2 and Fig. 1c).

Linear correlation analysis and multiple linear regression

Pearson's linear correlation analysis (the significance level considered at the probability of 10%) was performed between soil water content, soil temperature, FCO_2, and FO_2. A correlation between FCO_2 and soil water content ($r = 0.44$, $p < 0.10$) and soil temperature ($r = 0.63$, $p < 0.10$) was noted only in the native species, but the correlation was not significant for FO_2 ($r = 0.18$; $p > 0.10$), indicating that 63% of the variability in soil CO_2 emissions in the native species may be explained by the model involving soil temperature and 44% is explained by the model involving soil water content.

No significant correlations were observed between FCO_2 and FO_2 ($r = 0.19$ and -0.34; $p > 0.10$), soil water content ($r = 0.33$ and -0.32; $p > 0.10$), and soil temperature ($r = 0.13$ and 0.37; $p > 0.10$) in the eucalyptus and pine forests, respectively.

The temporal variability in FCO_2 in the study areas was better understood by performing multiple regression analysis by using the following variables: soil water content, temperature, and FO_2. The interaction between the variables helped explain 91 and 62% of the time variation in FCO_2 in the native species and pine forest, respectively; however, for the eucalyptus forest, no significant correlations were noted between any of the variables (Table 6).

Soil physical–chemical attributes

The granulometry analysis data suggested that the concentrations of clay in the soils of the three areas varied from 32.5 to 39.2%. The pine showed the lowest value of silt fraction (25.764 g kg^{-1}). For the native species, the soil had a higher concentration of clay, higher microporosity (0.394 m^3 m^{-3}), and higher total pore volume (0.446 m^3 m^{-3}), which contributed to the high soil water content, compared to that of the soils of the eucalyptus and pine forests. Alternatively, higher values of soil density were observed for the pine forest (1.571 g cm^{-3}) compared to that in the eucalyptus (1.478 g cm^{-3}) and native species forest (1.341 g cm^{-3}; $p < 0.05$; Table 3). The high soil density and low microporosity and macroporosity of the pine trees likely limited gas exchange in the soil.

In addition, an important aspect that may be related to the higher soil CO_2 emissions in the eucalyptus and native species, unlike that in the soil of the pine forest, could be the chemical characteristics of the soil in the pine area: the pine forest had lower SOM (20.04 g dm^{-3}) and carbon stock (41.850 Mg ha^{-1}) and the highest H_{LIFS} (27,523 arbitrary units). The larger H_{LIFS} indexes are related to the highest C:N ratio (45.999 g kg^{-1}; $p < 0.05$; Table 4).

The highest mean value of organic matter (29.76 g dm^{-3}) was noted for the soil of the eucalyptus forest, followed by that for the soil of the native species (25.20 g dm^{-3}) and pine forest ($p < 0.05$). In the 0.40 m layer, the eucalyptus showed greater C stock (56.26 t ha^{-1}), followed by that for the native species (51.00 t ha^{-1}) and pine forest. The carbon stock in the eucalyptus forest soil was 10.31% higher than that of native species soil and 34.43% higher than that of pine forest soil ($p < 0.05$).

In all layers, pines always exhibited the smallest C stock values. The C stock values of eucalyptus and native species were similar (Table 5). The total organic N in the native species soil was 8.48% higher than that of the eucalyptus soil and 62.46% higher than that of the pine soil ($p < 0.05$). In addition, at all depths, the pines showed the lowest values of N stock. The values differed only in the 0.10 m to 0.20 m layers for the native species (1.07 t ha^{-1}) and the eucalyptus forest (0.95 t ha^{-1}).

Table 3 Physical attributes of the soil at the 0.0–0.10 depth in the areas of eucalyptus, native species, and pines in 2015 and 2016

Area	BD		Macro		Micro		TPV		Sand		Silt		Clay	
Pine	1.571 ± 0.015	a	0.042 ± 0.003	b	0.368 ± 0.004	b	0.411 ± 0.005	b	648.279 ± 5.243	a	25.764 ± 3.660	b	325.956 ± 6.525	b
Eucalyptus	1.478 ± 0.020	b	0.082 ± 0.006	a	0.315 ± 0.006	c	0.397 ± 0.008	b	610.944 ± 9.884	b	56.471 ± 1.704	a	332.584 ± 9.385	b
Native species	1.34 ± 0.017	c	0.049 ± 0.007	b	0.394 ± 0.006	a	0.446 ± 0.006	a	542.387 ± 5.195	c	65.212 ± 2.770	a	392.399 ± 6.008	a
CV (%)	6.54		52.27		7.39		7.46		5.27		32.13		9.67	

N 25; Means followed by the same letter (lowercase) in the columns do not differ between each other by the Tukey test ($p < 0.05$)

BD soil bulk density (g cm^{-3}); Macro, Macroporosity (m^3 m^{-3}); *Micro* Microporosity (m^3 m^{-3}); TPV, total pore volume (m^3 m^{-3}); *Sand* contents of sand (g kg^{-1}); *Silt* contents of silt (g kg^{-1}); *Clay* contents of clay (g kg^{-1}); *CV* coefficient of variation. (mean ± standard error of the mean)

The soil in the pine forest had the lowest pH (4.00; $p < 0.05$) and the highest potential acidity (74.80 mmolc dm^{-3}). The soil pH for eucalyptus and native species was 4.31 and 4.40, respectively. The lowest pH can be attributed to the lower concentrations of Ca (5.120 mmolc dm^{-3}), Mg (3.2 mmolc dm^{-3}), K (0.796 mmolc dm^{-3}), SB (9.11 mmolc dm^{-3}), and V (11.8%), which probably contributed to the lower biological activity in the soil of the pine forest (Table 4).

Ratio of soil CO_2 emission and O_2 absorption (RQ)

Throughout the 193 days, the mean RQ values were the lowest for pine, eucalyptus, and native species (0.302, 0.474, and 0.475, respectively, observed on the 123rd, 42nd, and 6th days). Thus, during these times, FO_2 was greater than the FCO_2. On the 153rd day, the highest RQ values of 1.32, 1.21, and 1.23 were observed for eucalyptus, pine, and native species, respectively. This indicates that, during this time, the FCO_2 was greater than the FO_2. No precipitation occurred on the 153rd day (Fig. 2 and Table 1).

Principal component analysis

With the main components, a two-dimensional biplot was created (Fig. 3). Formation of two distinct groups was noted: group I, at the top of the biplot, indicating the formation of subgroups Ia (eucalyptus forest) with more scattered points and Ib (pine forest), which was more grouped. Group II, located at the bottom of the biplot, was represented by the native species. The data set consisted of 13 variables corresponding to PC1 and PC2 (Table 7). PC1 explained 49.00% of the variance of the chemical and physical attributes of soil and soil temperature, whereas PC2 explained 20.32% of the variance. The PC2 is related to the physical attributes of the soil and showed higher correlation with the native species. The discriminatory power (correlation of each variable with the main component) can be measured on the basis of linearity coefficients between each variable and the main principal component. In the order of significance, the properties that were the best correlated with PC1 were Mg (0.92), Al (−0.90), H_{LIFS} (−0.88), pH (0.85), Ca (0.82), SOM (0.78), K (0.73), BD (−0.70), and C:N (−0.60). The attributes with negative signs were inversely correlated. In PC2, the most significant properties were Ts (0.87), Ms. (−0.79), and Micro (−0.79).

Table 4 Chemical attributes of the soil at 0.0–0.10 m depth in the areas of eucalyptus, native species, and pines, and C stock and humification index (H_{LIFS}) at 0.0–0.40 m soil depth in 2015 and 2016

Attributes	Pine		Eucalyptus		Native species		CV (%)
P (mg dm^{-3})	6.320 ± 0.510	a	6.52 ± 0.516	a	6.16 ± 0.46	a	24.53
SOM (g dm^{-3})	20.040 ± 0.567	c	29.76 ± 1.128	a	25.2 ± 0.591	b	14.74
C stock (Mg ha^{-1})	41.850	c	55.398	a	51.002	b	7.45
N stock (Mg ha^{-1})	2.654	c	3.975	b	4.313	a	12.95
pH ($CaCl_2$)	4.000 ± 0.024	b	4.312 ± 0.078	a	4.44 ± 0.057	a	6.7
Ca^{+2} ($mmol_c$ dm^{-3})	5.120 ± 0.392	b	16.680 ± 3.162	a	16.96 ± 1.54	a	74.8
K^{+} ($mmol_c$ dm^{-3})	0.796 ± 0.089	b	1.436 ± 0.106	a	1.504 ± 0.07	a	37.14
Mg^{+2} ($mmol_c$ dm^{-3})	3.200 ± 0.336	b	13.200 ± 0.754	a	15.72 ± 1.45	a	45.15
H + Al ($mmol_c$ dm^{-3})	74.800 ± 3.90	a	55.68 ± 02.612	b	48.8 ± 1.88	b	22.09
CTC ($mmol_c$ dm^{-3})	83.916 ± 3.630	a	86.996 ± 3.102	a	82.984 ± 1.76	a	14.74
SB ($mmol_c$ dm^{-3})	8.564 ± 0.520	c	25.982 ± 3.752	b	33.068 ± 2.89	a	18.08
Al^{+3} ($mmol_c$ dm^{-3})	14.316 ± 0.730	a	5.880 ± 0.719	b	5.080 ± 0.719	b	37.92
V (%)	11.800 ± 1.340	b	34,600 ± 2.867	a	40.36 ± 2.75	a	40.16
CN ratio (g kg^{-1})	45.999 ± 0.300	a	41.505 ± 5.864	b	32.776 ± 0.258	b	22.43
$H_{LIFS\ (a.u.)}$	27,523 ± 2071.504	a	22,526 ± 1547.283	b	22,552 ± 915.216	b	8.53

N 25; Means followed by the same letter (lowercase) in the columns do not differ between each other by the Tukey test ($p < 0.05$)

P available phosphorus; SOM, organic matter in the soil; *C stock* stock of carbon in the soil; *N* nitrogen stock; pH, potential of hydrogen; *K* concentration of exchangeable potassium; *Ca* concentration of exchangeable calcium; *Mg* concentration of exchangeable magnesium; (H + Al) potential acidity; *CTC* cation exchange capacity; *SB* sum of bases; *Al* concentration of exchangeable aluminium; *V* base saturation (%); *CN ratio* CN ratio of litter. (mean ± standard error of the mean)

Discussion

Temporal variability analysis

The FCO_2 values in the eucalyptus, native species, and pine areas were similar to those reported previously in the areas of tropical forest in Amazônia (Sotta et al. 2004; Zanchi et al. 2012) and in a transition forest between Amazônia and Cerrado (Pinto Júnior et al. 2009).

Soil water content and soil temperature are the most frequently associated with temporal variation in FCO_2 (Davidson et al. 1988). In general, precipitation influenced the temporal variability in FCO_2 in the three areas during the study period.

Table 5 Carbon and nitrogen stock in the soil at 0.0–0.40 m depth in the areas of eucalyptus, native species, and pine in 2015 and 2016

Systems	Depth (m)								Total
	0.0–0.10		0.10–0.20		0.20–0.30		0.30–0.40		
Stock of Carbon (Mg ha^{-1})									
Pines	13.915 ± 0.393	c	10.440 ± 0.284	b	8.998 ± 0.164	b	8.491 ± 0.175	b	41.849
Eucalyptus	20.671 ± 0.784	a	12.907 ± 0.341	a	11.446 ± 0.298	a	10.371 ± 0.275	a	55.398
Native species	17.503 ± 0.410	b	12.506 ± 0.155	a	11.151 ± 0.187	a	9.842 ± 0.164	a	51.002
CV (%)	14.74		11.59		11.18		10.44		
Stock of Nitrogen (Mg ha^{-1})									
Pines	0.901 ± 0.165	b	0.667 ± 0.018	c	0.578 ± 0.112	c	0.508 ± 0.010	b	2.654
Eucalyptus	1.470 ± 0.09	a	0.955 ± 0.032	b	0.817 ± 0.024	b	0.731 ± 0.069	a	3.975
Native species	1.574 ± 0.032	a	1.072 ± 0.015	a	0.920 ± 0.018	a	0.747 ± 0.015	a	4.313
CV (%)	22.57		12.57		11.42		31.81		

N = 25; Means followed by the same letter in the columns do not differ between each other by the Tukey test ($p < 0.05$). (mean ± standard error of the mean)

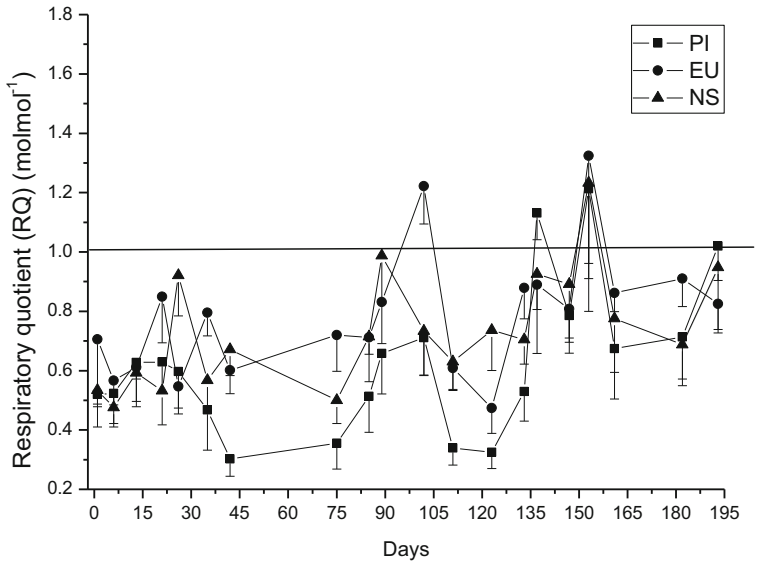

Fig. 2 Time variability of the respiratory quotient (RQ; mol mol^{-1})—ratio of soil CO_2 emission and O_2 absorption in the areas of pine (PI), eucalyptus (EU), and native species (NS) during the studied days

The increases in FCO_2 after precipitation events of 0.5 mm on the 13th day and 36 mm on the 42nd day of study were possibly related to the rise in soil water content in the eucalyptus and native species. Rapid increases in soil water content after precipitation increase the FCO_2 in the atmosphere, because of the substitution of air found in the pores between soil particles with water (Smart and Penuelas 2005; Table 1; Fig. 1a, d). Increases in soil CO_2 emissions after a rainy period have been reported in various systems in tropical regions (La Scala et al. 2001; Panosso et al. 2009; Siqueira Neto et al. 2011).

Schwendenmann et al. (2003) found that, in areas of tropical forest in Costa Rica, FCO_2 variations over time

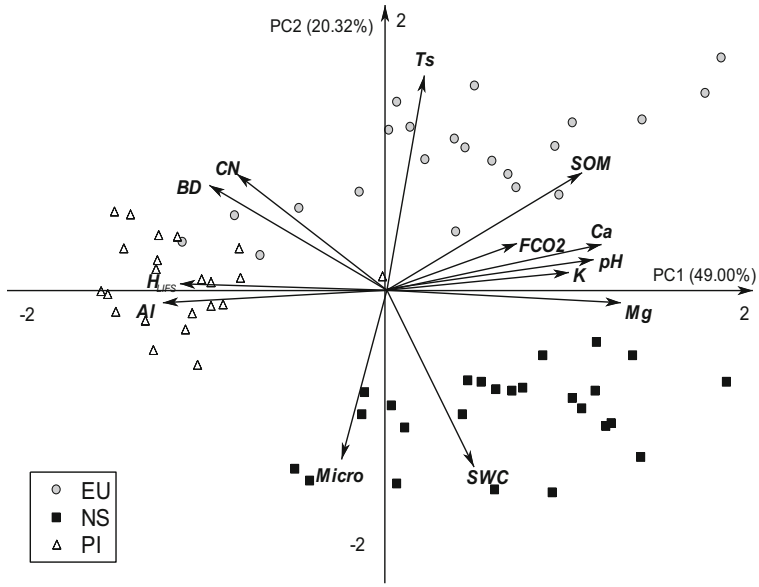

Fig. 3 Biplot of principal components PC1 and PC2 with all soil samples as variables: soil CO_2 emission (FCO_2); soil temperature (Ts); soil water content (SWC); soil organic matter (SOM); concentration of exchangeable calcium (Ca); concentration of exchangeable potassium (K); potential of hydrogen (pH); concentration of exchangeable magnesium (Mg); soil CN ratio; soil bulk density (Bd); humification index of soil organic matter (H_{LIFS}); aluminium content in the soil (Al); and microporosity (Micro) in the areas of eucalyptus (EU), native species (NS), and pine (PI)

could be explained by the soil water content, which is a determinant factor in gas exchanges: the water that fills the pores in soil stops the flow of gases (O_2 and CO_2; Van Straaten et al. 2010), thereby influencing the amount of CO_2 that will be released to the atmosphere (Davidson et al. 1988). However, in forest environments, canopy density and plant physiognomy in the canopy influence how precipitation is received and distributed (Ávila et al. 2014); this, in addition to the possibility of low biological activity of the soil, could explain the lack of the effect of precipitation on FCO_2 in pine areas on the 13th and 42nd days of study (Table 1 and Fig. 1a).

Changes in CO_2 emission, or in RQ, as observed on the 102nd day of the study, not related to soil moisture or soil temperature changes, could possibly be related to root respiration and suitable light and photosynthesis conditions on those days. According to Gavrichkova and Kuzyakov (2017), photosynthesis is one of the main factors driving soil CO_2 emission, and, along with soil temperature, can be a factor controlling diurnal variation of SR (Tang et al. 2005).

Decreases in FO_2 after rain events were also reported by Linn and Doran (1984). Oxygen transfer in the soil occurs mainly via diffusion, a process that depends on the physical characteristics of the soil, such as texture, structure, porosity, and soil water content (Neira et al. 2015). A decline in FCO_2 from the start of the dry season (the 147th day of study) has also been reported in tropical regions (Davidson et al. 2000; Hashimoto et al. 2004; Pinto Júnior et al. 2009). This was also observed for the absorption of O_2, which shows less biological activity in these areas (Fig. 1b). Low variability in soil temperature has also been observed in tropical forests by Davidson et al. (2000).

Our data analysis over the 193 days of study revealed that the pattern of temporal variation in SR was similar in all the three reforested areas. Notably, the present study was conducted in reforested areas (30 years of conversion), possibly with greater stability and higher degree of humidification of soil organic fraction.

Linear correlation analysis and multiple linear regression

Usually, soil temperature and soil water content are the most important variables that influence the temporal variation in SR. However, the highest variability in SR in the present study probably contributed to the low correlation values between FCO_2 and soil temperature in the three study areas (Tables 2 and 6).

The correlation values for soil water content found in the areas of eucalyptus and pine were consistent with those reported in tropical regions under different climatic, soil, vegetation, and management conditions (La Scala et al. 2006; Metcalfe et al. 2007). Despite the lower individual correlations of soil water content, soil temperature, and FO_2 with FCO_2 and the interaction between the variables in areas of native species and pine were closely related to the temporal variability in SR.

Soil physical–chemical attributes

The higher soil water content in the native species area was most likely because of its texture (Table 3). According to Aringhieri (2004), the concentration of clay is related to microporosity and thus to the total porosity. Although soil is important, transpiration rates and rainfall interception by the forest canopy are also relevant factors in explaining the differences in soil moisture between vegetation types. Canopy structure and leaf area index of the different vegetation types have been shown to influence rain interception and thus soil moisture content (Zhang et al. 1999; Dermody et al. 2007; Jiang et al. 2015).

The forests in our study are in a mid-slope; however, the toposequence position of the native species (foothill) generates an environment of deposition, contributing to higher concentration of clay. High levels of clay provide organic carbon colloidal protection, increasing the stability of organic matter. In addition, the diversity of plant species and decomposition of litter in native species may have affected the maintenance of soil water content, leading to the formation of a microclimate in the area (Monteith and Unsworth 1990).

The conversion of land use modifies both the input as well as output of soil C to the atmosphere. Carbon stock changes after afforestation strongly depend on the soil type and tree species (Li et al. 2012). Organic matter accumulation is caused by the addition of plant residues and their decomposition; however, the quantity and quality of litter are different for each forest species, and litter decomposition rate is also influenced by the microenvironment (Xiao et al. 2019).

Forest covers substantially contributed to organic material in the soil. Pine and eucalyptus forests accumulated large amounts of litter (10.74 Mg ha^{-1} and 10.54 Mg ha^{-1}, respectively; $p > 0.10$), whereas native

Table 6 Models of multiple linear regression of soil CO_2 emission (FCO_2) for the areas of native species and pine

Variables	Estimated parameter	SE	*P*
Native species			
Intercept	−98.41	26.39	0.003332***
Ts	9.400	2.296	0.001780**
Ts^2	−0.207	0.049	0.001527**
FO_2	123.93	43.843	0.016466*
FO_2^2	−12.008	3.719	0.008040**
$Ts.FO_2$	−4.764	1.679	0.016174*
$SWC.FO_2$	−18.240	3.502	0.000348***
$Ts.SWC.FO_2$	0.730	0.144	0.000365***
			R^2 0.91
Pine			
Interecpt	−53.88	37.05	0.1696
SWC	6.774	3.724	0.0920*
SWC^2	−0.044	0.021	0.0602*
Ts.SWC	−0.227	0.127	0.0980*
$SWC.FO_2$	−4.468	2.050	0.0483*
$Ts.SWC.FO_2$	0.177	0.078	0.0406*
			R^2 0.61

For the eucalyptus area, the model was not significant. SE = standard error. R^2 = fitted coefficient of determination. The presence of different letters indicates significant differences (*: $P < 0.05$, **: $P < 0.01$, ***: $P < 0.001$) between forests. Soil CO_2 emission (FCO_2), O_2 absorption (FO_2), temperature (Ts), and soil water content (SWC)

species (8.72 Mg ha^{-1}; $p < 0.10$) forests accumulated lower amounts. Zinn et al. (2002) found that pine forests accumulate a large amount of litter (37.0 Mg ha^{-1}), whereas eucalyptus (7.6 Mg ha^{-1}) and Cerrado (10.9 Mg ha^{-1}) forests accumulated lower amounts.

The lowest litter value in the native species was probably attributed to ecosystem characteristics, i.e. greater species diversity and less lignified materials. Furthermore, native species forests have an environment with greater heterogeneity of decomposing organisms, which contributes to the degradation of organic material.

The differences in SOM content, C stock, and N stock observed in the three areas studied probably reflect the quality of leaf litter in these areas. The rate of decomposition can be predicted on the basis of the C:N ratio. Low litter C:N ratios facilitate the decomposition of litter by microorganisms, which results in increased CO_2 production observed at the eucalyptus and native species forests (Table 4). However, coniferous litter has low decomposition rate owing to its higher C:N ratio than that of broadleaf litter. The high lignin content in pine needles interferes with the carbon degradation speed (Gama-Rodrigues et al. 2005).

Xiao et al. (2019) reported that coniferous litter proportion had a negative effect on litter decomposition rate by decreasing litter N content. In addition, they showed that lower litter N content would have a negative effect on microorganism decomposers. This can result in lower levels of soil C and N stock. In addition to determining soil C stock, measuring H_{LFIS} is also important to identify management-induced changes in SOM quality (Bordonal et al. 2017). Thus, the highest H_{LIFS} found in the pine forest was coherent with C results, indicating that organic material is recalcitrant to decomposition (Table 4). Therefore, high indexes of humification were expected to be related to lower C contents (Martins et al. 2011). This caused the lowest rates of FCO_2 in pine, because organic matter is the primary source of energy used by soil microorganisms for metabolic processes to produce CO_2 (Moitinhoet al. 2015).

The organic matter content and carbon stock were higher in the eucalyptus forest, followed by those in native species forest, probably because of the higher root density and higher decomposition of fine roots of eucalyptus (Fabião et al. 1985; Kätterer et al. 1995). Pulrolnik et al. (2009) found higher C stock in

eucalyptus forest (3.62 Mg ha^{-1}) areas, unlike that in the Cerrado native forest (1.13 Mg ha^{-1}).

Notably, the decomposition of pine needles that compose the litter in pine forests releases organic acids (Lilienfein et al. 2000), contributing to lower pH values in the pine forest. More acidic soils tend to have lower concentrations of Ca, Mg, and K; low base saturation; and high Al and H + Al, which consequently influenced the decomposition of SOM. da Silva et al. (2017) obtained similar results in a eucalyptus forest, pines, and native Cerrado. The lower pH levels could also be a limiting factor for FCO_2 in our study area (Luo and Zhou 2006; Oertel et al. 2016).

As many factors influence FCO_2, our results support the idea that the intensity of FCO_2 was driven by soil physicochemical characteristics in the different types of forests. Eucalyptus and pine forests had higher-than-ideal values of bulk density for clay soil (Arshad et al. 1996). However, the total pore volume in eucalyptus forest was higher than that in pine forest, because of the higher macroporosity. Fang et al. (1998) showed that higher total porosity facilitates O_2 diffusion into the soil, favouring biological activity and thus increasing the FCO_2. Large pores contribute to the movement of all gases. Indeed, the high bulk density and low macroporosity in the pine forest soil (Table 3) limited gas exchange, because of the formation of an environment with low O_2 and thus biological activity (Li et al. 2002; Teixeira et al. 2012), which causes lower SR.

Cavenage et al. (1999) conducted studies in the same region as ours and investigated deforested areas; areas cultivated with annual crops (corn, soya, and cotton); and areas reforested with pines, eucalyptus, and native species and compared them with native Cerrado vegetation. They indicated that the soils under the native Cerrado area showed favourable physical properties and concluded that the intense use of agricultural machinery in the initial years of cultivation changed the physical properties of soil compared with that in the natural vegetation.

Ratio of soil CO_2 emission and O_2 absorption (RQ)

SR is conceptually divided into autotrophic and heterotrophic respiration. The measure of SR varies considerably. It mainly depends on the parameters of soil water content and temperature (Brookes 1995). Substrate respiration or respiration quotient (RQ) may be indicated as moles of CO_2 released/mol of O_2 absorbed. In addition, Dilly (2001) reported that RQ values close to 1 indicate that both CO_2 evolution in soil and O_2 absorption may be reliably used for the estimation of microbial biomass. Almeida et al. (2018) reported the use of FO_2 as an index for categorising the source of FCO_2 respiration.

Throughout the 193 days, the values of RQ for the three evaluated areas were often less than 1 (Fig. 2). Dilly (2003) assessed the soil of different agricultural and forest ecosystems in northern Germany and often found values of RQ < 1, indicating that O_2 consumption in these areas was higher than CO_2 emissions. Furthermore, the soil microbial physiology in those areas had a relatively high O_2 requirement for basal metabolism, suggesting that O-poor compounds were predominantly mineralised.

In soil, distinguishing whether CO_2 is produced by heterotrophic or autotrophic respiration is very difficult. However, the respiration of roots is considerably representative of total SR (Kursar 1989; Chen et al. 2011). The contribution of roots to total respiration depends on the vegetal species and climate. A synergy exists between both respirations, and they compete for the availability of nutrients and O_2 (Ben-Noah and Friedman 2018). Doran and Parkin (1984) and Almeida et al. (2018) also reported RQ > 1 values after rainfall events and increased soil water content. However, the RQ > 1 values observed in this study were not associated with rainfall events Table 7.

Almeida et al. (2018) showed that RQ values depend on different systems and soil conditions, soil crop residue management, and soil water content in tropical regions. However, soil management, environmental conditions, and nutritional factors may control soil metabolism (Dilly et al. 2003). According to Angert et al. (2014), estimating RQ under field conditions is challenging since the concentration of O_2 is 500 times greater than that of CO_2, and the dynamics between CO_2 and O_2 in the soil are considerably complex (Reichardt and Timm 2004).

PCA

Soil fertility was a predominant factor for differentiating the two sub-groups of group I (Fig. 3). Our findings were similar to those of Carvalho et al. (2018) conducted in different agricultural systems in the southern Amazon in Brazil. Soil fertility, pH, soil temperature, and soil water content are important regulators of microbial decomposition activity (Six et al. 2006) and can

Table 7 Eigen values, amount of explained variation, correlation coefficients, and eigenvectors of soil CO_2 emission and soil physical–chemical attributes for the first two principal components in the areas studied

Components	PC1	PC2
Eigen values	6.37	2.64
Explained variance	49.00	20.32
Accumulated variance	49.00	69.32
Correlation (Eigenvector)		
FCO2	0.60* (0.235)	0.13 (0.081)
Ts	0.14 (0.057)	0.87* (0.533)
SWC	0.39 (0.153)	−0.79* (−0.487)
SOM	0.78* (0.309)	0.45 (0.280)
pH	0.85* (0.339)	0.06 (0.040)
K	0.73* (0.291)	0.01 (0.006)
Ca	0.82* (0.324)	0.18 (0.113)
Mg	0.92* (0.365)	−0.06 (−0.038)
Al	−0.90* (−0.356)	−0.01 (−0.004)
Micro	−0.17 (−0.069)	−0.79* (−0.483)
BD	−0.70* (−0.271)	0.44 (0.270)
CN ratio	−0.60* (−0.238)	0.44 (0.269)
H_{LIFS}	−0.88* (−0.350)	−0.01 (−0.007)
Interpretation	Soil CO_2 emission and its transport and production factors	Contrast between soil temperature and soil water content (soil water content and microporosity)

FCO_2 soil CO_2 emissions; *Ts* soil temperature; *SWC* soil water content; *SOM* organic matter in the soil; *pH* potential of hydrogen; *K* concentration of exchangeable potassium; *Ca* concentration of exchangeable calcium; *Mg* concentration of exchangeable magnesium; *Al* aluminium content in the soil; *Micro* Microporosity; *CN ratio* CN ratio of litter; *H_{LIFS}* humification index

maximise soil biological activity. The CO_2 production and carbon sequestration in soil are influenced by chemical and physical soil properties (Lamparter et al. 2009; Bicalho et al. 2014).

In general, the formation of sub-groups Ia (eucalyptus) and Ib (pine) indicates that the type of forest strongly influences the soil physical–chemical properties, basal respiration, organic carbon concentration, nitrogen, pH, and litter amount (Graae et al. 2004; Zhou et al. 2013).

In CP1, a positive dependence relationship was noted between soil chemical attributes and temperature in the area. Conversely, an indirect dependence was noted between these attributes and C:N ratio, Bd, H_{LIFS}, and Al. The soil C:N ratio is an important soil attribute related to soil carbon quality. Thus, the higher is the C:N in soil, lower is the N content available, limiting the biological activity of the soil and thus SOM humification state, thereby influencing FCO_2 (Bicalho et al. 2014); this could have caused the lower values of FCO_2 observed in pine.

The lowest emissions of CO_2 in pine may also be related to the structural characteristics of soil since density is an important physical parameter to estimate the C stock: it is directly related to gas exchanges in the soil. Group II represented the main controlling factors of the variability of SR, soil temperature, and soil water content (Kang et al. 2003; Sá et al. 2001).

Conclusions

Our study showed that temporal variations in soil CO_2 emissions in reforested areas in the Brazilian Cerrado biome were influenced by edaphoclimatic conditions. The temporal variation pattern of SR was similar at all three study areas. At the beginning of the dry season, SR decreased in the three forest systems, and little variation was noted between sites.

The pine showed the lowest total soil CO_2 emissions (7.97 Mg ha^{-1}), whereas the eucalyptus and native species forests had emissions of 11.26 Mg ha^{-1} and

10.99 Mg ha^{-1}, respectively. The soil water content in the native species reforested area was 46.13% greater than that of the eucalyptus and 35% relative to that of the pine. The pine and eucalyptus forests exhibited the largest accumulation of organic material. The organic matter of *Pinus* had high humidification. Its lowest lability was derived mainly from pine needles and resulted in lower soil C stocks. The soil C stock was influenced by the type of forest and litter on the ground. The values in the 0.0 to 0.40 m soil depth in the pine, eucalyptus, and native forests were 41.84 Mg ha^{-1}, 55.39 Mg ha^{-1}, and 51.00 Mg ha^{-1}, respectively. The poor quality of the soil in the pine forest limited the production and transportation of soil CO_2. Oxygen absorption was similar in the three forest systems. In reforests planted over 30 years ago, SR was greater than soil CO_2 emission. These results indicate that the ratio of soil FCO_2 and FO_2 (i.e. RQ) > 1 is associated with the effect of SR by the root system. Our results suggest that the conversion of land-use influences soil carbon input as well as output—soil carbon dynamic—owing to the changes in soil attributes.

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References

Almeida RF, de Bortoli Teixeira D, Montanari R, Bolonhezi AC, Teixeira EB, Moitinho MR, Panosso AR, Spokas KA, La Scala Junior N (2018) 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

Angert A, Yakir D, Rodeghiero M, Preisler Y, Davidson EA, Weiner T (2014) Using O_2 to study the relationships between soil CO_2 efflux and soil respiration. Biogeosciences. https://doi.org/10.5194/bg-12-2089-2015

Arshad MA, Lowery B, Grossman B (1996) Physical tests for monitoring soil quality. In: Doran W, Jones J (eds) methods for assessing soil quality, Madison, WI. Soil Sci Soc am 49: 123–141 (special publication)

Ávila LF, Mello CR de Pinto LC, da Silva AM (2014) Partição da precipitação pluvial em uma microbacia hidrográfica ocupada por Mata Atlântica na Serra da Mantiqueira, MG. Ciênc Florest. https://doi.org/10.1590/1980-509820142403007

Bataglia OC, Furlani AMC, Teixeir PF, Furlani PR, Gallo JR (1983) Métodos de análises químicas de plantas. Campinas, Instituto Agronômico, p 48. (Boletim Técnico, 78)

Ben-Noah I, SP Friedman (2018) Review and evaluation of root respiration and of natural and agricultural processes of soil aeration. Vadose Zone J. https://doi.org/10.2136/vzj2017.06.0119

Bicalho ES, Panosso AR, Teixeira DDB, Miranda JGV, Pereira GT, La Scala N (2014) Spatial variability structure of soil CO_2 emission and soil attributes in a sugarcane area. Agric Ecosyst Environ 189:206–215. https://doi.org/10.1016/j.agee.2014.03.043

Bordonal RO, Lal R, Ronquim CC, de Figueiredo EB, Carvalho JLN, Maldonado Jr W, Milori DMBP, La Scala Jr N (2017) Changes in quantity and quality of soil carbon due to the land-use conversion to sugarcane (*Saccharum officinarum*) plantation in southern Brazil. Agric Ecosyst Environ. https://doi.org/10.1016/j.agee.2017.02.016

de Brito LF, Marques Júnior J, Pereira GT, Souza ZM, La Scala Júnior N (2009) Soil CO_2 emission of sugarcane fields as affected by topography. Sci Agric. https://doi.org/10.1590/S0103-90162009000100011

Brookes DC (1995) The use of microbial parameters in monitoring soil pollution by heavy metals. Biol Fertil Soils. https://doi.org/10.1007/BF00336094

Caride C, Piñeiro G, Paruelo JM (2012) How does agricultural management modify ecosystem services in the argentine Pampas? The effects on C dynamics. Agric Ecosyst Environ. https://doi.org/10.1016/j.agee.2011.05.031

Carvalho JLN, Cerri CEP, Feigl BJ, Piccolo MC, Godinho VP, Cerri CC (2009) Carbon sequestration in agricultural soils in the Cerrado region of the Brazilian Amazon. Soil Tillage Res. https://doi.org/10.1016/j.still.2008.10.022

Carvalho MAC, Panosso AR, Teixeira EER, Araujo EG, Brancaglioni VA, Dallacort R (2018) Multivariate approach of soil attributes on the characterization of land use in the southern Brazilian Amazon. Soil Tillage Res. https://doi.org/10.1016/j.still.2018.08.004

Cavenage A, Moraes MLT, Alves MC, Carvalho MAC, Freitas MLM, Buzetti S (1999) Alterações nas propriedades físicas de um Latossolo Vermelho-Es-curo sob diferentes culturas. Rev Bras Cien Solo. https://doi.org/10.1590/S0100-06831999000400027

Davidson EA, Belk E, Boone RD (1988) Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. Glob Change Biol. https://doi.org/10.1046/j.1365-2486.1998.00128.x

Davidson EA, Verchot LV, Cattânio JH, Ackerman LI, Carvalho JEM (2000) Effects of soil water content on soil respiration in forests and cattle pastures of eastern Amazonia. Biogeochemistry. https://doi.org/10.1023/A:1006204113917

Dermody O, Weltzin JF, Engel EC, Allen P, Norby RJ (2007) How do elevated [CO2], warming, and reduced precipitation interact to affect soil moisture and LAI in an old field ecosystem? Plant Soil. https://doi.org/10.1007/s11104-007-9443-x

Dilly O (2001) Microbial respiratory quotient during basal metabolism and after glucose amendment in soils and litter. https://doi.org/10.1016/S0038-0717(00)00123-1

Dilly O (2003) Regulation of the respiratory quotient of soil microbiota by availability of nutrients. Micron Ecol. https://doi.org/10.1111/j.1574-6941.2003.tb01078.X

Don A, Schumacher J, Freibauer A (2011) Impact of tropical land-use change on soil organic carbon stocks—a meta-analysis. Glob Change Biol. https://doi.org/10.1111/j.1365-2486.2010.02336.x

Doran JW, Parkin TB (1994) Defining and assessing soil quality. In: Doran JW, Coleman DC, Bezdicek DF, Stewart BA (eds) Defining soil quality for a sustainable environment. Madison, SSSA, pp 3–21

Ellert BH, Bettany JR (1995) Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can J Soil Sci 75(4):529–538

Embrapa—Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA-CNPS) (1997) Rio de Janeiro, Brazil Manual de métodos de análise de solo (In Portuguese) Centro Nacional De Pesquisa De Solos (2nd ed.). https://www.agencia.cnptia.embrapa.br/Repositorio/Manual+de+Metodos_000fzvhotqk02wx5ok0q43a0ram31wtr.pdf. Accesed June 2016

Fabião A, Persson HA, Steen E (1985) Growth dynamics of superficial roots in Portuguese plantations of *Eucalyptus globulus* Labill, studied with a mesh bag technique. Plant Soil. https://doi.org/10.1007/BF02184295

Fang C, Moncrieff JB, Gholz HL, Kenneth LC (1998) Soil CO_2 efflux and its spatial variation in a Florida slash pine plantation. Plant Soil. https://doi.org/10.1023/A:1004304309827

Fialho RC, Zinn YL (2014) Changes in soil organic carbon under eucalyptus plantations in Brazil: a comparative analysis. Land Degrad Dev. https://doi.org/10.1002/ldr.2158

Gama-Rodrigues EF, Barros NF, Gama-Rodrigues AC, Santos GA (2005) Nitrogênio, carbono e atividade da biomassa microbiana do solo em plantações de eucalipto. Rev Bras Cien Solo. https://doi.org/10.1590/S0100-06832005000600007

Gavrichkova O, Kuzyakov Y (2017). The above-belowground coupling of the C cycle: fast and slow mechanisms of C transfer for root and rhizomicrobial respiration. Plant Soil https://doi.org/10.1007/s11104-016-2982-2

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. Scientific World Journal. https://doi.org/10.1155/2014/141345

Graae BJ, Økland RH, Petersen PM, Jensen K, Fritzbøger B (2004) Influence of historical, geographical and environmental variables on understorey composition and richness in Danish forests. J Vege Sci. https://doi.org/10.1111/j.1654-1103.2004.tb02285

Hashimoto S, Tanaka N, Suzuki M, Inoue A, Takizawa H, Kosaka I, Tanaka K, Tantasirin C, Tangtham N (2004) Soil respiration and soil CO_2 concentration in a tropical forest. Eur J For Res. https://doi.org/10.1007/s10310-003-0046-y

Jassal RS, Blacka TA, 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. https://doi.org/10.1016/j.agrformet.2012.03.009

Jiang Y, Zang R, Lu X et al (2015) Effects of soil and microclimatic conditions on the community-level plant functional traits across different tropical forest types. Plant Soil 390: 351. https://doi.org/10.1007/s11104-015-2411-y

Johnson RA, Wichern DW (2002) Applied multivariate statistical analysis. Prentice Hall, New Jersey

Kang S, Doh S, Lee D, Lee D, Jin VL, Kimball J (2003) Topographic and climatic controls on soil respiration in six temperate mixed-hardwood forest slopes, Korea. Glob Chang Biol. https://doi.org/10.1046/j.1365-2486.2003.00668.x

Kätterer T, Fabião A, Madeira M, Ribeiro C, Steen E (1995) Fine-root dynamics, soil moisture and soil carbon content in an *Eucalyptus globulus* plantation under different irrigation and fertilization regimes. For Ecol Manag. https://doi.org/10.1016/0378-1127(95)03529-J

Kursar TA (1989). Evaluation of soil respiration and soil CO_2 concentration in a lowland moist forest in Panama. Plant Soil. https://doi.org/10.1007/BF02181917

Lamparter A, Bachmann J, Goebel M-O, Woche SK (2009) Carbon mineralization in soil: impact of wetting-drying, aggregation and water repellency. Geoderma. https://doi.org/10.1016/j.geoderma.2009.02.014

La Scala N, Marques J, Pereira GT, Cora JE (2000) Carbon dioxide emission related to chemical properties of a tropical bare soil. Soil Biol Biochem. https://doi.org/10.1016/S0038-0717(00)00053-5

La Scala Júnior N, Lopes A, Marques Junior J, Pereira GT (2001) Carbon dioxide emissions after application of tillage systems for a dark red latosol in southern Brasil. Soil Tillage Res. https://doi.org/10.1016/S0167-1987(01)00212-4

La Scala N, Bolonhezi D, Pereira GT (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. https://doi.org/10.1016/j.still.2005.11.012

Lal R (2009) Challenges and opportunities in soil organic matter research. Eur J Soil Sci. https://doi.org/10.1111/j.1365-2389.2008.01114.x

Li X, Inubushi K, Sakamoto K (2002) Nitrous oxide concentrations in Andisol profile and emissions to the atmosphere as influenced by the application of nitrogen fertilizers and manure. Biol Fertil Soils. https://doi.org/10.1007/s00374-002-0447-7

Li DJ, Niu SL, Luo YQ (2012) Global patterns of the dynamics of soil carbon and nitrogen stocks following afforestation: a meta analysis. New Phytologist. https://doi.org/10.1111/j.1469-8137.2012.04150.x

Lilienfein J, Wilcke W, Ayarza MA, Vilela L, Lima S do Zech, CW (2000) Soil acidification in *Pinus caribaea* forests on Brazilian savanna Oxisols. For Ecol Manage. https://doi.org/10.1016/S0378-1127(99)00143-7

Linn DM, Doran JW (1984) Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and no-tilled soils. Soil Sci Soc Am J. https://doi.org/10.2136/sssaj1984.03615995004800060013x

Luo Y, Zhou XU (2006) Soil respiration and the environment. Academic Press, Elsevier, San Diego, p 328

Martins T, Martins SC Saab, Milori DMBP, Brinatti AM, Rosa JÁ, Cassaro FAM, Pires LF (2011) Soil organic matter humification under different tillage managements evaluated by Laser Induced Fluorescence (LIF) and C:N ratio. Soil Tillage Res. https://doi.org/10.1016/j.still.2010.10.009

Metcalfe DB, Meir P, Aragão LEOC, Malhi Y, da Costa ACL, Braga A, Gonçalves PHL, de Athaydes L, de Almeida SS, Williams M (2007) Factors controlling spatio-temporal variation in carbon dioxide efflux from surface litter, roots, and soil organic matter at four rain forest sites in the eastern Amazon. J Geophys Res Atmos. https://doi.org/10.1029/2007JG000443

Milori DMBP, Galeti HVA, Martin-Neto L, Dieckow J, González-Pérez M, Bayer C, Salton J (2006) Organic matter study of whole soil samples using laser-induced fluorescence spectroscopy. Soil Sci Soc Am J. https://doi.org/10.2136/sssaj2004.0270

Moitinho MR, Padovan MP, Panosso AR, Teixeira DDB, Ferraudo AS, La Scala N (2015). On the spatial and temporal dependence of CO_2 emission on soil properties in sugarcane (*Saccharum* spp.) production. Soil Tillage Res. https://doi.org/10.1016/j.still.2014.12.012

Monteith JL, Unsworth MH (1990) Principles of environmental physics, 2nd edn. Edward Arnold, London, p 291

Moraes JFL, Volkoff B, Cerri CC, Bernoux M (1996) Soil properties under Amazon forest and changes due to pasture installation in Rondônia, Brazil. Geoderma. https://doi.org/10.1016/0016-7061(95)00072-0

Neira J, Ortiz M, Morales-Salinas L, Acevedo E (2015) Oxygen diffusion in soils: Understanding the factors and processes needed for modeling. Chil J Agr Res. https://doi.org/10.4067/S0718-58392015000300005

Oertel C, Matschullat J, Zurba K, Zimmermann F, Erasmi, S (2016) Greenhouse gas emissions from soils—A review. Chemie der Erde—Geochemistry. https://doi.org/10.1016/j.chemer.2016.04.002

Ohashi M, Makita N, Katayama A, Kume T, Matsumoto K, Kumagai T, Endo I, Khoon Kho L (2019) Characteristics of root decomposition based on in situ experiments in a tropical rainforest in Sarawak, Malaysia: impacts of root diameter and soil biota. Plant Soil. https://doi.org/10.1007/s11104-018-03929-3

Panosso AR, Pereira GT, Marques Junior J, La Scala Junior N (2008) Variabilidade espacial da emissão de CO_2 em Latossolos sob cultivo de cana-de-açúcar em diferentes sistemas de manejo. Eng Agríc. https://doi.org/10.1590/S0100-69162008000200003

Panosso AR, Ribeiro CER, Zanini JR, Pavani LC, Pereira GT, La Scala N (2009) Variabilidade espacial da emissão de CO_2, da temperatura e umidade de um latossolo desprovido de vegetação sob diferentes lâminas de molhamento. Semina: Ciênc. Agrár. https://doi.org/10.5433/1679-0359.2009v30n4Sup1p1017

Panosso AR, Marques J, Milori DMBP, Ferraudo AS, Barbieri DM, Pereira GT, La Scala N (2011) Soil CO_2 emission and its relation to soil properties in sugarcane areas under Slash-and-burn and Green harvest. *Soil Tillage* Res. https://doi.org/10.1016/j.still.2010.10.002

Pinto Júnior OB, Sanches L, Dalmolin AC, de Nogueira J S (2009) Efluxo de CO_2 do solo em floresta de transição Amazônia Cerrado e em área de pastagem. Acta Amazonica. https://doi.org/10.1590/S0044-59672009000400009

Pulrolnik K, Barros ND, Silva IR, Novais RF, Brandani CB (2009) Estoques de carbono e nitrogênio em frações lábeis e estáveis da matéria orgânica de solos sob eucalipto, pastagem e Cerrado no vale do jequitinhonha—Mg. Rev Bras Cien Solo. https://doi.org/10.1590/s0100-06832009000500006

R: A Language and Environment for Statistical Computing. (2019) R Core team, organization R Foundation for statistical computing, Vienna, Austria. https://www.R-project.org/. Accessed Aug 2016

Raich JW, Schlesinger WH (1992) The global carbon-dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus Ser B Chem Phys Meteorol. https://doi.org/10.1034/j.1600-0889.1992.t01-1-00001.x

Raich JW, Tufekciogul A. (2000) Vegetation and soil respiration: correlations and controls. Biogeochemistry. https://doi.org/10.1023/A:1006112000616

Raij BV (2001) Análise química para avaliação da fertilidade de solos tropicais. Campinas, Instituto Agronômico, p 285

Reichardt K, Timm LC (2004) Solo, planta e atmosfera: conceitos, processos e aplicações. Barueri, Manole, p 478

Roitman I, Bustamante MMC, Haidar RF, Shimbo JZ, Abdala GC, Eiten G, et al. (2018) Optimizing biomass estimates of savanna woodland at different spatial scales in the Brazilian Cerrado: Re-evaluating allometric equations and environmental influences. PLoS ONE. https://doi.org/10.1371/journal.pone.0196742

Rolim GS, Camargo MBP, Lania DG, Moraes JFL (2007) Classificação climática de Köppen e de Thornthwaite e sua aplicabilidade na determinação de zonas agroclimáticas para o estado de São Paulo. Bragantia. https://doi.org/10.1590/S0006-87052007000400022

Sá JCM, Cerri CC, Dick WA, Lal R, Filho SPVB, Piccolo MC, Feigl BE (2001) Organic matter dynamics and carbon sequestration rates for a tillage chronosequence in a Brazilian oxisol. Soil Sci Soc am J 65:486–1499. https://doi.org/10.2136/sssaj2001.6551486x

Santos CH, Romano RA, Nicodelli G, Carvalho CM, Villas-Boas PR Martin-Neto L Montes CR, Melfi AJ, Milori DMBP (2015) Performance evaluation of a portable laser-induced fluorescence spectroscopy system for the assessment of the humification degree of the soil organic matter. J Braz Chem Soc. https://doi.org/10.5935/0103-5053.20150039

Schwendenmann L, Veldkamp E, Brenes T, O'Brien JJ, Mackensen J (2003) Spatial and temporal variation in soil CO_2 efflux in an old-growth neotropical rain forest, La Selva. Costa Rica Biogeochemistry doi 64:111–128. https://doi.org/10.1023/A:1024941614919

da Silva BE, Moitinho MR, Teixeira De Bortoli D, Panosso AR, Spokas KA, La Scala N (2017) Soil greenhouse gases: relations to soil attributes in a sugarcane production area. Soil Sci Soc Am J 81. https://doi.org/10.2136/sssaj2017.02.0043

Siqueira Neto M, Piccolo MDC, Costa Junior C, Cerri CC, Bernoux M (2011) Greenhouse gas emission caused by different land-uses in Brazilian Savannah. Rev Bras Cien Solo. https://doi.org/10.1590/S0100-06832011000100006

Six J, Frey SD, Thies RK, Batten KM (2006) Bacterial and fungal contributions to carbon sequestration in agroecosystems. Soil Sci Soc Am J https://doi.org/10.2136/sssaj2004.0347, 70

Smagin AV, Dolgikhb AV, Karelin DV (2016) Experimental studies and physically substantiated model of carbon dioxide emission from the exposed cultural layer of Velikii Novgorod. Eurasian J Soil Sci. https://doi.org/10.1134/S1064229316040116

Smart DR, Penuelas J (2005) Short-term CO_2 emissions from planted soil subject to elevated CO_2 and simulated precipitation. Appl Soil Ecol. https://doi.org/10.1016/j.apsoil.2004.07.011

Soil Survey Staff (2014) 'Keys to soil taxonomy,' 12th edn. United States Department of Agriculture, United States of America

Sotta ED, Meir P, Malhi Y, Nobre AD, Hodnett M, Grace J (2004) Soil CO_2 efflux in a tropical forest in the central Amazon. Glob Change Biol. https://doi.org/10.1111/j.1529-8817.2003.00761.x

Stern L, Baisden WT, Amundson R. (1999) Processes controlling the oxygen isotope ratio of soil CO_2 analytic and numerical modeling. Geoch Cosmochim Acta. https://doi.org/10.1016/S0016-7037(98)00293-2

Tang J, Baldocchi D, Xu L (2005) Tree photosynthesis modulates soil respiration on a diurnal time scale. Glob Chang Biol. https://doi.org/10.1111/j.1365-2486.2005.00978.x

Tedesco MJ, Gianello C, Bissani CA, Bohnen H, Wolkweiss SJ (1995) Análises de solo, plantas e outros materiais, 2nd edn. Universidade Federal do Rio Grande do Sul, Porto Alegre

Teixeira DDB, Bicalho ES, Panosso AR, Perillo LI, Iamaguti JL, Pereira GT, La Scala N (2012) Uncertainties in the prediction of spatial variability of soil CO_2 emissions and related properties. Rev Bras Cienc Solo. https://doi.org/10.1590/S0100-06832012000500010

Van Straaten O, Veldkamp E, Köhler, M Anas I (2010) Spatial and temporal effects of drought on soil CO_2 efflux in a cacao agroforestry system in Sulawesi, Indonesia. Biogeosciences. https://doi.org/10.5194/bg-7-1223-2010

Warrick AW, Nielsen DR (1980) Sapatial variability of soil physical properties in the field. In: Hille LD (ed) Application of soil physics. Academic Press, New York, pp 319–344

Whittaker ET, Robinson G (1967) Trapezoidal and Parabolic rules. A Trease of Numerical Mathematics, Dover, NY, The Calculus Observation

Xiao W, Chen HYH, Kumar P, Chen C, Guan Q (2019) Multiple interactions between tree composition and diversity and microbial diversity underly litter decomposition. Geoderma. https://doi.org/10.1016/j.geoderma.2019.01.045

Zanchi FB, Waterloo MJ, Kruijt B, Kesselmeier J, Luizão FJ, Manzi AO, Dolman AJ (2012) Soil CO_2 efflux in central Amazonia: environmental and methodological effects. Acta Amazon. https://doi.org/10.1590/S0044-59672012000200001

Zhang L, Dawes WR, Walker GR (1999). Walker predicting the effect of vegetation changes on catchment average water balance tech. Rep. 99/12 coop. Res. Cent. For catch. Hydrol., Canberra, ACT (1999)

Zhou Z, Zhang Z, Zha T, Luo Z, Zheng J, Sun OJ (2013) Predicting soil respiration using carbon stock in roots, litter and soil organic matter in forests of Loess Plateau in China. Soil Biol Biochem. https://doi.org/10.1016/j.soilbio.2012.08.010

Zinn YL, Resck DVS, Silva JE (2002) Soil organic carbon as affected by afforestation with Eucalyptus and Pinus in the Cerrado region of Brazil. https://doi.org/10.1016/S0378-1127(01)00682-X