CO_2, N_2O and CH_4 Emissions and C Storage in Eucalyptus Forests with Different Managements of Harvest Residues

Raphael Oliveira de Melo (raphael.o.melo@ufv.br)
UFV: Universidade Federal de Vicosa
Nairam Felix de Barros
UFV: Universidade Federal de Vicosa
Rafael Silva Teixeira
UFV: Universidade Federal de Vicosa
Aymbire Angeleti Fonseca
UFV: Universidade Federal de Vicosa
Samuel Vasconcelos Valadares
UFV: Universidade Federal de Vicosa
Ricardo Previdente Martins
BRACELL
Iago Nery Melo
BRACELL

Research Article

Keywords: Eucalyptus plantations, Climate Change, GHG emission, Organic Matter

Posted Date: March 2nd, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1312926/v1

Abstract

The objective of this study was to evaluate CO_2, N_2O and CH_4 fluxes and C fixation in the soil-plant system, in an area with different managements of eucalyptus harvest residues. Before the experiment was set up, a plot was selected at the end of the third rotation (5 years) and harvested using the Harvester + Forwarder system. After harvest, the coppicing system was adopted and three types of residue management were established: 1. Maintenance of all harvest residues and litter from the previous rotation (HR+L), 2. Maintenance of litter from the previous rotation (L), 3. Removal of harvest residues and litter from the previous rotation (WR). Soil gas flux was sampled 5 days before harvest and at 4 times (distributed along the dry and rainy seasons) over 22.3 months. To collect the gases, PVC chambers were introduced into the soil to a depth of 5 cm in the planting rows and inter-rows. Subsequently, the gas samples were analyzed by gas chromatography. To evaluate C inputs in the system, the quantity of C in the plants and organic matter content in the first ten centimeters of soil were quantified at the end of the experiment (22.3 months). There was higher CO_2 equivalent flux in the soil in the area with HR+L at 0.3 and 9.3 months after harvest, with no differences between the treatments WR and L. CO_2 equivalent fluxes were similar among all treatments in the samplings performed at 15.8 and 22.3 months after harvest. No differences were observed in the treatments regarding organic matter content in the soil and C fixation in plant biomass.

1. Introduction

Increased global temperature has been mainly attributed to the increase in the concentration of greenhouse gases (GHG) in the atmosphere. According to the According to the World Meteorological Organization (2015), since the first industrial revolution, the overall concentrations of the three main GHGs (CO_2, CH_4 and N_2O) have increased by 144, 256 and 121%, respectively. Brazil is the fifth country that most contributes to GHG emissions, and soils managed under agriculture and forestry production account for 32% of total emissions [1]. These figures indicate that soil is a strategic compartment in the combat of climate change [2].

The management adopted in planted forests can potentiate or mitigate GHG emissions to the atmosphere [3, 4] Conservation cropping systems, which focus on the input of residues and reduce soil turning, can maintain or even increase C stocks in the soil [5]. Planted forests produce large amounts of plant residues, especially during the harvesting operation, mainly composed of branches, bark, tips and leaves. Approximately 20% of eucalyptus biomass turns into residues at harvest [6].

The use of forest residues for energy generation has intensified in several countries due to increased energy demand, exhaustion of non-renewable sources and pressure for greater use of “clean” energy sources [7]. In Brazil, several forestry companies consider the possibility of fully or partially collecting eucalyptus residues with a view to their utilization for energy production [8, 6, 9].

In 2015, in the Paris agreement, Brazil pledged to increase by 18% the share of biomass in primary energy production and reach 45% of renewable energy use [9]. The country has great potential for energy generation using forest biomass, as it has about 7.8 million hectares of planted forests, edaphoclimatic conditions favorable to high forest productivity, availability of area and technology [10].

The removal of residues from forest harvest affects soil microbiota [11, 12, 13], reducing nutrient cycling [14, 15] and also reducing C stocks in the soil [12, 16]. Conversely, the permanence of forest residues in the area reduces erosive processes [17], and decreases soil compaction during the traffic of machines and implements [18, 19]. On the other hand, their permanence may increase CO_2, CH_4 and N_2O emissions in the short term, since in the initial stages of decomposition significant fractions of C and N present in plant residues return to the atmosphere in oxidized forms [14, 20].

GHG emission in forest plantations is the result of the balance between C inputs and outputs to the atmosphere in oxidized form (CO_2 and CH_4), with N_2O also being an important greenhouse gas, and the N present in agricultural residues has a considerable contribution to the emissions of this GHG [21]. C inputs into the system occur through photosynthesis, and part of this fixed C is transferred to the soil and transformed into stable organic matter during plant decomposition. The outputs occur through root respiration and soil microorganisms [22].

In general, studies conducted in Brazil show that eucalyptus planted forests reduce the potential for global warming, due to the accelerated growth of plant biomass and, in most cases, due to the conservation soil tillage techniques adopted, which in turn reduce the respiration of soil microorganisms [11]. There are few studies relating forest residue management and greenhouse gas emissions; consequently, the effects of retention or removal of eucalyptus harvest residues on GHG emissions are still not conclusive.

Thus, in this study the following hypotheses were evaluated: i) the retention of harvest residues increases CO_2, CH_4 and N_2O emissions in the short term in the soil; ii) the removal of eucalyptus harvest residues from the area reduces C stock in the soil-plant system.

In view of the above, this study aimed to evaluate the fluxes of CO_2, CH_4 and N_2O, in addition to the C stored in the forest and in the soil surface (0-10 cm layer), in an area subjected to different managements of eucalyptus harvest residues.

2. Material And Methods

2.1. Experimental design

The experiment began in the first half of 2019 (Figure 1) and was carried out in commercial eucalyptus plantations belonging to BRACELL company, located in the municipality of Entre Rios-BA (38°3'36" S and 12°1'17" W at 180 m altitude; Figure 2). The relief of the area is flat and the climate is predominantly Af type (humid tropical), with average annual precipitation of 1,250 mm. The original natural vegetation cover is Atlantic Forest, but currently there is a

predominance of pastures and commercial eucalyptus forests. The soil of the experimental area is classified as cohesive *Argissolo Amarelo* (Santos et al., 2018), which corresponds to Ultisol in Soil Taxonomy (Soil Survey Staff, 2014) (Table 1).

Table 1
Chemical and physical characteristics of the cohesive Ultisol, in samples collected in the row (R) and inter-row (IR) of eucalyptus plantations at different dept 100 cm)

Position*	Soil layer	pH	TOC	P	K	Ca	Mg	S	Al	V	Sand	Silt
	Cm		%	mg dm^{-3}	———— $cmol_c$ dm^{-3} ————					%	————kg kg^{-1}——	
	0-10	$6.21^{\pm0.60}$	$1.27^{\pm0.23}$	$3.45^{\pm0.58}$	$53.25^{\pm6.74}$	$3.80^{\pm1.24}$	$0.43^{\pm0.07}$	$4.03^{\pm1.85}$	$0.00^{\pm0.00}$	$70.23^{\pm15.2}$	$0.75^{\pm0.02}$	$0.01^{\pm0.01}$
	10-20	$5.93^{\pm0.67}$	$1.11^{\pm0.07}$	$2.55^{\pm0.58}$	$45.50\pm^{9.15}$	$3.21^{\pm0.97}$	$0.35^{\pm0.06}$	$4.28^{\pm2.35}$	$0.05^{\pm0.09}$	$61.60^{\pm17.4}$	$0.73^{\pm0.02}$	$0.01^{\pm0.01}$
R	20-40	$5.68^{\pm0.83}$	$0.89^{\pm0.04}$	$1.48^{\pm0.19}$	$52.75\pm^{12.54}$	$2.43^{\pm1.14}$	$0.27^{\pm0.07}$	$6.13^{\pm6.14}$	$0.17^{\pm0.22}$	$50.55^{\pm20.8}$	$0.66^{\pm0.04}$	$0.01^{\pm0.01}$
	40-60	$5.25^{\pm0.63}$	$0.70^{\pm0.09}$	$0.60^{\pm0.44}$	$57.5\pm^{19.72}$	$1.46^{\pm0.70}$	$0.20^{\pm0.07}$	$19.6^{\pm11.10}$	$0.45^{\pm0.34}$	$36.58^{\pm15.2}$	$0.56^{\pm0.05}$	$0.01^{\pm0.01}$
	60-100	$4.98^{\pm0.55}$	$0.48^{\pm0.09}$	$0.13^{\pm0.19}$	$30.00\pm^{12.89}$	$1.12^{\pm0.73}$	$0.18^{\pm0.07}$	$34.58^{\pm9.18}$	$0.57^{\pm0.41}$	$30.80^{\pm17.0}$	$0.49^{\pm0.03}$	$0.01^{\pm0.01}$
	0-10	$6.04^{\pm0.20}$	$1.40^{\pm0.01}$	$4.55^{\pm1.67}$	$34.50\pm^{5.49}$	$3.83^{\pm0.30}$	$0.60^{\pm1.26}$	$3.33^{\pm0.45}$	$0.00^{\pm0.00}$	$68.03^{\pm6.91}$	$0.76^{\pm0.02}$	$0.01^{\pm0.01}$
	10-20	$5.84^{\pm0.15}$	$1.13^{\pm0.13}$	$4.65^{\pm2.10}$	$27.00\pm^{4.90}$	$3.03^{\pm0.33}$	$0.49^{\pm0.19}$	$3.40^{\pm0.60}$	$0.00^{\pm0.00}$	$58.98^{\pm4.60}$	$0.70^{\pm0.03}$	$0.01^{\pm0.01}$
IR	20-40	$5.29^{\pm0.20}$	$0.75^{\pm00.07}$	$2.95^{\pm3.41}$	$24.50^{\pm1.90}$	$1.70^{\pm0.03}$	$0.33^{\pm0.06}$	$11.78^{\pm2.60}$	$0.24^{\pm0.05}$	$41.40^{\pm4.86}$	$0.57^{\pm0.02}$	$0.01^{\pm0.01}$
	40-60	$5.05^{\pm0.21}$	$0.58^{\pm0.20}$	$0.35^{\pm0.33}$	$30.50^{\pm19.28}$	$1.31^{\pm0.48}$	$0.26^{\pm0.04}$	$20.90^{\pm2.43}$	$0.52^{\pm0.25}$	$34.83^{\pm6.34}$	$0.49^{\pm0.03}$	$0.01^{\pm0.01}$
	60-100	$4.90^{\pm0.21}$	$0.62^{\pm0.20}$	$0.25^{\pm0.24}$	$33.75^{\pm24.77}$	$1.28^{\pm0.89}$	$0.22^{\pm0.05}$	$32.68^{\pm5.25}$	$0.43^{\pm0.35}$	$30.50^{\pm11.5}$	$0.46^{\pm0.07}$	$0.01^{\pm0.01}$

pH in water (1:2.5 ratio); P and K (Mehlich-1 extractant); Ca^{+2}, Mg^{+2} and Al^{3+} (1 mol L^{-1} KCl extractant); V = (SB/T) x 100; Organic Carbon – Walkley-Black; Pa the pipette method (Ruiz, 2005); θ FC: moisture at field capacity, with matric potential of -10KPa; θ PWP: moisture at the permanent wilting point, with matric deviation around the means (n=4).

A plot with clone 1404 (*Eucalyptus urophylla* x *E. grandis)* was selected at the end of the third rotation (5 years), originally planted at a spacing of 4.0 x 2.4 m. The cut was performed with a Harvester and the wood was removed with a Forwarder. Next, the residues on the soil were treated in three ways (treatments): i) Maintenance of harvest residues (HR: leaves, branches and bark) and litter (L): (HR+L); ii) Maintenance of litter (L); and iii) Removal of residues (WR). In the HR+L management, 24.0 Mg ha^{-1} of dry matter of HR (13, 34 and 53% of weight corresponded to leaves, branches and bark, respectively) and 10.7 Mg ha^{-1} of dry matter of L (35 and 65% of weight corresponded to leaves and branches, respectively) were kept on the soil. Thinning was performed when the sprouts were between 1.0 and 2.0 m tall, leaving only the most vigorous sprout per stump.

The experimental design used was randomized blocks, with four replicates. The plot (1,380 m^2) established after harvest was composed of 144 plants (12 x 12), considering the 64 central plants (8 x 8, 614 m²) as usable plot.

2.2. GHG sampling in soil

GHG (CO_2, CH_4 and N_2O) emissions were measured in five seasons: one in pre-harvest (5 days before harvest) and four in post-harvest, at 0.3, 9.3, 15.8 and 22.3 months after harvest (MAH), with two evaluations in the rainy season (0.3 and 15.8 MAH) and two in the dry season (9.3 and 22.3 MAH) (Figure 1).

Static chambers made with PVC rings (20 cm high and 30 cm diameter) were installed to collect GHGs in the soil. The chambers were allocated in duplicate in each of the positions corresponding to the rows (R) and inter-rows (IR). At the time of gas sampling, the chambers were closed with PVC caps with rubber septum on the top, which allowed the collection of gases inside the chamber and restricted the passage of air from the soil to the atmosphere [23]. The gases were collected at intervals of 0, 10, 20, 40 minutes after closing the chambers, using 60-mL syringes equipped with three-way stopcock valves, which were closed after the collection of gases for storage.

At the time of gas collection, near each chamber, measurements of temperature (ºC) and soil moisture (%, v v^{-1}) were taken at 5 cm depth using the EC-5 sensor (Decagon Devices Inc., Pullman, WA).

After collection, the gas samples were taken to the laboratory to determine the concentrations of CO_2, CH_4 and N_2O in a gas chromatograph equipped with mass spectrometer (GCMSQP2010SE – Shimadzu Corporation). Soil CO_2, CH_4 and N_2O fluxes were calculated according to Equation 1, proposed by [24].

$$Flux = \frac{\frac{\Delta Q}{\Delta t} xMxPxV}{RxTsxA}$$ *Equation 1*

Where, $\Delta Q/\Delta t$ is the angular coefficient (ppm s^{-1}), obtained from the adjustment of gas concentrations over the predetermined collection time; M is the molar mass of the gas (g mol^{-1}); P is the constant pressure of 1 atm; V is the volume of the chamber (L); R is the gas constant (0.08205746); Ts is soil temperature (K) and A is the area of the chamber (m^2).

To measure the potential of global warming, CO_2 equivalent (CO_2eq) was calculated by multiplying the seasonal emissions of N_2O and CH_4 by the respective radioactive potentials [25], according to Equation 2.

$CO_2eq = (25 \times CH_4) + (298 \times N_2O) + (1 \times CO_2)$ *Equation 2*

To estimate the gas flux in the area (ha^{-1}), a weighted average was applied, considering the coverage area of each sampling position. In the experiment, the planting row was 1.10 m wide, totaling an area of 2,750 m^2 ha^{-1}, while the remainder, 7,250 m^2 ha^{-1}, was considered to be inter-rows. Thus, it was possible to create weights of 27.5 and 72.5% for planting row and inter-row, respectively.

At 22.3 MAH, soil samples were collected in the 0-10 cm layer to determine the total organic C content of the soil (TOC) by the Walkley-Black method and total N (TN) by the Kjeldahl method [26]. The collections were performed in the rows and inter-rows.

To evaluate the impacts of the wood harvesting and forwarding operation (traffic of HV and FW, respectively) on bulk density, associated with compaction and with the consequent effects on soil C storage, the area was subdivided into four blocks. In each block, three random points were selected, in the rows and inter-rows of the plantation, for the collection of undisturbed soil samples. Sampling was performed, before and after harvest, using cylindrical rings of approximately 5 cm in height and diameter, in the center of the 0-10, 10-20, 20-40, 40-60 and 60-100 cm layers. These samples were used to evaluate soil bulk density (Ds), according to [26] (Figure 3). Thus, with the TOC and TN contents and Ds (Figure 3), it was possible to calculate the stocks of TOC and TN for the 0-10 cm layer after 22.3 MAH (Equation 3).

TOC or TN stock (Mg ha^{-1}) = (TOC or TN x Ds x h) x 10 *Equation 3*

Where, TOC is the total organic carbon content at 0-10 cm depth (g kg^{-1}); TN is the total nitrogen content at 0-10 cm depth; Ds is bulk density of the 0-10 cm layer (g cm^{-3}); and h is the thickness of the layer considered (cm). To consider the values per unit of area (ha^{-1}), a weighted average was applied, considering the coverage area of each sampling position, 27.5 and 72.5% for planting row and inter-row, respectively.

2.3. Decomposition of residues

Decomposition chambers made of PVC pipe (25 cm height and 10 cm diameter), containing nine holes with 5 cm in diameter and distributed on the lateral surface of the pipe, constituted the microplots. Each pipe was covered with 2-mm-mesh steel screen to allow roots to enter. At the top of the pipe, six holes of 2 cm in diameter, located 20 cm high, were opened to allow the entry and exit of soil fauna [27; 11; 28; 29; 30]. The inside of the pipe was filled with undisturbed soil, collected from the 20 cm layer of a natural pasture area adjacent to the experiment (Table 2). The pipes were transported to the experimental area and inserted into the soil to a 20 cm depth, so that the lateral holes were at the soil surface level (Figure 3).

On the surface of the pipe (above the soil surface), the amounts of plant residues referring to each plot of the treatment were deposited. The amounts were calculated based on area proportions (Table 3). The upper part of the pipes was then covered with plastic screen (1 x 1 cm mesh) to prevent the entry of any material that did not constitute the treatments.

In each experimental plot, three pipes were installed (Figure 4). One pipe was collected at each evaluation time after imposing the treatments: 6.3, 13.0 and 19.2 months. At the moment of collection at each evaluation time, plant residues were removed from the pipes, taken to a forced ventilation oven at 65°C and kept until reaching constant weight. Before weighing to determine the mass loss, the residues were cleaned with a brush, to remove the adhered soil. Then, the C and N contents of the residues in each evaluation season were determined via dry combustion (Perkin Elmer, PE-2400). The contents of C and N and the weight of the remaining dry matter of the residues were used to determine the quantities of these elements.

The half-life time ($T_{1/2}$) of the quantities of C and N present in the residues in each treatment (Table 2) was calculated using an exponential mathematical model described by [31], of the type $X = X_o\ e^{-kt}$, where X is the quantity of C and N remaining after a period of time t, in months; Xo is the initial quantity of C and N; and k is the constant of decomposition of the residue. The value of k was used to calculate the half-life time ($T_{1/2} = 0.693/k$) [32].

Table 2
Dry matter weight of the components of the residues (litter and harvest residues) placed in the decomposition chambers, and contents, quantities and half-life time ($T_{1/2}$) of carbon (C) and nitrogen (N) of the residues of each treatment: without residues (WR), litter (L) and harvest residue + litter (HR+L)

Treatments	Litter		Harvest residues			Content			Quantity		$T_{1/2}$	
	Leaf	Branch	Leaf	Bark	Branch	C	N	C/N	C	N	C	N
	———— g pipe^{-1} ————					——— % ———			– Mg ha^{-1}–		months	
WR	-	-	-	-	-	-	-	-	-	-	-	-
L	1.2	2.2	-	-	-	45.6	0.51	130.0	5.12	0.04	8.5	8.5
HR + L	1.2	2.2	1.0	4.0	4.7	47.7	0.37	91.5	15.8	0.18	9.3	5.9

2.4. Plant analyses

2.4.1. Analysis of residues and litter collected at the beginning of the experiment

The weight of the harvest residues was determined by quantifying the biomass of five trees whose diameters and heights corresponded to those of the average tree, felled 10 days after harvesting the stand. Leaves, bark, branches and tips were weighed. Litter was quantified seven days prior to harvest using a quadrangular metal frame (0.5 m^2), with the separation of leaves and branches to determine their weights. Twenty-four random samplings were carried out in the entire experimental area. Samples of the plant material from the harvest residues and litter were dried in an oven with closed circulation and air removal at 65°C until reaching constant dry weight. Subsequently, the material was weighed to obtain the dry matter weight.

2.4.2. Analysis of tree biomass and litter

At the end of the experiment, 22.3 months after harvest, a tree with average diameter at breast height (DBH) of each experimental plot was selected and felled. The plant was divided into five parts: leaves, branches, trunk, bark and roots. Leaves, branches, trunk and bark were weighed in the field to obtain the fresh weight. Samples of leaves, branches, sawdust and bark were collected to determine the dry weight. Sawdust and bark were sampled at three different points corresponding to 33%, 66% and 99% of the total height. Leaves and branches were randomly sampled along the canopy. Litter was also sampled when the trees were felled, using a quadrangular metal frame (0.5 m^2). Four random samplings were performed in each experimental plot. Fresh weight was determined in the field, and a sample was collected to determine the dry weight.

At the time of felling of the selected tree, roots that were in the first 40 cm depth of ¼ of the area occupied by the tree were sampled using a probe with collection capacity of 886 cm³ of soil. There were four collection points with predefined spacings in the planting rows and inter-rows (Figure 5). The collected soil was transported to the laboratory for manual collection of roots, and then this material was washed and taken to a forced circulation oven (65 ºC) to determine the dry weight. The C contents of the samples (root, litter, trunk, bark, branch and leaf) were determined by dry combustion (Perkin Elmer, PE-2400).

2.5. C balance

C balance, according to the treatments, was calculated as the difference between the average CO_2 equivalent emissions during the experimental period and the C inputs during the experiment (22.3 months). C emissions were calculated using the averages of CO_2 equivalent observed at 0.3, 9.3, 15.8 and 22.3 months after the experiment was set up. The average obtained in each treatment was multiplied by the number of experiment days (675) and number of hours in one day (24), according to equation 4.

C emission (Mg ha^{-1}) = average CO_2 equivalent (kg ha^{-1} h^{-1}) x 675 x 24 / 1000 *Equation 4*

The conversion of CO_2 to C was based on the molecular weights of the elements. The results obtained in CO_2 equivalent were multiplied by a conversion factor (0.272), considering that one mol of CO_2 contains 12.011 and 15.999 g of C and O, respectively.

C immobilization includes the C content of the biomass of eucalyptus at 22.3 months, and Δ C of the 0-10 cm soil layer, obtained through the differences between the C stock at the beginning of the experiment (collection performed at pre-harvest) and at the end (collection performed 22.3 months after imposition of treatments).

2.6. Statistical analysis

The obtained data were subjected to analysis of the assumptions of parametric statistics, through the Shapiro-Wilk test, to evaluate the homoscedasticity, and Hartley test to verify the normality of the data. Next, the data were subjected to analysis of variance and the means were compared by Tukey test at 5% probability level. Statistical analyses were performed in R software version 4.0.0 [33]. The results of soil temperature, moisture and GHG fluxes were subjected to Pearson's linear correlation analysis.

3. Results And Discussion

3.1 CO_2 fluxes

The mean variation of soil CO_2 flux (CO_2-F) for the residue management systems during the experimental period ranged from 0.7 to 1.3 kg ha^{-1} h^{-1} (Figure 6-A1). The results are consistent with CO_2-F values found in other studies carried out in commercial eucalyptus forests in Brazil: 1.19 - 1.82 kg ha^{-1} h^{-1} [34]; 1.31 - 1.56 kg ha^{-1} h^{-1}[35]; 1.28 kg ha^{-1} h^{-1} [36]; 0.75 - 1.51 kg ha^{-1} h^{-1} [37].

The higher CO_2 fluxes (CO_2-F) in areas with HR+L, observed at 0.3 and 9.3 months after harvest (MAH) (Figure 6-A1), are due to the greater amounts of residues present in this treatment, which increases the rate of microbial activity. In a similar study, [14] found average CO_2-F of 0.93 kg ha^{-1} h^{-1} in an area without residues and 1.50 kg ha^{-1} h^{-1} in an area where eucalyptus harvest residues and litter from the previous rotation were left. The increase in the population of soil microbial biomass is associated with the amounts of decomposable residues left in the area [38, 12], which must have occurred in the period corresponding to 15.8 and 22.3 MAH, leading to a reduction in CO_2-F (Figure 7A1). Similar results were observed by [39], who found that, immediately after sugarcane harvest, CO_2 emissions increased linearly with the increase in the amount of straw deposited on the soil, followed by a decrease six months after the deposition of plant residues on the soil.

In the area where all residues were removed (WR), at 9.3 MAH, CO_2-F was equal to 1.11 kg ha^{-1} h^{-1}, being higher than that of the L treatment and similar to that of the HR+L treatment. The higher fluxes may also have been stimulated by higher soil temperature (Ts) (Table 3). The sampling performed at 9.3 MAH coincided with the dry period, when high temperatures are recorded (Figure 1). Additionally, in this sampling period, the soil was more exposed to solar radiation, considering the low size of the plants and, consequently, less shading. The uncovered soil, without the presence of residues, is more exposed to solar radiation, which in turn increases Ts [40]. Increments in Ts stimulate microbial respiration, which in turn increases CO_2 emissions to the atmosphere [41, 42]. [43] observed that there was higher CO_2-F in soils that were uncovered and without plant residues due to higher Ts values.

In the treatment where only litter from the previous rotation was left (L), the CO_2-F remained constant as a function of the collection times (Figure 6-A1). Litter has a greater amount of materials with higher degree of recalcitration, in which most of the labile C has already suffered interference from decomposer microbial activity [44]. C:N ratio in the L treatment was 42% higher than in the HR+L treatment. In addition, the quantity of C is three times lower in L (Table 2).

Throughout the experiment, regardless of the treatments, higher ($p < 0.05$) CO_2-F values were observed in the planting rows compared to the inter-rows, even at 9.3 MAH (Figure 6-A2). Eucalyptus planting rows have higher CO_2-F than the inter-rows [11, 23]. [45] noted a gradual increase in GHG emissions as the samplings approached the base of the pine tree.

Planting rows are sites with higher root volume, due to the proximity of the stumps; in addition, the growth of the trees is favored by the better physical conditions of the soil promoted by minimum tillage [46] particularly in cohesive soils such as that of the present experiment [47]. Moreover, fertilization in eucalyptus plantations is directed to the planting row region [48]. Greater amounts of roots increase CO_2-F as a consequence of root respiration [49]. The higher CO_2-F levels found in the planting rows at 0.3 and 9.3 MAH may result, although partially, from the death and renewal of the roots of sprouts. [50] suggest that, up to 60 days after cutting eucalyptus trees, there is high mortality of thin roots in the 0.0-1.0 m layer, which contributes to C supply along the soil profile. The rhizosphere is a site enriched with exudates, mucilage, lysates and secretions that can be used as substrate by the various groups of soil microorganisms, in interactions developed with the root system [51].

Another factor that may explain the higher CO_2-F observed in the planting rows compared to the inter-rows is the lower bulk density (Ds) found in this position in all soil layers evaluated (Figure 3). High Ds, and the consequent decrease in soil porous space, limits the diffusion of gases [52, 53] After harvest, there was a significant increase in Ds in the 0-10 and 60-100 cm layers in the inter-rows (Figure 4). The same did not occur in the planting rows, since machine traffic occurs predominantly in the inter-rows [54].

No significant correlation was observed between CO_2-F and soil moisture and temperature (Table 4). The results of the present study differ from those reported by [2, 53, 55] Neto et al. (2011), Bicalho et al. (2017) and Vicentini et al. (2019), who found significant correlations between soil moisture and temperature and CO_2-F. However, these studies evaluated the influence of soil moisture and temperature as well as CO_2-F separately, without the presence of organic residues. This is evidence that, in this case, the decomposition of organic residues in the soil also influences carbon dioxide emissions, as well as soil moisture and temperature. [14] conducting an experiment in tropical environment, as in the present study, found no influence of eucalyptus harvest residues on soil moisture and temperature in most of the experimental time (2 years).

3.2 CH_4 fluxes

The observed CH_4 fluxes ranged from 0.001 to -0.0006 kg ha^{-1} h^{-1} (Figure 6C1), with magnitude similar to that found in other experiments in commercial eucalyptus forests: -0.00002 to -0.00015 kg ha^{-1} h^{-1} [57]; 0.0027 to -0.0028 kg ha^{-1} h^{-1} [58]; -0.00010 to -0.0009 kg ha^{-1} h^{-1} [59]; 0.0001 to -0.0006 kg ha^{-1} h^{-1} [60]; -0.0002 to -0.0007 kg ha^{-1} h^{-1} [61].

In this study, the CH_4 fluxes to the atmosphere (CH_4-F), or influxes to the soil (CH_4-I), were temporarily related to the presence of plant residues on the soil (Figure 6-B1). The highest CH_4-F values (0.0009 kg ha^{-1} h^{-1}) were found in the pre-harvest. After harvest, fluxes were observed in the collections performed at 0.3 and 9.3 MAH, in treatments with litter (L) or harvest residues plus litter (HR+L). Influxes were observed in these same treatments in the collections performed at 15.8 and 22.3 MAH. In the sites with no residues (WR), there was a reduction in CH_4-F compared to the pre-harvest, and influxes were observed at all sampling times.

At five days before harvest (PH) and at 0.3 MAH, collections that coincided with the rainy season, the large amount of residues on the soil in the treatments (L and HR+L) and PH may have reduced the diffusion of gases between the atmosphere and the soil. [62] in a study conducted in forest areas, found a 16%

increase in CH_4 influx with the removal of litter. This result was attributed to the fact that litter hinders the diffusion of gases [63]. In addition, this situation of higher soil moisture (Us) and presence of residues may favor higher microbial respiration, increasing sites with low concentrations of O_2 [64]. The Us values at these evaluation times were above field capacity in the sampled layers (Table 2 and 3). Characteristics of the soil, that is, presence of textural B horizon, of cohesive nature, and flat topography may have contributed to a lower water drainage in the soil profile [65] and consequent increase in CH_4 flux. Rainfall events with greater volumes promote environments with low amount of O_2, stimulating the activity of methanogenic microorganisms, which decompose the organic matter available in the soil, producing CH_4 [38].

and consequent increase in CH_4 flux. Rainfall events with greater volumes promote environments with low amount of O_2, stimulating the activity of methanogenic microorganisms, which decompose the organic matter available in the soil, producing CH_4 [66, 67] During the decomposition of forest residues, there may be emission of CH_4 caused by fungi [68] It has been observed in some studies that UV radiation and high temperature on dry and fresh leaves and on structural components, including pectin, lignin and cellulose, lead to the increase of CH_4-F [69, 70, 71].

At 15.8 and 22.3 MAH, CH_4 emissions were reduced in the treatments L and HR+L (Figure 6-B1). The reduction in the amount of residues, especially leaves, and the consequent reduction in C contents may have led to reduction in CH_4 emissions (Figure 7). [39] described similar results when detecting CH_4 emissions in areas with sugarcane straw up to six months after harvest, with a reduction after that, due to the advanced degree of decomposition of the residues.

In the collections performed at 0.3 and 9.3 MAH in the HR+L treatment, CH_4 fluxes were more pronounced in the planting rows. This position and these sampling times also had higher CO_2 fluxes, which possibly contributed to the generation of anaerobiosis sites. Unavailability of O_2 is the main factor causing CH_4 emission from the soil to the atmosphere [72].

There was no significant correlation between Us and Ts and CH_4 fluxes or influxes in rows and inter-rows (Table 4). In the treatment L or HR+L, the possible hypoxia events in the rainy season and the release of CH_4 by the action of temperature and UV radiation in the dry season may have been equated. In addition, at 15.8 and 22.3 MAH, CH_4 fluxes were observed in all treatments, regardless of the evaluation time (dry or rainy season) (Figure 6-B1).

3.3 *N_2O fluxes*

N_2O flux ranged from 0.0009 kg ha^{-1} h^{-1} to -0.0009 kg ha^{-1} h^{-1} (Figure 6C1), corroborating results reported in previous experiments in commercial eucalyptus forests, whose variations were: 0.0011 to -0.00037 kg ha^{-1} h^{-1}[58]; 0.00015 to -0.00005 kg ha^{-1} h^{-1} [73]; 0.00015 to -0.00005 [74] and 0.00098 kg ha^{-1} h^{-1} [75].

N_2O fluxes (N_2O-F) to the atmosphere, or influxes to the soil (N_2O-I), varied with the different residue managements (Figure 6-C1). In the pre-harvest (PH) and HR+L treatment, the highest N_2O-F values were observed at 0.3 and 9.3 MAH. In comparison with PH, the total (WR) or partial (L) removal of residues caused reduction in N_2O-F to the atmosphere. In the L treatment, fluxes were observed only at 0.3 MAH. In the WR treatment, influxes were observed at all sampling times.

Residue management is among the main factors that influence nutrient cycling in eucalyptus plantations [30]. Nitrogen in organic forms, such as the one added to the soil in the form of residues, can be converted into N_2O [76]. With the partial or total removal of residues, there is a reduction in N stocks (Table 2), limiting N availability in the soil, which leads to reduction in N_2O emission [77].

In this experiment, for the situation corresponding to HR+L, where there was a greater amount of residues on the soil, higher N_2O-F values were observed at 0.3 and 9.3 MAH (Figure 6-C1). When litter and the residues generated in eucalyptus harvesting are kept in the area of the stand, N content in the soil increases [78]. Results obtained by [79, 58] demonstrate the relationship between the amount of residues on the soil and N_2O-F. [80] observed that the N_2O-F of an area is closely related to the N released from the residues maintained in that area.

Also in HR+L, the evaluations performed at 15.8 and 22.3 MAH showed N_2O influxes (Figure 6-C1). There was a significant release of N up to 10 months; after that, the quantities and the rate of release of the nutrient contained in the residues decreased (Figure 7A2). The leaves present in the residues have high lability for decomposition, so there was accelerated decomposition of this organ and great release of N in the first months (Figure 7A1). Similar results were observed by [81].

In the L treatment, N_2O fluxes were observed at 0.3 MAH (Figure 6-C1). However, the emission of this gas was lower than in the HR+L treatment. In the beginning of the experiment, the quantity of N in the L treatment was approximately 450% lower than in the HR+L treatment (Table 2). N_2O influxes were observed in the samplings performed at 9.3, 15.8 and 22.3 MAH (Figure 6-C1). In addition to the low quantities of N in the residues (Table 2), there was also a lower N release speed compared to the HR+L treatment (Figure 7B2). Litter is a material with high degree of decomposition. Compared to the HR+L treatment, the C:N ratio of litter was 42% higher than that found under the condition in which it was combined with the other residues, which led to a longer half-life time (Table 2).

There was no significant correlation between Us, Ts and N_2O fluxes or influxes (Table 4). In the treatments HR+L and L, N_2O-F occurred in the rainy season; the presence of residues may have reduced the diffusion of gases at the atmosphere-soil interface. Soil moisture is the variable that most favors N_2O-F to the atmosphere [82] With high Us, certain microorganisms can use NO_3^- as final electron acceptors in place of O_2 [83].

The higher N_2O-F values observed in the HR+L treatment in the dry period may be linked to the high temperatures in the soil (Table 3). Temperature influences N_2O emissions from the soil to the atmosphere, and denitrification can be extremely sensitive to rising temperatures, as increased microbial respiration results in O_2 depletion [84, 85]. In the present study, when high CO_2 fluxes were observed (HR+L treatment; at 0.3 and 9.3 MAH - Figure 6-A1), higher N_2O fluxes were also observed (Figure 6-C1) compared to the other treatments. According to [86] the addition of plant residues on the soil rapidly stimulates microbial activity, creating anaerobiosis sites and, consequently, stimulating the denitrification process.

Table 3
Soil temperature (Ts) and soil moisture (Us) measured at 5 cm depth, in the row and inter-row of eucalyptus plantation, 5 days before harvest (pre-harvest) and at 0.3, 9.3, 15.8 and 22.3 months after harvest. The samples were collected in the following treatments: without the presence of residues (WR), with litter from the previous rotation (L) and with harvest residues and litter from the previous rotation (HR+L)

Sampling season	Treatment	Planting row		Planting inter-row	
		Ts	Us	Ts	Us
		(°C)	(%, v v^{-1})	(°C)	(%, v v^{-1})
	Pre-harvest				
Rainy period	-	29.7	17.4	31.3	16.6
	0.3 Months after harvest				
Rainy period	WR	27.0 a	19.8 a	28.5 a	17.6 a
	L	27.0 a	17.5 a	27.5 ab	16.8 a
	HR+L	27.0 a	17.3 a	27.0 b	16.0 a
	CV (%)	0	15.7	1.8	10.3
	9.3 Months after harvest				
Dry period	WR	29.5 a	1.8 a	31.0 a	1.5 a
	L	29.0 ab	2.3 a	30.5 ab	3.0 a
	HR+L	28.25 b	2.1 a	29.0 b	2.1 a
	CV (%)	1.7	35.9	3.2	43.1
	15.8 Months after harvest				
Rainy period	WR	22.5 a	22.2 a	22.5 a	23.9 a
	L	22.5 a	24.2 a	22.1 a	22.0 a
	HR+L	22.5 a	23.8 a	22.7 a	25.6 a
	CV (%)	1.3	5.3	1.7	12.8
	22.3 Months after harvest				
Dry period	WR	25.3 a	8.1 b	24.7 a	8.4 b
	L	25.5 a	8.8 b	25.4 a	10.2 a
	HR+L	25.3 a	10.5 a	25.4 a	10.6 a
	CV (%)	2.1	7.8	1.3	8.5

Means followed by equal lowercase letters vertically do not differ from each other by Tukey test ($p < 0.05$). CV (%) denotes the coefficient of variation around the mean (n=8).

Table 4
Pearson's correlation coefficients between CO_2, CH_4 and N_2O fluxes and soil temperature and moisture measured in the planting row (R) and inter-row (IR) in areas without the presence of residues (WR), with litter from the previous rotation (L) and with harvest residues and litter from the previous rotation (HR+L)

	Greenhouse gases					
Description	CO_2		CH_4		N_2O	
Sampling position	R	IR	R	IR	R	IR
Soil moisture	-0.24 ^{ns}	0.01^{ns}	-0.18 ^{ns}	-0.27 ^{ns}	-0.10 ^{ns}	-0.06 ^{ns}
Soil temperature	0.22 ^{ns}	0.12 ^{ns}	0.05 ^{ns}	0.54 ^{ns}	0.16 ^{ns}	0.09 ^{ns}

^{ns} Non-significant correlation; * Significant correlation ($p < 0.05$)

3.4 *CO_2 equivalent flux*

CO_2eq-F was similar at all evaluation times when comparing the WR and L managements. In the HR+L treatment, the flux was higher than in the others, at 0.3 and 9.3 MAH. In the other samplings, the fluxes were similar to those found in the other treatments (Figure 8-A). The high C and N release rates in the HR+L treatment in the first months, via decomposition (Figure 7-A2), can be explained by the high amount of residues (34.7 t ha^{-1}).

During the decomposition process, plant residues release mostly C and N, of which, on average, 50 and 70%, respectively, return to the atmosphere in oxidized forms [20]. Despite the higher CO_2eq-F in the HR+L treatment, it should be noted that with the maintenance of residues, C and N inputs to the soil are expected [19, 87, 12] which could increase C and N stocks in the soil, constituting an important strategy for reducing GHG concentrations in the atmosphere in forestry and agricultural systems [88].

When analyzing the contributions of gases to the overall emissions, a quantitatively high contribution of CO_2 is observed (Figure 6-A1). CH_4 and N_2O emissions or influxes were similar (Figure <link rid="fig6">6</link>-B1 and 6-C1), but N_2O has a higher warming potential compared to CH_4 [25]. In the HR+L treatment, the highest CO_2 fluxes were observed in the collections performed at 0.3 and 9.3 MAH (Figure 6-A1). Higher CH_4 and N_2O fluxes were also observed (Figure <link rid="fig6">6</link>-B1 and 6-C1). The close relationship between CO_2 fluxes in the soil and CH_4 and N_2O fluxes is reported in other studies. [64] conducting an experiment under controlled conditions, artificially injected CO_2 to 10 cm deep into the soil through a probe and observed that N_2O and CH_4 emissions increased linearly with CO_2 concentration and time of application.

3.5. *Quantities of carbon and nitrogen in plant biomass and soil*

The tree biomass and its quantity of C at 22.3 MAH did not differ under the influence of residue management (Table 5), despite the nutrients released by eucalyptus harvest residues. Positive responses in the growth of eucalyptus plants in the presence of residues in soils with low levels of organic matter, P, K, Ca, Mg, and S are attributed mainly to the release of nutrients from the residues to the soil [14, 89]. In this experiment, the absence of response to the maintenance of residues may be due to the existence of nutrients at appropriate levels to the plants (Table 1), both natural from the soil and residual from the fertilizers and limestone applied in previous rotations. Similar results have been reported by other authors [90]. Increases in forest productivity only after two successive rotations of harvest residue maintenance in the same area [12].

Table 5
Quantity of carbon in tree biomass and soil, at 22.3 months after eucalyptus harvest, in the area without the presence of residues (WR), with litter from the previous rotation (L) and with harvest residues and litter from the previous rotation (HR+L). Means followed by equal lowercase letters vertically do not differ from each other by Tukey test ($p < 0.05$). CV (%) denotes the coefficient of variation around the mean (n=4)

	Plant biomass			Quantity of carbon		
Treatments	Below ground[1]	Above ground	Total	Below ground[1]	Above ground	Total
	Mg ha^{-1}					
WR	0.67 a	63.92 a	64.57 a	0.28 a	28.86 a	29.13 a
L	1.18 a	62.76 a	63.94 a	0.52 a	26.71 a	27.22 a
HR+L	0.92 a	65.34 a	66.26 a	0.41 a	27.57 a	27.99 a
CV (%)	36.44	8.42	8.59	42.83	8.43	8.68

[1] 0-40 cm soil layer

The removal of residues from planted forests aimed at bioenergy production, for instance, leads to the export of soil nutrients [15, 77, 91], hence requiring greater nutritional replacements via fertilizers. In such situations, there may be greater release of GHG to the atmosphere, resulting from the manufacture of fertilizers and their contact with the soil [92, 93, 94].

C (Figure 10A) and N (Figure 10B) stocks in the soil surface layer (0-10 cm) at 22.3 MAH were similar in all treatments, despite the different quantities of C and N supplied to the area in the form of residues (Table 2). Changes in soil C stocks are slow, with difficult detection in the laboratory in short experimental periods [95]. Therefore, long-term studies for monitoring C stocks in soil are essential to determine these changes, which are often noticeable only after several years or decades [96].

The absence of increase of soil organic matter in the HR+L and L treatments compared to the treatment without residues (WR) may also be due to the fact that the experimental area is in the third rotation and received residues from the harvest of two previous rotations successively. [14] also found no increase in organic matter content in the soil with retention of eucalyptus harvest residues. These authors attributed this observation to the low quality of the residues. [97] in eucalyptus forests, observed that regardless of the quantity and quality of litter on the soil surface there was no influence on soil organic C contents. The input of C in quantity and quality in forest soils does not always result in an increase of C in the soil due to the differences in the biochemical characteristics of the residues, mineralogy through the physical protection of SOM and the priming effect in the soil [98].

Additionally, the surface layers of the soil under study are sandy (Table 1), hence offering little physical protection to residues, facilitating microbial decomposition and hindering the formation of stable organic matter [99]. Results similar to these were found by [100] in sandy soil in the third rotation of eucalyptus planting.

3.6. *Balance between CO_2 equivalent emissions and quantity of C in the plant-soil system*

In all treatments, there were higher quantities of C immobilized in the plant-soil system compared to atmospheric GHG emissions, thus indicating C sequestration (Figure 11). There is consensus that planted eucalyptus forests, mainly in tropical or subtropical areas, contribute to greater C sequestration than other forests, mainly due to the accelerated growth of tree biomass [22, 101, 102, 103, 104].

Where the harvest residues were kept (HR+L), C balance was 14.4 and 16.7% lower compared to the treatments in which the residues were partially or totally removed (L and WR), respectively (Figure 11). The lower C balance in the HR+L treatment is due to the higher CO_2 equivalent fluxes observed at 0.3 and 9.3 months of experiment, compared to the other treatments (Figure 8). Furthermore, during the experimental period, no differences were observed between treatments in C fixation in plant biomass (Figure 9) and in soil (Figure 10).

Although the CO_2eq-F values found in the treatment are higher where harvest residues were left (HR+L), at 0.3 and 9.3 MAH, it should be considered that the partial (L) or total (WR) removal of forest residues will cause GHG emissions. GHG emissions will occur in the process of removing material from the field, during transportation and in the processing in the industry for energy production. In this scenario, the consumption of fossil fuels should be accounted for, considering the removal of residues from the field and transport to industry. Diesel consumption is the main source of GHG emissions throughout the eucalyptus production cycle, corresponding to approximately 64% of the total emission according to [105]. The relevant GHG emissions during biomass combustion for energy generation should also be considered [106].

Additionally, it should be considered that the permanence of forest residues in the planting area favors nutrient cycling [12, 15], contributes to increasing soil diversity and microbial activity [12, 13], attenuates the physical deterioration of the soil under machine traffic [18, 19], reduces soil losses via water erosion [17], reduces thermal oscillations of the soil [107, 108] and minimizes soil water loss via evaporation [108].

4. Conclusions

Maintenance of eucalyptus harvest residues increases CO_2, CH_4 and N_2O fluxes from the soil in the first months after harvest compared to the area with removal of residues or with only litter.

Maintenance of harvest residues does not increase the quantity of C in the plant and in the soil surface layer (0-10 cm) after 22.3 months of eucalyptus planting. However, long-term studies should be conducted to investigate the management of eucalyptus harvest residues and C sequestration capacity in the soil-plant system.

Declarations

Acknowledgements: thanks are due to the BRACELL Company for fnancial support, providing access to the experimental area and assistence with the feldwork. We also thank the Programa em Nutrição e Solos Florestais (NUTREE—UFV).

Project funding: the work is fully funded by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES, fnance code 001).

Availability of data and material the raw-datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

The authors declare that they have no conflicts of interests in carrying the research and publishing the manuscript.

Code Availability: not applicable.

Declarations Ethics Approval: not applicable.

References

1. Albuquerque I, Alencar A, Angelo C, et al (2020) Análise das Emissões Brasileiras de Gases de Efeito Estufa e suas Implicações para as Metas de Clima do Brasil 1970-2019. www.seeg.eco.br. Accessed 12 June 2021
2. Neto MS, Piccolo M de C, Junior CC, et al (2011) Greenhouse gas emission caused by different land-uses in Brazilian savannah. Rev Bras Cienc do Solo 35:63–76. https://doi.org/10.1590/s0100-06832011000100006
3. Martins CSC, Nazaries L, Macdonald CA, et al (2016) Corrigendum to “Water availability and abundance of microbial groups are key determinants of greenhouse gas fluxes in a dryland forest ecosystem”. Soil Biol. Biochem. 86 pp. 5-16. Doi: 10.1016/j.soilbio.2015.03.012.
4. Powlson DS, Whitmore AP, Goulding KWT (2011) Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false. Eur J Soil Sci 62:42–55. https://doi.org/10.1111/j.1365-2389.2010.01342.x
5. Ruan L, Philip Robertson G (2013) Initial nitrous oxide, carbon dioxide, and methane costs of converting conservation reserve program grassland to row crops under no-till vs. conventional tillage. Glob Chang Biol 19:2478–2489. https://doi.org/10.1111/gcb.12216
6. Daystar J, Reeb C, Gonzalez R, et al (2015) Environmental life cycle impacts of cellulosic ethanol in the Southern U.S. produced from loblolly pine, eucalyptus, unmanaged hardwoods, forest residues, and switchgrass using a thermochemical conversion pathway. Fuel Process Technol 138:164–174. https://doi.org/10.1016/j.fuproc.2015.04.019
7. U.S. Energy Information Admnistration (2019) Internaltional Energy Outlook 2019. US Energy Inf Adm September:25–150
8. Santiago FLS, Rezende MA (2014) Utilization of eucalyptus forest residues from the cellulose manufacturing industry for thermal and electrical energy. Rev Energ na Agric 29:241–253. https://doi.org/10.17224/EnergAgric.2014v29n4p241-253
9. Machado PG, Cunha M, Walter A, et al (2020) The potential of a bioeconomy to reduce Brazilian GHG emissions towards 2030: a CGE-based life cycle analysis. Biofuels, Bioprod Biorefining 14:265–285. https://doi.org/10.1002/bbb.2064
10. INDÚSTRIA BRASILEIRA DE ÁRVORES (2019) Report 2019. https://iba.org/datafiles/publicacoes/relatorios/iba-relatorioanual2019.pdf. Accessed 28 June 2021
11. Oliveira FCC, Ferreira GWD, Santos RS, et al (2021) Soil CO_2 concentration, efflux, and partitioning in a recently afforested grassland. New For 52:737–757. https://doi.org/10.1007/s11056-020-09824-z
12. Rocha THJ, J L, et al (2018) Forest Ecology and Management Forest residue removal decreases soil quality and affects wood productivity even with high rates of fertilizer application. For Ecol Manage 430:188–195. https://doi.org/10.1016/j.foreco.2018.08.010
13. Kumaraswamy S, Mendham DS, Grove TS, et al (2014) Harvest residue effects on soil organic matter, nutrients and microbial biomass in eucalypt plantations in Kerala, India. For Ecol Manage 328:140–149. https://doi.org/10.1016/j.foreco.2014.05.021
14. Versini A, Nouvellon Y, Laclau J, et al (2013) Forest Ecology and Management The manipulation of organic residues affects tree growth and heterotrophic CO_2 efflux in a tropical Eucalyptus plantation. For Ecol Manage 301:79–88. https://doi.org/10.1016/j.foreco.2012.07.045
15. Santana RC, Barros NF de, Novais RF, et al (2008) Alocação de nutrientes em plantios de eucalipto no Brasil. Rev Bras Cienc do Solo 32:2723–2733. https://doi.org/10.1590/s0100-06832008000700016
16. Teixeira RS, Fialho RC, Costa DC et al (2020) Land-use change with pasture and short rotation eucalypts impacts the soil C emissions and organic C stocks in the Cerrado biome L. Degrad Dev 31:909–923. https://doi.org/10.1002/ldr.3480
17. Matthews S (2005) The water vapour conductance of Eucalyptus litter layers. Agric For Meteorol 135:73–81. https://doi.org/10.1016/j.agrformet.2005.10.004
18. de Melo RO, da Fonseca AA, de Barros NF, et al (2021) Retention of eucalyptus harvest residues reduces soil compaction caused by deep subsoiling. J. For. Res. https://doi.org/10.1007/s11676-021-01370-4
19. de Jesus GL, Silva IR, Almeida LFJ, et al (2015) Produtividade do eucalipto, atributos físicos do solo e frações da matéria orgânica influenciadas pela intensidade de tráfego e resíduos de colheita. Rev Bras Cienc do Solo 39:1190–1203. https://doi.org/10.1590/01000683rbcs20140494
20. Stevenson F. (1994) Humus Chemistry: Genesis, Composition, Reactions, 2nd Edition ohn Wiley and Sons Ltd., New York
21. Rochette P, Liang C, Pelster D, et al (2018) Soil nitrous oxide emissions from agricultural soils in Canada: Exploring relationships with soil, crop and climatic variables. Agric Ecosyst Environ 254:69–81. https://doi.org/10.1016/j.agee.2017.10.021
22. Gatto A, Barros NF de, Novais RF, et al (2010) Estoques de carbono no solo e na biomassa em plantações de eucalipto. Rev Bras Cienc do Solo 34:1069–1079. https://doi.org/10.1590/s0100-06832010000400007
23. Fialho RC, da Silva Teixeira R, Teixeira APM, da Silva IR (2018) Short-term carbon emissions: Effect of various tree harvesting, transport, and tillage methods under a eucalyptus plantation. L Degrad Dev 29:3995–4004. https://doi.org/10.1002/ldr.3161
24. Smith KA, Conen F (2004) Impacts of land management on fluxes of trace greenhouse gases. Soil Use Manag 20: 255-263, 2004. https://doi.org/10.1079/SUM2004238
25. IPCC (2007) Climate Change 2007: the Physical Science Basis. Cambridge: Cambridge University Press.
26. Teixeira PC, Donagemma GK, Fontana A, Teixeira WG (2017) Manual de métodos de análise de solo, 3rd ed. EMBRAPA, Rio de Janeiro
27. Bradford MA, Tordoff GM, Eggers T, et al (2002) Microbiota , fauna , and mesh size interactions in litter decomposition. Oikos 99:317–323

28. Blumfield TJ, Xu Z, Mathers NJ, Saffigna PG (2004) Decomposition of Nitrogen-15 Labeled Hoop Pine Harvest Residues in Subtropical Australia. Soil Sci Soc Am J 68:1751–1761. https://doi.org/10.2136/sssaj2004.1751
29. Souza IF de, Barros NF de, Silva IR da, et al (2016) Decomposition of eucalypt harvest residues as affected by management practices, climate and soil properties across southeastern Brazil. For Ecol Manage 374:186–194. https://doi.org/10.1016/j.foreco.2016.05.012
30. Ferreira GWD, Soares EMB, Oliveira FCC, et al (2016) Nutrient release from decomposing Eucalyptus harvest residues following simulated management practices in multiple sites in Brazil. For Ecol Manage 370:1–11. https://doi.org/10.1016/j.foreco.2016.03.047
31. Thomas RJ, Asakawa NM (1993) Decomposition of leaf litter from tropical forage grasses and legumes. Soil Biol. Biochem. 25: 1351–1361.
32. Society E (2012) Energy Storage and the Balance of Producers and Decomposers in Ecological Systems Author (s): Jerry S . Olson Reviewed work (s): Published by : Ecological Society of America Stable URL : http://www.jstor.org/stable/1932179 . 44:322–331
33. R development core team (2018) R: A language and environment for statistical computing. Vienna, R Foundation for Statistical Computing. Available at: http://CRAN.R-project.org/package=ExpDes. Accessed 21 June 2021
34. Campoe OC, Stape JL, Laclau J, et al (2012) Part of an invited issue on carbon allocation Stand-level patterns of carbon fluxes and partitioning in a Eucalyptus grandis plantation across a gradient of productivity , in São Paulo State , Brazil. Tree Physiol 32:696–706. https://doi.org/10.1093/treephys/tps038
35. Epron D, Laclau J, Almeida JCR, et al (2011) Part of an invited issue on carbon allocation Do changes in carbon allocation account for the growth response to potassium and sodium applications in tropical Eucalyptus plantations ? Tree Physiol 667–679. https://doi.org/10.1093/treephys/tpr107
36. Nouvellon Y, Epron D, Marsden C, Saint-andre L (2012) Age-related changes in litter inputs explain annual trends in soil CO_2 effluxes over a full Eucalyptus rotation after afforestation of a tropical savannah. Biochemistry 515–533. https://doi.org/10.1007/s10533-011-9685-9
37. Ryan MG, Luiz J, Binkley D, et al (2010) Factors controlling Eucalyptus productivity : How water availability and stand structure alter production and carbon allocation. For Ecol Manage 259:1695–1703. https://doi.org/10.1016/j.foreco.2010.01.013
38. Moreira FMS, Siqueira JO (2006) Microbiologia e Bioquímica do Solo. Lavras: UFLA, 2006.
39. Signor D, Pissioni LLM, Cerri CEP (2014) Emissões de gases de efeito estufa pela deposição de palha de cana-de-açúcar sobre o solo. Bragantia 73:113–122. https://doi.org/10.1590/brag.2014.019
40. Gasparim E, Ricieri RP, Silva SDL, et al (2005) Temperatura no perfil do solo utilizando duas densidades de cobertura e solo nu. Acta Sci Agron 27:107–114. https://doi.org/10.4025/actasciagron.v27i1.2127
41. Bélanger N, Collin A, Khlifa R, Lebel-Desrosiers S (2021) Balsam Fir and American Beech Influence Soil Respiration Rates in Opposite Directions in a Sugar Maple Forest Near Its Northern Range Limit. Front For Glob Chang 4:1–14. https://doi.org/10.3389/ffgc.2021.664584
42. Russell CA, Voroney RP (1998) Carbon dioxide efflux from the floor of a boreal aspen forest. I. Relationship to environmental variables and estimates of C respired. Can J Soil Sci 78:301–310. https://doi.org/10.4141/S97-054
43. da Silva DMN, Venturim CHP, Valory Capucho MEO, et al (2018) Impact of soil cover systems on soil quality and organic production of yacon. Sci Hortic (Amsterdam) 235:407–412. https://doi.org/10.1016/j.scienta.2018.03.024
44. Pegoraro RF, Silva IR, Novais RF, et al (2013) Fenóis derivados da lignina, carboidratos e aminoaçúcares em serapilheira e solos cultivados com eucalipto em sistemas convencional e fertirrigado. Rev Arvore 37:519–529. https://doi.org/10.1590/S0100-67622013000300015
45. El Ghoz, NCC, Zanatta, JA, Zanella, K, Veloso G, Higa RCV, Bayer, C (2013) Posição das câmaras de coleta para monitoramento da emissão de gases de efeito estufa do solo em plantios florestais de Pinus. In: Reunião Paranaense de Ciência do Solo, Londrina: IAPAR, p.349.
46. Gonçalves SB, Lopes E da S, Fiedler NC, et al (2016) Efeito da profundidade de trabalho na qualidade da operação de subsolagem para implantação florestal. Rev Arvore 40:29–37. https://doi.org/10.1590/0100-67622016000100004
47. Stape JL, Andrade SC, Gomes AN, et al (2002) Definições de métodos de preparo de solo para silvicultura em solos coesos do litoral norte da Bahia. pp 259–296
48. Leonardo J, Gonçalves DM, Alcarde C, et al (2013) Integrating genetic and silvicultural strategies to minimize abiotic and biotic constraints in Brazilian eucalypt plantations. For Ecol Manage 301:6–27. https://doi.org/10.1016/j.foreco.2012.12.030
49. Ben-Noah I, Friedman SP (2018) Review and Evaluation of Root Respiration and of Natural and Agricultural Processes of Soil Aeration. Vadose Zo J 17:170119. https://doi.org/10.2136/vzj2017.06.0119
50. Mello SL de M, Gonçalves JL de M, Gava JL (2007) Pre- and post-harvest fine root growth in Eucalyptus grandis stands installed in sandy and loamy soils. For Ecol Manage 246:186–195. https://doi.org/10.1016/j.foreco.2007.03.060
51. Haichar F el Z, Santaella C, Heulin T, Achouak W (2014) Root exudates mediated interactions belowground. Soil Biol Biochem 77:69–80. https://doi.org/10.1016/j.soilbio.2014.06.017
52. Ball BC (2013) Soil structure and greenhouse gas emissions: A synthesis of 20 years of experimentation. Eur J Soil Sci 64:357–373. https://doi.org/10.1111/ejss.12013
53. da Silva Bicalho E, Moitinho MR, De Bortoli Teixeira D, et al (2017) Soil Greenhouse Gases: Relations to Soil Attributes in a Sugarcane Production Area. Soil Sci Soc Am J 81:1168–1178. https://doi.org/10.2136/sssaj2017.02.0043
54. Elaoud A, Chehaibi S (2011) Soil compaction due to tractor traffic. J Fail Anal Prev 11:539–545. https://doi.org/10.1007/s11668-011-9479-3
55. Vicentini ME, Pinotti CR, Hirai WY, et al (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. https://doi.org/10.1007/s11104-019-04262-z

56. Valentini R, Matteucci G, Dolman AJ, et al (2000) Respiration as the main determinant of carbon balance in European forests. Nature 404:861–865. https://doi.org/10.1038/35009084
57. Ibarr MA, Zanatta JA, Dieckow J, et al (2021) Nitrous oxide and methane emissions from soil and nitrogen uptake by eucalyptus fertilized with enhanced efficiency fertilizers. Plant Soil 463: 615–630. https://doi.org/10.1007/s11104-021-04938-5
58. Oliveira AD, Ribeiro FP, Ferreira EAB, et al (2020) CH_4 and N_2O fluxes from planted forests and native cerrado ecosystems in brazil. Sci Agric 78:1–11. https://doi.org/10.1590/1678-992x-2018-0355
59. Wanyama I, Pelster DE, Verchot L V, et al (2019) Soil carbon dioxide and methane fluxes from forests and other land use types in an African tropical montane region. Biogeochemistry 143:171–190. https://doi.org/10.1007/s10533-019-00555-8
60. Fest B, Hinko-najera N, Fischer JC Von, et al (2017) Soil Methane Uptake Increases under Continuous Throughfall Reduction in a Temperate Evergreen , Broadleaved Eucalypt Forest. Ecosystems 20:368–379. https://doi.org/10.1007/s10021-016-0030-y
61. Fest BJ, Hinko-najera N, Wardlaw T, et al (2016) Soil methane oxidation in both dry and wet temperate eucalypt forests show near identical relationship with soil air-filled porosity. Biogeosci Discuss. https://doi.org/10.5194/bg-2016-181
62. Leitner S, Sae-tun O, Kranzinger L, et al (2016) Contribution of litter layer to soil greenhouse gas emissions in a temperate beech forest. Plant Soil 455–469. https://doi.org/10.1007/s11104-015-2771-3
63. Piechl M, Arain MA, Ullah S, Moore TM (2010) Carbon dioxide, methane, and nitrous oxide exchanges in an agesequence of temperate pine forests. Glob Change Biol 16:2198–2212 temperate pine forests. 10.1111/j.1365-2486.2009.02066.x
64. He W, Kim Y, Ko D, et al (2019) Changes in soil N_2O and CH_4 emissions and related microbial functional groups in an artificial CO_2 gassing experiment. Sci Total Environ 690:40–49. https://doi.org/10.1016/j.scitotenv.2019.06.400
65. Santos H, Jacomine P, Anjos L, et al (2018) Sistema Brasileiro de Classificação de Solos, 5th ed. EMBRAPA, Brasília
66. Barba J, Bradford MA, Brewer PE, et al (2019) Methane emissions from tree stems: a new frontier in the global carbon cycle. New Phytol 222:18–28. https://doi.org/10.1111/nph.15582
67. Covey KR, Megonigal JP (2019) Methane production and emissions in trees and forests. New Phytol 222:35–51 1. https://doi.org/10.1111/nph.15624
68. Lenhart K, Bunge M, Ratering S, et al (2012) Evidence for methane production by saprotrophic fungi. Nat Commun 3:. https://doi.org/10.1038/ncomms2049
69. McLeod AR, Fry SC, Loake GJ, et al (2008) Ultraviolet radiation drives methane emissions from terrestrial plant pectins. New Phytol 180:124–132. https://doi.org/10.1111/j.1469-8137.2008.02571.x
70. Vigano I, Van Weelden H, Holzinger R, et al (2008) Effect of UV radiation and temperature on the emission of methane from plant biomass and structural components. Biogeosciences 5:937–947. https://doi.org/10.5194/bg-5-937-2008
71. Bruhn D, Mikkelsen TN, Øbro J, et al (2009) Effects of temperature, ultraviolet radiation and pectin methyl esterase on aerobic methane release from plant material. Plant Biol 11:43–48. https://doi.org/10.1111/j.1438-8677.2009.00202.x
72. Le Mer J, Roger P (2001) Production, oxidation, emission and consumption of methane by soils: A review. Eur J Soil Biol 37:25–50. https://doi.org/10.1016/S1164-5563(01)01067-6
73. Alvarez CR, Lupi AM, Romaniuk RI, et al (2020) Soil nitrous oxide emissions from Eucalyptus plantation in Argentina. For Ecol Manage 473:118301. https://doi.org/10.1016/j.foreco.2020.118301
74. Monteiro DA, Fonseca S, Aragão R De, et al (2020) Structural and functional shifts of soil prokaryotic community due to Eucalyptus plantation and rotation phase. Scient. Rep 1–14. https://doi.org/10.1038/s41598-020-66004-x
75. Cuer CA, Rodrigu RDAR, Balieiro FC, et al (2018) Short-term effect of Eucalyptus plantations on soil microbial communities and soil-atmosphere methane and nitrous oxide exchange. Sci Rep 8:15133. https://doi.org/10.1038/s41598-018-33594-6
76. Strawn DG, Hohn HL, O´Connor GA (2020) Soil chemistry, 5th Editio. John Wiley & Sons
77. Achat DL, Deleuze C, Landmann G, et al (2015) Quantifying consequences of removing harvesting residues on forest soils and tree growth - A meta-analysis. For Ecol Manage 348:124–141. https://doi.org/10.1016/j.foreco.2015.03.042
78. Versini A, Zeller B, Derrien D, et al (2014) The role of harvest residues to sustain tree growth and soil nitrogen stocks in a tropical eucalyptus plantation. Plant Soil 376:245–260. https://doi.org/10.1007/s11104-013-1963-y
79. Carvalho AM, Oliveira WRD, Ramos MLG, et al (2017) Soil N_2O fluxes in integrated production systems, continuous pasture and Cerrado. Nutr Cycl Agroecosystems 108:69–83. https://doi.org/10.1007/s10705-017-9823-4
80. Pugesgaard S, Petersen SO, Chirinda N, Olesen JE (2017) Crop residues as driver for N_2O emissions from a sandy loam soil. Agric For Meteorol 233:45–54. https://doi.org/10.1016/j.agrformet.2016.11.007
81. Rocha JHT, Marques ERG, Gonçalves JL d. M, et al (2016) Decomposition rates of forest residues and soil fertility after clear-cutting of Eucalyptus grandis stands in response to site management and fertilizer application. Soil Use Manag 32:289–302. https://doi.org/10.1111/sum.12283
82. Butterbach-Bahl K, BagDannenmann, R. K, S. Z-B (2013) Nitrous oxide emissions from soils: How well do we understand the processes and their controls? Philos Trans R Soc 368:1–13. https://doi.org/10.1098/rstb.2013.0122
83. Dendooven L, Bonhomme E, Merckx K, Vlassak K (1998) Injection of pig slurry and its effects on dynamics of nitrogen and carbon in a loamy soil under laboratory conditions. Biol Fertil Soils 27:5–8
84. Muñoz C, Rojas D, Candia O, et al (2009) Supervisory control system to enhance partial nitrification in an activated sludge reactor. Chem Eng J 145:453–460. https://doi.org/10.1016/j.cej.2008.04.032

85. Ribeiro K, Sousa-Neto ER de, Carvalho JA de, et al (2016) Land cover changes and greenhouse gas emissions in two different soil covers in the Brazilian Caatinga. Sci Total Environ 571:1048–1057. https://doi.org/10.1016/j.scitotenv.2016.07.095
86. Baggs E., Ress R., Smith KA (2000) Nitrous oxide emission from soils after incorporating crop residues. Exp Agric 82–87
87. Mayer M, Prescott CE, Abaker WEA, et al (2020) Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. For Ecol Manage 466:118127. https://doi.org/10.1016/j.foreco.2020.118127
88. Change, Intergovernmental Panel On Climate. "Ipcc." Climate change (2014).
89. de São José JFB, Vargas LK, Bayer C, et al (2020) Initial growth and nutrition of eucalyptus under different management of harvest residues. Floresta e Ambient 27:. https://doi.org/10.1590/2179-8087.016118
90. Bizerra Barros I, Santos Cavalcante V, Soares Moulin A, et al (2021) Integrating forest residue and mineral fertilization: effects on nutrient acquisition, nutrient use efficiency and growth of eucalypt plants. For Ecol Manage 496:. https://doi.org/10.1016/j.foreco.2021.119461
91. Cavalett O, Slettmo SN, Cherubini F (2018) Energy and environmental aspects of using eucalyptus from Brazil for energy and transportation services in Europe. Sustain 10:1–18. https://doi.org/10.3390/su10114068
92. Chai BC, van der Voort JR, Grofelnik K, et al (2019) Which diet has the least environmental impact on our planet? A systematic review of vegan, vegetarian and omnivorous diets. Sustain 11:. https://doi.org/10.3390/su11154110
93. Snyder CS, Bruulsema TW, Jensen TL, Fixen PE (2009) Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agric Ecosyst Environ 133:247–266. https://doi.org/10.1016/j.agee.2009.04.021
94. Shrestha RK, Strahm BD, Sucre EB (2015) Greenhouse gas emissions in response to nitrogen fertilization in managed forest ecosystems. New For 46:167–193. https://doi.org/10.1007/s11056-014-9454-4
95. Bayer C, Mielniczuk J, Martin-Neto L (2000) Efeito de sistemas de preparo e de cultura na dinâmica da matéria orgânica e na mitigação das emissões de CO_2. Rev Bras Ciência do Solo 24:599–607. https://doi.org/10.1590/s0100-06832000000300013
96. Peralta AL, Wander MM (2008) Soil organic matter dynamics under soybean exposed to elevated [CO_2]. Plant Soil 303:69–81. https://doi.org/10.1007/s11104-007-9474-3
97. Wang Y, Zheng J, Xu Z, et al (2019) Effects of changed litter inputs on soil labile carbon and nitrogen pools in a eucalyptus-dominated forest of southeast Queensland, Australia. J Soils Sediments 19:1661–1671. https://doi.org/10.1007/s11368-019-02268-9
98. Lajtha K, Bowden RD, Crow S, et al (2018) The detrital input and removal treatment (DIRT) network: Insights into soil carbon stabilization. Sci Total Environ 640–641:1112–1120. https://doi.org/10.1016/j.scitotenv.2018.05.388
99. Shi A, Marschner P (2013) Addition of a clay subsoil to a sandy top soil alters CO_2 release and the interactions in residue mixtures. Sci Total Environ 465:248–254. https://doi.org/10.1016/j.scitotenv.2012.11.081
100. Epron D, Mouanda C, Mareschal L, Koutika LS (2015) Impacts of organic residue management on the soil C dynamics in a tropical eucalypt plantation on a nutrient-poor sandy soil after three rotations. Soil Biol Biochem 85:183–189. https://doi.org/10.1016/j.soilbio.2015.03.010
101. Viera M, Rodríguez-Soalleiro R (2019) A complete assessment of carbon stocks in above and belowground biomass components of a hybrid eucalyptus plantation in southern Brazil. Forests 10:1–12. https://doi.org/10.3390/f10070536
102. Souza CL, Schettino S, Silva DD, Guimarães NV (2019) Balanço de Carbono do processo de produção de madeira de reflorestamento no Norte de Minas Gerais. Caderno de Ciências Agrárias, v. 11, p. 1-8.
103. Cook RL, Binkley D, Stape JL (2016) Eucalyptus plantation effects on soil carbon after 20 years and three rotations in Brazil. For Ecol Manage 359:92–98. https://doi.org/10.1016/j.foreco.2015.09.035
104. Kaul M, Mohren GMJ, Dadhwal VK (2010) Carbon storage and sequestration potential of selected tree species in India. Mitig Adapt Strateg Glob Chang 15:489–510. https://doi.org/10.1007/s11027-010-9230-5
105. Crow SE, Reeves M, Turn S, et al (2016) Carbon balance implications of land use change from pasture to managed eucalyptus forest in Hawaii. Carbon Manag 7:171–181. https://doi.org/10.1080/17583004.2016.1213140
106. Timmons DS, Buchholz T, Veeneman CH (2016) Forest biomass energy: Assessing atmospheric carbon impacts by discounting future carbon flows. GCB Bioenergy 8:631–643. https://doi.org/10.1111/gcbb.12276
107. Gonçalves G, Ferreira M das G (1997) Fisiologia da brotação de eucalipto com ênfase nas suas relações hídricas. Série Técnica IPEF 11:9–22
108. Gholz HL, Wedin DA, Smitherman SM, et al (2000) Long-term dynamics of pine and hardwood litter in contrasting environments: Toward a global model of decomposition. Glob Chang Biol 6:751–765. https://doi.org/10.1046/j.1365-2486.2000.00349.x

Figures

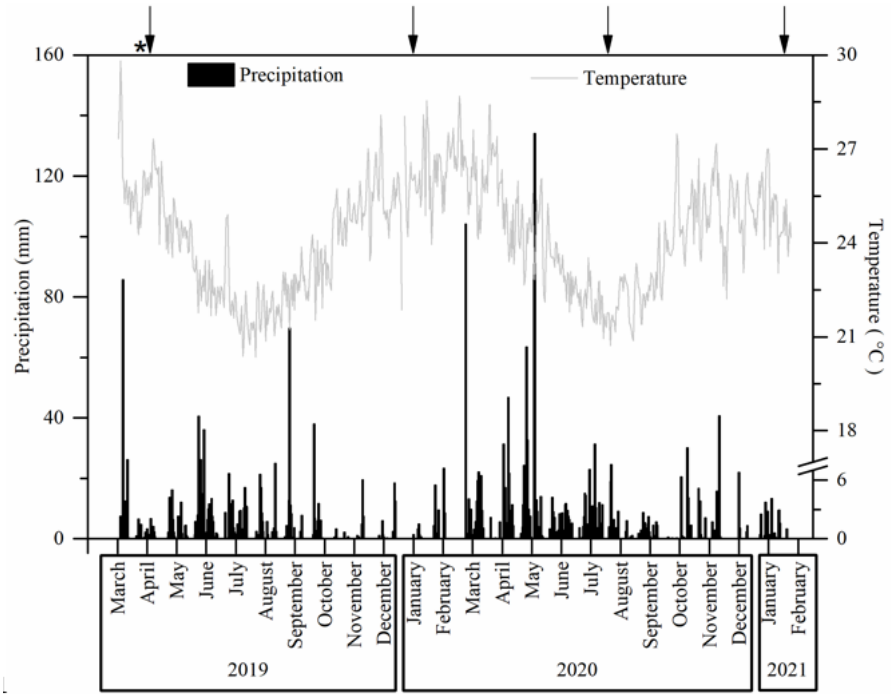

Figure 1

Precipitation and average temperature recorded during the experimental period. The data were obtained by a weather station located within a 7 km radius from the experimental site. Source: BRACELL. * indicates the start of evaluations (5 days before harvest) and ↓ indicates sampling times after harvest (0.3, 9.3, 15.8 and 22.3 months).

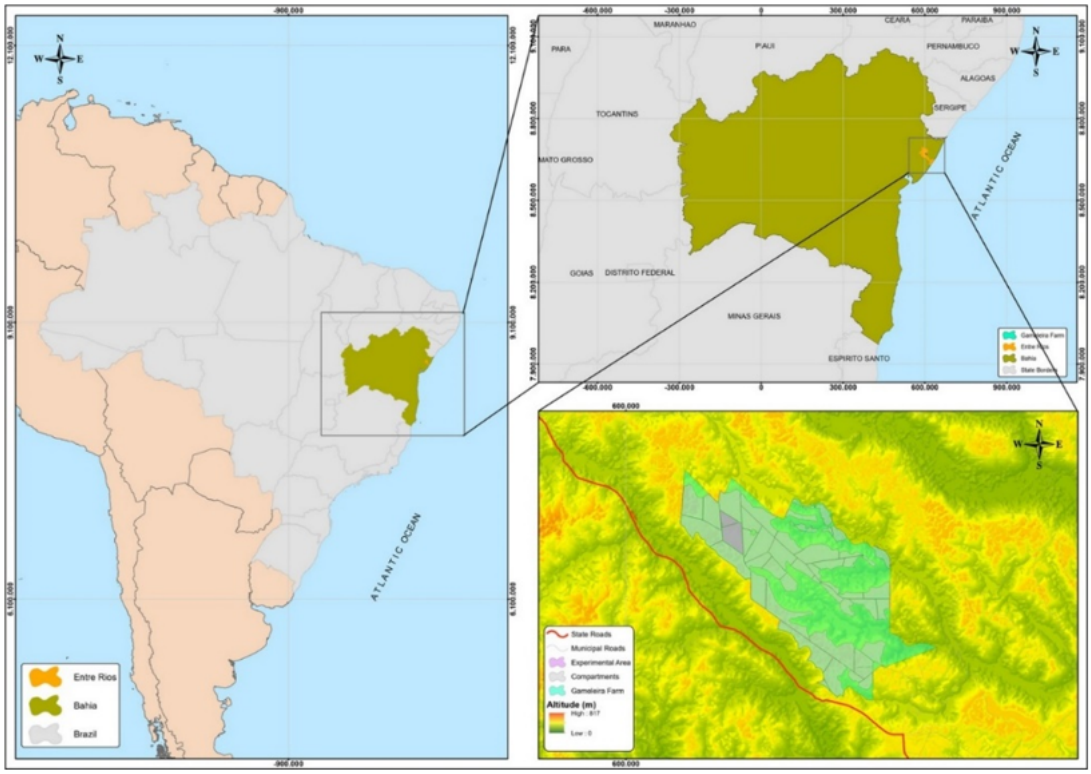

Figure 2

Location of the experimental area, in the municipality of Entre Rios - BA. Source: [18]

Figure 3

Bulk density (Ds; g cm^{-3}) in the rows (R) and inter-rows (IR) of eucalyptus plantation, before (A) and after (B) harvest. Means followed by equal uppercase letters do not differ between sampling positions (R and IR), within the same evaluation time by the F test ($p < 0.05$). Means followed by equal lowercase letters do not differ between sampling times within the same sampling position (R and IR) by the F test ($p < 0.05$). Horizontal bars denote standard deviation around the mean (n=4). Data extracted from [18].

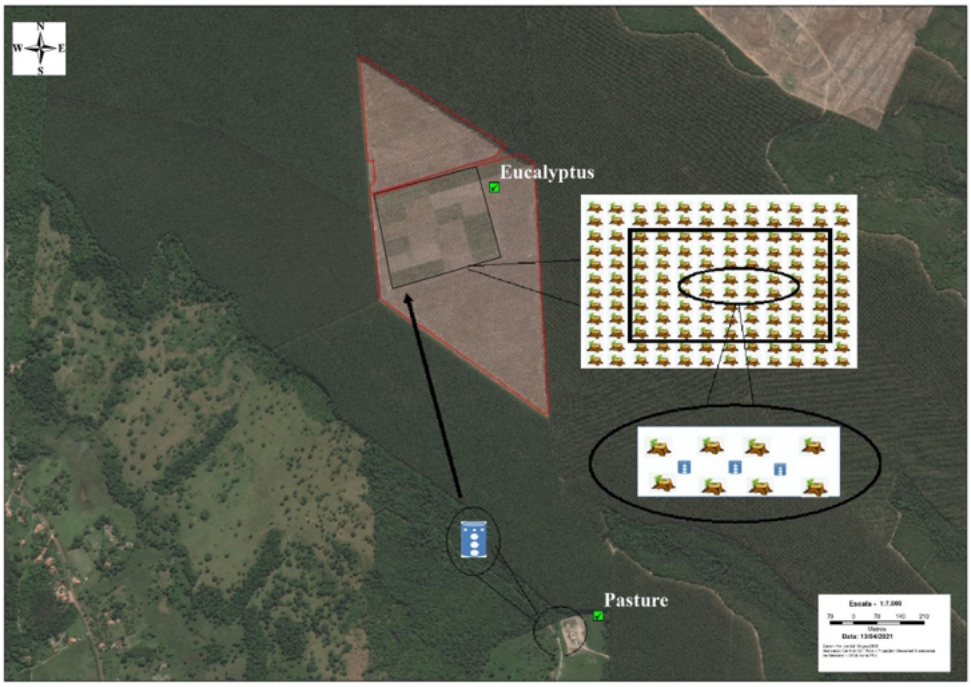

Figure 4

Installation scheme of the pipes used to measure the speed of decomposition of plant residues.

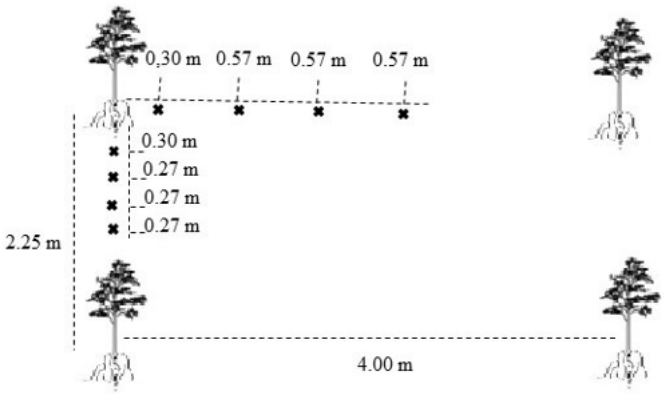

Figure 5

Sampling scheme used for root collection, in the rows and inter-rows. The area shown represents ¼ of the total tree area.

Figure 6

CO_2 (A1), CH_4 (B1), N_2O (C1) fluxes in pre-harvest (PH) and post-harvest without the presence of residues (WR), with litter from the previous rotation (L) and with harvest residues and litter from the previous rotation (HR+L) within each sampling season (at 0.3, 9.3, 15.8 and 22.3 months after harvest). Bars denote

confidence interval at 5% significance level, around the mean (n =16). In A2, B2 and C2 there are comparisons of CO_2, CH_4 and N_2O fluxes performed in the planting row and inter-row within each sampling season (pre-harvest and at 0.3, 9.3, 15.8 and 22.3 months after harvest). Bars denote confidence interval at 5% significance level, around the mean (n=8).

Figure 7

Mass loss of harvest residues + litter from the previous rotation (A1) and C and N release rates (A2). In B1, mass loss of litter from the previous rotation and, in B2, C and N release rates. Bars denote standard deviation around the mean (n=4).

Figure 8

CO_2 equivalent flux (A) in pre-harvest (PH) and post-harvest without the presence of residues (WR), with litter from the previous rotation (L) and with harvest residues and litter from the previous rotation (HR+L) within each sampling season (pre-harvest and at 0.3, 9.3, 15.8 and 22.3 months after harvest). Bars denote confidence interval at 5% significance level, around the mean (n =16). In (B) there are comparisons of the CO_2 equivalent fluxes determined in the planting row and inter-row within each sampling season (0.3, 9.3, 15.8 and 22.3 months after harvest). Bars denote confidence interval at 5% significance level, around the mean (n=8).

Figure 9

Caption not included with this version.

Figure 10

Stocks of organic carbon (A) and organic nitrogen (B) in the 0-10 cm soil layer, at 22.3 months after eucalyptus harvest, in the area without the presence of residues (WR), with litter from the previous rotation (L) and with harvest residues and litter from the previous rotation (HR+L). Bars denote standard deviation around the mean (n=4).

Figure 11

Net balance between C inputs (biomass + Δ C of soil in the 0-10 cm layer) and C outputs (CO_2 emission) in the different harvest residue managements during the initial growth cycle of eucalyptus (22.3 months).