RAPHAEL OLIVEIRA DE MELO

MANEJO DE RESÍDUOS DA COLHEITA E FERTILIZAÇÃO MINERAL DO EUCALIPTO INFLUENCIAM A FÍSICA E ATRIBUTOS MICROBIOLÓGICOS DO SOLO E A EMISSÃO DE GASES DO EFEITO ESTUFA

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Solos e Nutrição de Plantas, para obtenção do título de *Doctor Scientiae*.

Orientador: Nairam Félix de Barros

Coorientador: Leonardus Vergütz

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Assentimento:

Raphael Oliveira de Melo

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Autor

Barros

Nairam Félix de Barros
Orientador

A Deus luz em nossos caminhos.

Aos meus pais, meu espelho.

A todos os familiares e amigos que certamente se alegram por essa conquista.

Dedico

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Marcos 8:17-21

RESUMO

MELO, Raphael Oliveira, D.Sc., Universidade Federal de Viçosa, novembro de 2021. **Manejo de resíduos da colheita e fertilização mineral do eucalipto influenciam a física e atributos microbiológicos do solo e a emissão de gases do efeito estufa**. Orientador: Nairam Félix de Barros. Coorientador: Leonardus Vergütz.

A qualidade do solo pode ser influenciada pelo manejo aplicado aos resíduos da colheita florestal. O objetivo da presente pesquisa foi avaliar atributos físicos e microbiológicos do solo e o fluxo de gases do efeito estufa frente ao manejo dos resíduos de colheita de eucalipto. A pesquisa foi realizada na empresa BRACELL no município de Entre Rios, BA. Três manejos de resíduos da colheita do eucalipto foram avaliados: remoção de todos os resíduos (SR); remoção de todos os resíduos da colheita e manutenção da serapilheira da rotação anterior (S); manutenção dos resíduos da colheita inclusive a serapilheira do cultivo anterior (RC+S). Foram conduzidos três estudos, nos quais foram avaliados o impacto da retirada de resíduos de colheita de eucalipto e serapilheira: na física do solo (capítulo I); na emissão gases do efeito estufa e balanço de C no sistema solo-planta (capítulo II); e em indicadores microbiológicos do solo (capítulo III). Neste capítulo, além dos manejos de resíduos, foram estudados três níveis de fertilização: A0- sem adubação; A1- Adubação convencional, composta de 60 kg ha^{-1} de N, 110 de P_2O_5 e 158 de K_2O (A1); A2- adubação potencial, composta de 72 kg ha^{-1} de N, 133 de P_2O_5 e 188 de K_2O. No Capítulo I evidenciou-se que o manejo RC+S evitou o aumento na densidade e na resistência mecânica à penetração do solo frente ao tráfego da subsoladora durante o preparo do solo para a reforma do plantio. No Capítulo II demonstrou-se que ocorre maior fluxo de CO_2 equivalente no solo nos primeiros meses após a retenção dos resíduos (RC+S), influência que cessa depois de um certo período, não sendo mais observadas diferenças entre os tratamentos. Além disso, durante o período experimental, não foram observadas diferenças no teor de matéria orgânica do solo e fixação de C na biomassa vegetal causadas pelos tratamentos. No Capítulo III detectou-se que a retenção de resíduos da colheita (tratamento RC+S ou S) aumenta a respiração e o carbono da biomassa microbiana nos primeiros meses após a colheita, independentemente dos níveis de adubação. A fertilização reduziu atividade da enzima urease, durante todo o experimento independentemente do manejo de resíduos. Constatou-se que houve interação entre o manejo de resíduos e níveis de fertilizantes para a atividade da fosfatase alcalina e qCO_2. Embora as projeções mostrem crescente demanda global na utilização de resíduos da colheita do eucalipto, sua manutenção na área de plantio pode atenuar a deterioração física do solo frente ao tráfego máquinas pesadas e manter e/ou melhorar a atividade microbiana do solo, principalmente por reduzir a quantidade de fertilizantes minerais aplicados. Para melhor entendimento dos efeitos do manejo de resíduos no balanço de C no sistema solo-planta e emissão de gases do efeito estufa, são recomendados estudos de maior duração.

Palavras-chave: *Eucalyptus.* Sustentabilidade. Resíduos florestais

ABSTRACT

MELO, Raphael Oliveira, D.Sc., Universidade Federal de Viçosa, November 2021. **Management of eucalyptus harvest residues and mineral fertilization influence soil physical and microbiological attributes and greenhouse gas emissions**. Advisor: Nairam Félix de Barros. Co-advisor: Leonardus Vergütz.

Soil quality can be influenced by the management applied to the forest harvest residues. The objective of this study was to evaluate soil physical and microbiological attributes and the flux of greenhouse gases as affected by the management of eucalyptus harvest residues. The study was carried out at the BRACELL company in the municipality of Entre Rios, BA, Brazil. Three managements of eucalyptus harvest residues were evaluated: removal of all residues (SR); removal of all harvest residues and maintenance of litter from the previous rotation (S); maintenance of harvest residues including litter from the previous crop (RC+S). Three studies were conducted, evaluating the impact of the removal of eucalyptus harvest residues and litter: on soil physical attributes (chapter I); on the emission of greenhouse gases and C balance in the soil-plant system (Chapter II); and on microbiological indicators of the soil (Chapter III). In this chapter, in addition to managements of residues, three levels of fertilization were studied: A0- without fertilization; A1- conventional fertilization, composed of 60 kg ha^{-1} of N, 110 of P_2O_5 and 158 of K_2O; A2- potential fertilization, composed of 72 kg ha^{-1} of N, 133 of P_2O_5 and 188 of K_2O. In Chapter I it was shown that the RC+S management avoided the increase in soil bulk density and resistance to mechanical penetration under the traffic of the subsoiler during soil tillage for planting a new rotation. In Chapter II it was shown that there is a greater CO_2 equivalent flux in the soil in the first months after retention of residues (RC+S), an influence that ceases after a certain period, with no more differences between treatments. In addition, during the experimental period, no differences were observed in soil organic matter content and C fixation in plant biomass between treatments. In Chapter III it was found that the retention of harvest residues (RC+S or S treatment) increases microbial biomass respiration and carbon in the first months after harvest, regardless of the fertilization levels. Fertilization reduced urease enzyme activity throughout the experiment, regardless of residue management. It was found that alkaline phosphatase activity and metabolic quotient were influenced by the interaction between residue management and fertilizer levels. Although projections show increasing global demand for the use of eucalyptus harvest residues, their maintenance in the planting area can mitigate the physical deterioration of the soil caused by heavy machinery traffic and maintain and/or improve soil microbial activity, mainly by reducing the quantity of mineral fertilizers applied. For a better understanding of the effects of residue management on the C balance in the soil-plant system and greenhouse gas emission, longer studies are recommended.

Keywords: *Eucalyptus*. Sustainability. Forest residues.

SUMÁRIO

1. Introdução Geral

As florestas plantadas de eucaliptos no Brasil são manejadas intensivamente, o que resulta em alta produção de biomassa comparativamente com muitos outros países. Isso leva a rotações de curta duração, que são mais comparáveis aos sistemas agrícolas do que à silvicultura clássica, tanto da perspectiva da intensidade do manejo como na influência sobre os fatores ambientais. O alto nível de produtividade no Brasil é alcançado em razão do clima favorável à eucaliptocultura na maior parte do território aliado ao melhoramento genético, manejo da fertilização e práticas silviculturais (Binkley et al., 2017; Gonçalves et al., 2013; Scolforo et al., 2019; Stape et al., 2010).

Na colheita florestal gera-se grande quantidade de resíduos, compostos principalmente por galhos, cascas, folhas e serapilheira. Aproximadamente 20 % da biomassa do eucalipto se reverte em resíduos no momento da colheita (Daystar et al., 2014). No Brasil, normalmente os resíduos gerados na colheita são mantidos na área produtiva (Amorim et al., 2021), e, na maioria das vezes, não são incorporados quando é feito preparo do solo, ocorrendo incorporação em algum grau apenas na linha de plantio, pelo uso, quase sempre, de subsoladores (Gonçalves et al., 2016).

Os resíduos gerados na colheita possuem potencial para uso energético (Amorim et al., 2021; Motghare et al., 2015; Ayer & Dias, 2018), além de poder ser utilizados como matéria prima em indústrias que utilizam serragem e cavacos (Amorim et al., 2021; IBÁ 2019). A utilização de resíduos de florestais para geração de energia tem se intensificado em vários países, em razão do aumento da demanda energética, exaustão de fontes não renováveis e por pressões ambientais (U.S. Energy Information Admnistration, 2019). Em 2015, no acordo de Paris, o Brasil firmou o compromisso de aumentar em 18 % a participação da biomassa na produção de energia primária, e atingir 45 % de utilização de energia renovável (Machado et al., 2020). O País possuí enorme potencial para geração de energia pela utilização da biomassa florestal, pois tem cerca de 7,8 milhões hectares de florestas plantadas, com condições para aumento da área cultivada e elevação da produtividade em razão das condições edafoclimática favoráveis, disponibilidade de área e tecnologia (IBÁ, 2019).

Sendo assim, atualmente discute-se a possibilidade de recolher totalmente ou parcialmente os resíduos da colheita do eucalipto com vistas ao seu aproveitamento para produção de energia (Luiz *et al.,* 2014; Daystar *et al.,* 2015; Machado *et al,.* 2020). Dessa maneira, torna-se importante o monitoramento do efeito da retirada dos resíduos florestais da área produtiva, havendo a necessidade de avaliar o impacto dessa prática na qualidade do solo e produtividade florestal, a curto, médio e longo prazo. Alguns estudos já mostram que a retirada dos resíduos da colheita florestal afeta a microbiota do solo (Oliveira et al., 2021; Rocha et al., 2018; Kumaraswamy et al., 2014), reduzindo a ciclagem de nutrientes (Versini et al., 2014; Santana et al., 2008) e diminuindo também os estoques de C no solo (Teixeira et al., 2020; Rocha et al., 2016). Além disso, a retenção de resíduos florestais reduz os processos erosivos (Matthews, 2005) e diminuí a compactação do solo durante o tráfego de máquinas e implementos (Melo et al., 2021; de Jesus et al., 2015). A retirada de resíduos impacta a produtividade florestal (São José et al., 2020; Mendham et al., 2014). Outros estudos mostram que a retenção de resíduos florestais não afeta a produtividade florestal a curto (Barros et al., 2021) e médio prazo (Rocha et al., 2016)

Embora seja eminente o aumento de projetos que preveem a retirada dos resíduos da colheita do eucalipto da área da floresta, as pesquisas no Brasil que avaliam os efeitos dessa prática no solo ainda são escassas. Deve-se considerar que o país possui grandes dimensões territoriais, e as respostas dos manejos dos resíduos do eucalipto podem variar com o manejo empregado ou com as características edafoclimáticas da região em que está inserida a exploração florestal.

Nesse contexto, o objetivo deste trabalho foi avaliar os atributos físicos, microbiológicos e o balanço da emissão de gases do efeito estufa, sob diferentes manejos de resíduos da colheita do eucalipto.

Para atingir os objetivos, foram realizadas avaliações em uma floresta comercial de eucalipto que passou por diferentes manejos de resíduos da colheita, e aplicação de diferentes níveis de adubação (este último fator se aplica apenas para o capítulo 3), os resultados são apresentados em três capítulos:

Capítulo 1: Retention of eucalyptus harvest residues reduces soil compaction caused by deep subsoiling. O artigo está publicado no periódico *Journal Forest Research.*

Capítulo 2: CO_2, N_2O and CH_4 emissions and C storage in eucalyptus forests with different managements of harvest residues.

Capítulo 3: Manejo de resíduos da colheita e fertilização mineral do eucalipto influenciam atributos microbianos do solo.

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Retention of eucalyptus harvest residues reduces soil compaction caused by deep subsoiling

Abstract

Eucalyptus harvesting, forwarding and soil tillage operations are among the main causes for compaction of forest soils, with potential impacts on productivity. This concern is especially important in areas with soils that are naturally compacted (fragipans and duripans). In these soils, tillage operations include the use of subsoilers that can reach depths of more than one metre and require heavy tractors that exert high pressure on the soil. One of the ways to try to minimize the effect of this compaction is by retaining harvest residues. In this context, the objective of this study was to evaluate the impacts of eucalyptus harvesting on soil physical attributes, as well as to determine the potential of different types of residue management to reduce compaction from the soil tillage operation. Two experiments were conducted in the same area with a Yellow Argisol. In the first experiment, compaction caused by mechanized harvesting with harvester + forwarder was evaluated. In the second experiment, different managements of harvest residues were examined as potential modifiers of soil compaction during tillage for new plantings. For this, three managements systems were tested: a) retention of all harvest residues and litter from the previous rotation (HR+L), b) retention of litter from the previous rotation (L), and c) removal of harvest residues and litter from the previous rotation (WR). Before and after harvest, sampling was carried out in the planting rows and inter-rows, and after tillage, samples were collected in the traffic line of the subsoiler-tractor set. In both experiments, undisturbed soil samples were collected from the center of the 0–10, 10–20, 20–40, 40–60 and 60–100 cm layers to determine soil density and total porosity. In each period and site of evaluation, mechanical resistance to penetration up to the 60- cm depth was also determined. The harvesting operation increased soil density at 0–10 and 60–100 cm depths only in the inter-rows. Retention of harvest residues and litter (HR+L) after harvesting avoided increases in soil density and penetration resistance caused by machine traffic during tillage. The results indicate the importance of retaining harvest residues on forest soils for achieving sustainable utilization and for conserving soil quality.

Key words: Soil penetration resistance; Harvester + forwarder; Soil tillage; Soil density; Cohesive soils

Introduction

Brazil has the largest area planted with eucalyptus in the world, approximately 7.5 $\times 10^6$ ha (IBGE 2019), in addition to having one of the highest average productivities, 36 m^3 ha^{-1} (IBÁ 2019). An important part of the eucalyptus stands in Brazil is located in the region of the Coastal Tablelands, concentrated mainly in the states of Espírito Santo and Bahia. The soils in this region generally have naturally cohesive subsurface horizons (Moreau et al. 2006; Lima Neto et al. 2009; Gomes et al. 2012), with the presence of pans which can range from very hard to extremely hard when dry and from friable to firm when moist (Santos et al. 2018).

The hardened layers in the soils of the Coastal Tablelands can restrict permeability and root development, being strong limiting factor for plant production. Under these conditions, even the root system of tree species such as eucalyptus can undergo morphological and physiological changes that adversely affect growth and productivity (Bengough et al. 2011; Silva et al. 2018).

In commercial eucalyptus plantations on the coast of Bahia, subsoiling is commonly carried out to a depth of 1.1 m (Stape et al. 2002). This practice improves soil penetration and facilitates the growth of tree roots, which are able to explore larger volumes of soil and to absorb greater amounts of water and nutrients (Gonçalves et al. 2016). Studies have indicated the effectiveness of deep subsoiling in commercial eucalyptus plantations on cohesive soils in the region of Entre Rios, Bahia, with greater initial growth of seedlings compared to the use of holes for planting (Stape et al. 2002).

Although it can be efficient as a form of soil tillage, subsoiling at great depths requires robust and heavy machines with high traction power. D8T-type tractors are often used, which exert high pressure on soils and increase compaction. Compaction reduces aeration and hydraulic conductivity and increases resistance to root system development (Tracy et al. 2011), which can limit the absorption of water and nutrients, negatively affecting productivity (Luciano et al. 2012).

At the same time, forestry activities generate large volumes of residues after harvesting operations, when up to 20% of the biomass might be left on the surface (Daystar et al. 2015). When residues are left, a protective layer is formed which reduces the contact and pressure of machines, hence lessening compaction. Maintaining the residues generated in eucalyptus harvesting minimizes the effects of soil compaction caused by machine traffic during wood forwarding (de Jesus et al. 2015; Tassinari et al. 2019). However, the compaction-reducing effect promoted by harvest residues is little known for tillage operations, especially when using robust tractors that perform subsoiling at great depths.

The hypothesis of this study is that leaving eucalyptus harvest residues on site reduces the effects of compaction caused by heavy machines used in deep subsoiling on soils with naturally cohesive horizons.

This study evaluates the impact of eucalyptus harvesting on soil physical attributes and whether the retention of harvesting residues effectively lessens compaction caused during soil tillage at great depths.

Material and methods

Experimental site

The experiment was conducted in commercial eucalyptus plantations of the BRACELL company located in the municipality of Entre Rios (Bahia), at 38° 3'36″ S and 12° 1' 17″ W (Fig. 1). The altitude is 180 m, with a predominant flat relief. The climate is Af, rainy tropical with dry summers (Fig. 2). The original natural vegetation was Atlantic Rainforest which has been replaced by pastures and commercial eucalyptus plantations.

The soil is sandy-loam, dystrophic cohesive Yellow Argisol according to Santos et al. (2018), which corresponds to Ultisol in the soil classes of Soil Taxonomy (Soil Survey Staff 2014). The soil belongs to the set termed ‘Coastal Tablelands’ of the Barreiras Group, a formation that consists of sandy-clay sediments with the sand fraction dominated almost exclusively by quartz and the clay fraction by kaolinite, in addition to low levels of iron oxides (Vilas Bôas et al. 2001).

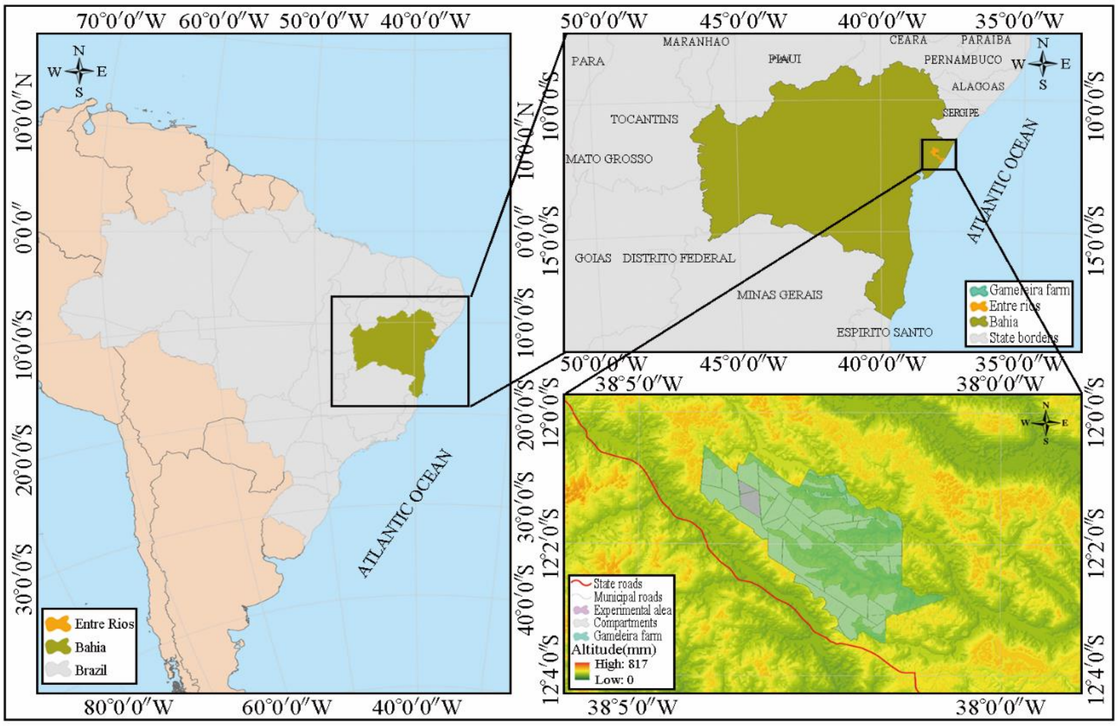

Fig. 1 Location of the experimental area in the municipality of Entre Rios - BA, Brazil (Source: BRACELL company)

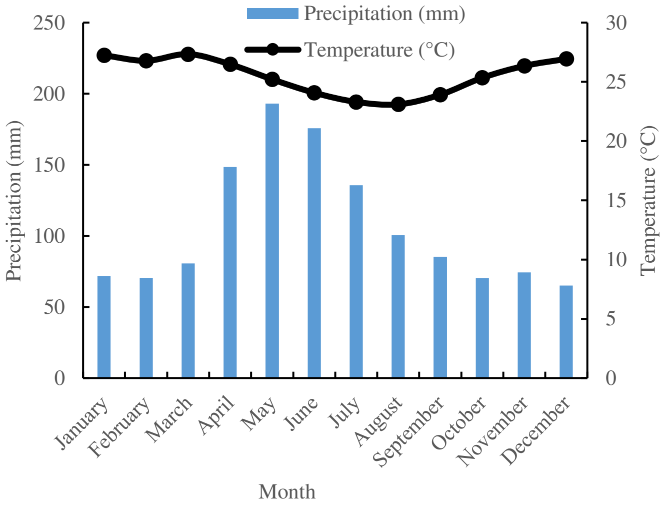

Fig. 2 Average monthly precipitation and temperature for 1988–2018 obtained at the Quatis weather station in the municipality of Entre Rios - BA, Brazil, located approximately 7 km from the experimental area (Source: BRACELL company)

Experimental design

A 10-ha plot (Fig. 3) of the eucalyptus clone 1404 (*Eucalyptus urophylla* × *Eucalyptus grandis*), following its third rotation, was selected and planted at 4.0 × 2.4 m spacing. The harvesting operation was of the shallow- cut type with the use of a Komatsu Harvester (HV)

PC200-8 model equipped with tracks, 110 kW (148 HP) power and a mass of 24 Mg. Logs were forwarded with a Komatsu Forwarder (FW), 895 model, with extra-wide tires, 193 kW power (262 HP), mass of 18 Mg and load capacity of 20 Mg.

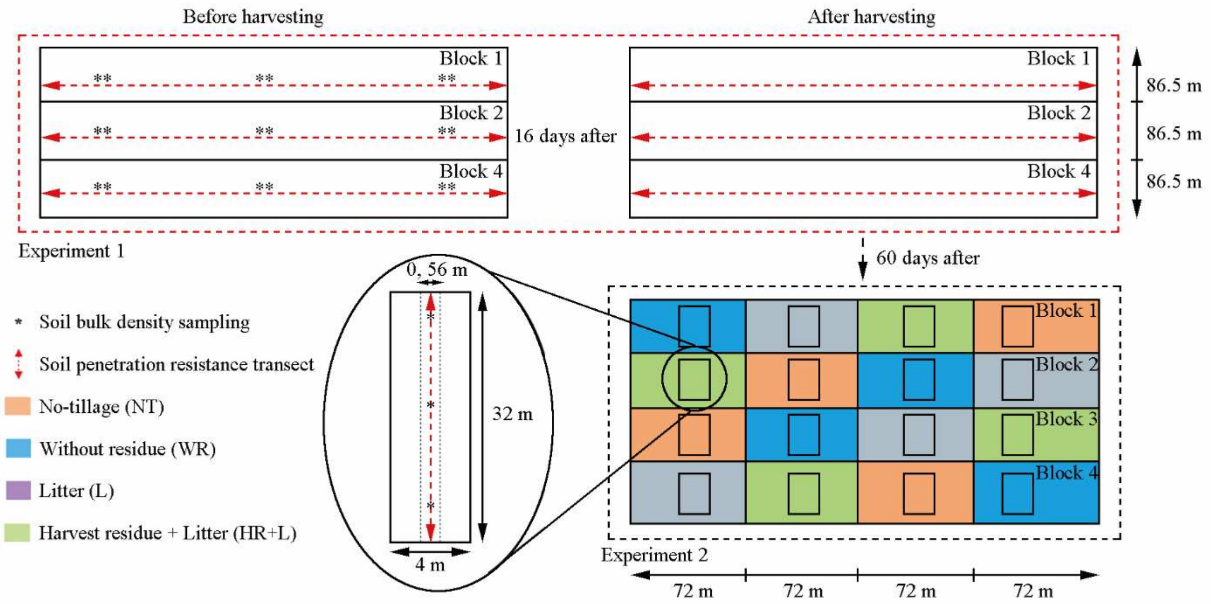

Fig. 3 Sketch of the experimental area and the experimental evaluations performed

After harvesting and removing the wood, the area was divided to receive three treatments related to different management of forest residues: retention of harvest residues (leaves, branches and bark) and litter from the previous rotation (HR+L); retention of only litter (L); and, removal of all harvest residues and litter (WR). When present, the dry matter weight of the residues was equivalent to 24.0 and 10.7 Mg ha^{-1} for HR and L, respectively.

The relative proportions in the dry mass of harvest residues was 13.3% ± 0.2 % leaves, 22.7% ± 3.7 % branches, 52.6% ± 3.4 % bark and 11.4% ± 0.3 % tips (trunk segment with diameters < 4 cm). In the litter, 35.4% ± 5.7% and 64.6% ± 6.9 % corresponded to leaves and branches, respectively. The composition of the relative proportion in mass of HR was obtained after felling five trees with diameters corresponding to the mean of the stand. The means obtained were extrapolated to the number of trees present on 1 ha. Litter composition was quantified 7 days before harvest from 24 samples randomly collected using a 0.5 m × 0.5 m square metal frame. Samples of the components of the harvest residues and litter were dried in a closed-circulation oven with air renewal at 65 °C until reaching constant weight for moisture correction.

Tillage for the new plantation was carried out 60 days after harvest using a Caterpillar D8T tractor with tracks, 253 kW (343 HP) power and an operating mass of 38.9 Mg, using a single-shank trailed subsoiler operated to form furrows with 1.1 m depth and width. Subsoiling was performed in the center of the inter-row of the previous plantation.

Experimental evaluations

The study consisted up two soil compaction evaluations, the first to evaluate the result of harvesting operations and the second to evaluate the effect of the retention of harvest residues on the reduction of compaction caused by deep subsoiling.

For the evaluation of the impacts of wood harvesting and forwarding operations (traffic of HV and FW, respectively) on the physical quality of the soil, the area was subdivided into four blocks (Fig. 3). In each block, three random points were selected in the rows and inter-rows to collect undisturbed soil samples. Sampling was carried out before and after harvesting using cylindrical rings 5 cm in height and diameter in the center of the 0–10, 10–20, 20–40, 40–60 and 60–100 cm soil layers. These samples were used to determinesoil bulk density (Ds) according to Teixeira et al. (2017). To reduce spatial variability, the samplesbefore and after harvest were carried out in areas close to each other, achieved by painting the bases of tree trunks before harvest to mark the site.

Before and after harvesting, soil penetration resistance (PR) was evaluated up to a 60–cm depth with a FALKER digital penetrometer, PenetroLOG - PLG 1020 model with automatic data acquisition. The penetrometer was set to record readings every 1 cm increment of depth, working at a constant penetration speed. PR data processing was carried out using PenetroLOG software. In each block before and after harvest, 36 observations were made in the rows and 36 in the inter-rows following a transect (Fig. 3). At the time of PR evaluations, soil samples were collected at depths of 0–10, 10–20, 20–40 and 40–60 cm using a hand auger to determine soil moisture by the thermogravimetric method as described by Teixeira et al. (2017).

The effects of harvest residues on the mitigation of soil compaction caused by deep subsoiling were evaluated in the same experimental area (Fig. 3). An experiment was set up in a randomized complete block design with four replicates to evaluate the three types of residue management (HR+L, L and WT). Additionally, a nearby reference area which was harvested but not subject to subsoiling was also evaluated. Each replicate was formed by one 32 m× 4 m area.

At the time of soil tillage and in the traffic lines of the D8T tractor (0.4-m-wide strip) pulling the subsoiler, three undisturbed samples were collected in each replicate and in the center of the 0–10, 10–20, 20–40 and 40–60 and 60–100 cm soil layers to determine bulk density (Fig. 3). These same samples were used to evaluate particle density and both used to calculate total porosity (Teixeira et al. 2017). Soil penetration resistance was evaluated again up to 60 cm at 12 points in each replicate.

The data were subjected to the Shapiro-Wilk test to evaluate homoscedasticity and to the Hartley test to verify data normality. The data were subjected to ANOVA to test the effect of treatment on bulk density and total porosity by the Tukey test ($p<0.05$). All statistical analyses were performed in R software version 4.0.0 (R Core Team 2018). Soil penetration resistance data were subjected to descriptive statistical analysis.

Results and discussion

Effect of harvesting and forwarding on soil density and mechanical resistance to penetration

The highest means of bulk densities were found in the upper 10 cm surface layer and the lowest in the deepest soil layer (60–100 cm) (Fig. 4). The sand content decreased with increasing depth (Table 1). Quartz present in higher percentages in the sand fraction makes the soil denser (Libardi 2005). Bulk density in the upper -10 and 60–100 cm layers in the inter-rows increased by 7% and 9% ($p<0.05$), respectively, due to wood harvesting and removal (Fig. 4).This is the predominant traffic position of the Harvester (HV) and Forwarder (FW).

The more superficial soil layers are more susceptible to compaction, as they are subject to direct pressure. In addition, they are more porous and hence more vulnerable when receiving external loads from machine traffic (Szymczak et al. 2014). However, Berisso et al. (2012) observed that machine traffic can cause soil bulk density to increase up to 90 cm deep. The compaction process is intensified in soils with higher clay contents (Suzuki et al. 2008). As depth increased in the soil under study, there was an increase in clay content (Table 1), which led to a significant increase in bulk density in the 60–100 cm layer after HV and FW traffic in the inter-rows (Fig. 4).

Soil penetration resistance, unlike bulk density, was reduced after the harvest operation (Fig. 5). This was contrary to what was expected, and such divergence may be explained by differences in soil moisture at the time of each evaluation (pre- and post-harvest) (Fig. 5). The correlation between bulk density and penetration resistance depends on soil moisture at the time of penetration resistance evaluation (Dexter et al. 2007).

Table 1 Physical and chemical characteristics of the cohesive Yellow Argisol soil in the rows and inter-rows of eucalyptus plantations at different soil layers

Position	Soil layers (cm)	Sand^1 (kg kg^{-1})	Silt^1(kg kg^{-1})	Clay^1(kg kg^{-1})	θ FC^2(kg kg^{-1})	θ PWP^3(kg kg^{-1})	SOM^4 (%)
Planting row	0-10	$0.75^{\pm0.02}$	$0.01^{\pm0.01}$	$0.24^{\pm0.02}$	$0.13^{\pm0.01}$	$0.07^{\pm0.01}$	$2.19^{\pm0.40}$
	10-20	$0.73^{\pm0.02}$	$0.01^{\pm0.01}$	$0.26^{\pm0.03}$	$0.15^{\pm0.01}$	$0.07^{\pm0.01}$	$1.92^{\pm0.13}$
	20-40	$0.66^{\pm0.04}$	$0.01^{\pm0.01}$	$0.33^{\pm0.04}$	$0.18^{\pm0.02}$	$0.10^{\pm0.01}$	$1.55^{\pm0.08}$
	40-60	$0.56^{\pm0.05}$	$0.01^{\pm0.01}$	$0.43^{\pm0.05}$	$0.20^{\pm0.02}$	$0.11^{\pm0.01}$	$1.21^{\pm0.16}$
	60-100	$0.49^{\pm0.03}$	$0.01^{\pm0.01}$	$0.50^{\pm0.02}$	$0.21^{\pm0.03}$	$0.13^{\pm0.02}$	$0.84^{\pm0.17}$
Planting inter-row	0-10	$0.76^{\pm0.02}$	$0.01^{\pm0.01}$	$0.23^{\pm0.02}$	$0.12^{\pm0.01}$	$0.06^{\pm0.01}$	$2.42^{\pm0.01}$
	10-20	$0.70^{\pm0.03}$	$0.01^{\pm0.01}$	$0.28^{\pm0.03}$	$0.13^{\pm0.01}$	$0.07^{\pm0.01}$	$1.95^{\pm0.23}$
	20-40	$0.57^{\pm0.02}$	$0.01^{\pm0.01}$	$0.42^{\pm0.03}$	$0.15^{\pm0.01}$	$0.08^{\pm0.01}$	$1.31^{\pm0.13}$
	40-60	$0.49^{\pm0.03}$	$0.01^{\pm0.01}$	$0.50^{\pm0.04}$	$0.17^{\pm0.01}$	$0.10^{\pm0.02}$	$1.01^{\pm0.36}$
	60-100	$0.46^{\pm0.07}$	$0.01^{\pm0.01}$	$0.53^{\pm0.08}$	$0.20^{\pm0.03}$	$0.12^{\pm0.02}$	$1.08^{\pm0.36}$

Notes: ^{1} Particle size analysis with the pipette method (Ruiz 2005);^{2} Moisture at field capacity at -10 kPa matrix potential; ^{3} Moisture at the permanent wilting point with matrix potential of -1500 kPa; ^{4} Soil organic matter = C.org × 1.724 (Walkley Black).

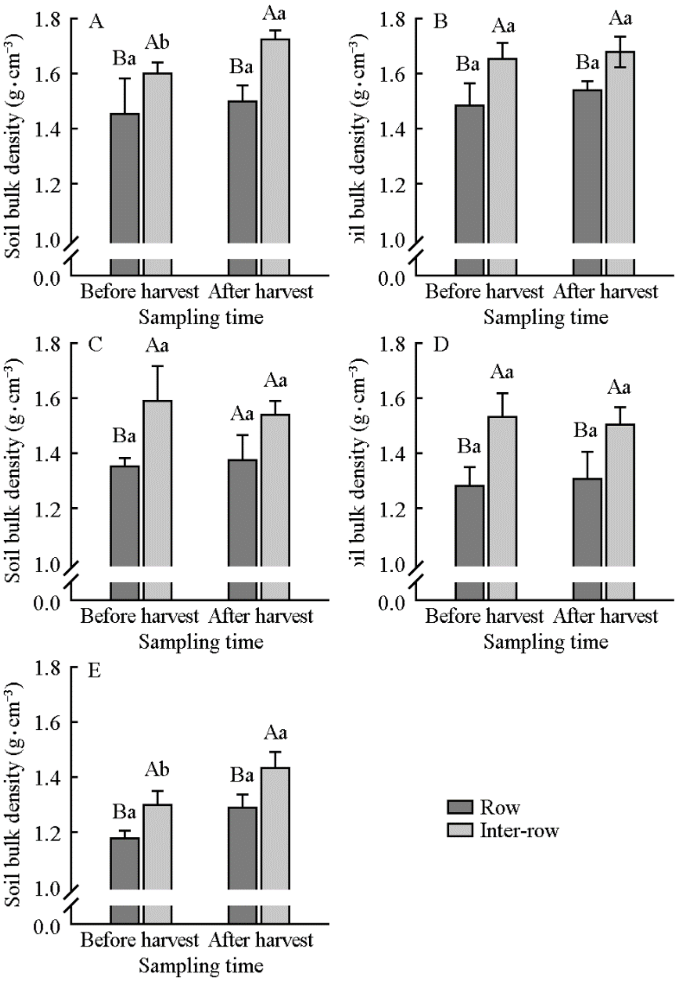

Fig. 4 Soil bulk density (g cm^{-3}) in the planting rows and inter-rows, before and after eucalyptus harvest; (A) 0–10, (B) 10–20, (C) 20–40, (D) 40–60 and (E) 60–100 cm soil layers. Equal uppercase letters did not differ from each other regarding sampling position for the same time of evaluation by Tukey test ($p < 0.05$). Equal lowercase letters did not differ regarding sampling time by Tukey test ($p < 0.05$).

Soil penetration resistance evaluations at pre-harvest were performed on dry soil, with soil moisture close to the permanent wilting point (Table 1; Fig. 5). However, after harvest, soil moisture was close to field capacity (Table 1; Fig. 5). According to Assis et al. (2009), soil penetration resistance is dependent on soil moisture, and the higher the water content in the soil, the greater the changes in the conditions of friction between the perforating cone and the soil, facilitating the penetration of the rod and making the soil more plastic due to the lubricating action of the water. The cohesive Yellow Argisol soil is extremely hard when dry, and firm to friable when moist (Silveira et al. 2010; Santos et al. 2018).

Soil penetration resistance values indicate a more intense physical impediment in the inter-rows compared to the rows, regardless of the evaluation time (Fig. 4). On this site, regardless of the passage of the harvester and forwarder, in the 0–10, 10–20 and 20–40 cm layers, the average bulk density was higher than 1.5 g cm^{-3}; this did not occur in the planting rows (Fig. 4). In medium-textured soil, as in the present study, Ribeiro et al. (2010) found that bulk density values ≥ 1.5 g cm^{-3} inhibited the development of the eucalyptus root systems. On the Coastal Tablelands of Brazil, regardless of agricultural mechanization, the average soil bulk density is 1.5–1.8 g cm^{-3} (Giarola and da Silva 2002). There is little information on the development of eucalyptus roots in cohesive soils. Nevertheless, root system expansion occurs mainly in rainy periods when soil moisture approaches field capacity and there is a reduction in mechanical resistance to penetration (Fig. 5). Another factor that contributes to eucalyptus root development in cohesive soils is the practice of deep subsoiling (Stape et al. 2002).

Subsoiling performed five years after soil tillage was responsible for the lower values of bulk density and soil penetration resistance in the planting rows (Figs. 4 and 5), as turning the soil causes the fracture of aggregates and development of macropores, leading to reduction of bulk density and less resistance to root penetration (Tormena et al. 2002). Additionally, there may have been more biopore formation in the planting rows due to the greater activity of edaphic fauna and tree roots, contributing to the lower bulk density and penetration resistance values (Bodner et al. 2014). The lower physical impediment in the planting rows (Fig. 4 and 5) can be critical when choosing to grow suckers instead of replanting seedlings, as soil tillage is a costly activity, especially when performed at great depths as in the Coastal Tablelands.

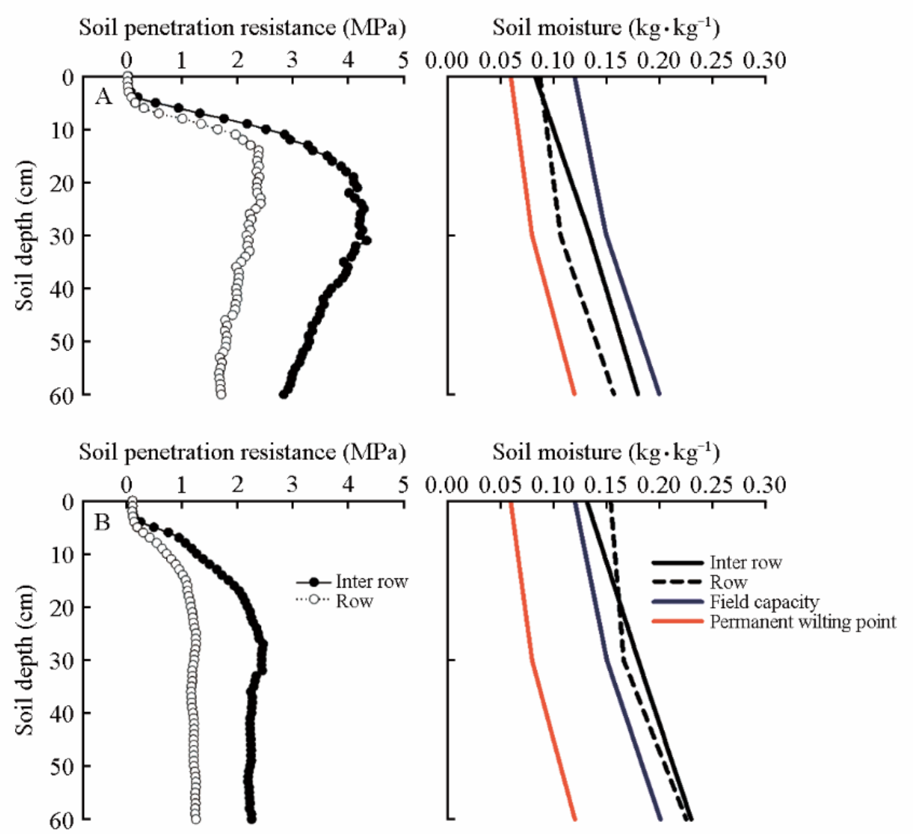

Fig. 5 Soil penetration resistance (MPa) and soil moisture (kg kg^{-1}) in the planting rows and inter-rows, before (A) and after (B) eucalyptus harvest

Retention of harvest residues related to compaction

The amount and type of harvest residues influenced the bulk density and total porosity after passing of the D8T subsoiler used for tillage. The lowest values of bulk density and the highest of total porosity were found in the upper 10 cm layer where the D8T impact did not occur (WT) (Fig. 6 and Table 2). The only treatment evaluated that showed results similar to those of the control area (WT) at the same depth was HR+L, in which the subsoiler passed on the harvest residues and litter from the previous rotation. At the other depths, there were no differences in bulk density and total porosity between treatments.

In the upper 10 cm layer, D8T traffic increased the bulk density by 9%, 11% and 6 % and reduced porosity by 14%, 16% and 10 % in the L, WR and HR+L treatments, respectively, compared to WT. The increase in bulk density due to D8T traffic in the different treatments was not more pronounced only because of the history of pressures to which the soil was subjected, since mechanized harvesting was adopted at the beginning of the present experiment. With the harvesting and forwarding operations, bulk density in the inter-rows had increased by 7% and 9% in the 0–10 and 60–100 cm layers, respectively, compared to the pre-harvest figure

(Fig. 6). According to Williamson and Neilsen (2000), the higher the density of the soil, the less it will be prone to undergo additional compaction. Once compacted, the soil is relatively less compressible due to the higher proportion of micropores compared to macropores.

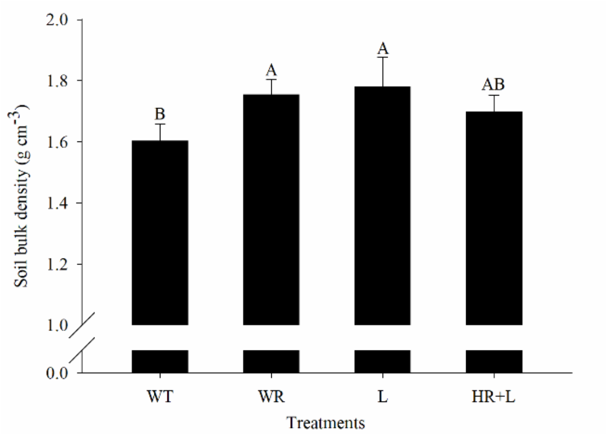

Fig. 6 Soil bulk density (g cm^{-3}) at the 0–10 cm soil layer of the site where the D8T tractor passes on eucalyptus harvest residues and litter from the previous rotation (HR+L); only on the litter from the previous rotation (L); soil without residues (WR); and control, where tractor traffic did not occur (WT). Means followed by the same letter did not differ from each other by Tukey test ($p < 0.05$).

The amount and type of residues that remain on the surface mitigates the increase in bulk density and porosity resulting from machine traffic (Fig. 6; Table 2). When only litter was kept on the surface, there was no reduction of the impacts of D8T traffic, i.e., after tillage, the physical conditions of the soil were similar to areas with no residues. Bark and branches remaining on the surface in the HR+L treatment (76% of the relative weight of harvest residues) are likely to be important for reducing physical damage caused by machine traffic. Silva et al. (2007), evaluating the impact of a forwarder on brushwood, brushwood + bark, soil without residues and a site without machine traffic, concluded that forest residues minimized soil compaction. They also found that soil without residues was more susceptible to compaction and that the presence of brushwood + bark promoted the greatest resistance to compaction.

Penitration resistance was also affected by D8T traffic, as can be seen from the difference between the areas under subsoiler traffic (WR, L and HR+L) and the reference area WT (Fig. 7). As in the present study, Andrade et al. (2011), also found an increase in penetration resistance in the traffic lines of a subsoiler. In this study, the differences were observed in the 20–60 cm layer and resulted from the increase of clay content in the subsurface which are more compressible than sandy soils (Suzuki et al. 2008).

Table 2 Total porosity (m^3 m^{-3}) at the site where the D8T tractor passes on eucalyptus harvest residues and litter from the previous rotation (HR+L); only on litter from the previous rotation (L); soil without residues (WR); and control, where tractor traffic did not occur (WT)

Treatments	Soil layers				
	0-10 cm	10-20 cm	20-40 cm	40-60 cm	60-100 cm
	Porosity (m^3 m^{-3})				
WT	42.8 a	40.7 a	39.7 a	46.7 a	49.2 a
WR	37.0 b	41.9 a	40.8 a	46.0 a	49.5 a
L	35.9 b	41.9 a	41.2 a	47.8 a	45.8 a
HR+L	38.4 ab	39.7 a	40.5 a	51.2 a	51.8 a
CV (%)	6.7	6.0	9.3	6.2	5.6

Notes: Means followed by the same letters did not differ from each other by Tukey's test (p <0.05).

It was not possible to observe a well-defined penetration resistance under different types of residue management except for the 10–20 cm layer, in which areas with retention of residues (L and HR+L) were similar to those of the reference area (WT) (Fig. 7). Plant residues reduce the contact pressure at the machine wheel-soil interface due to the increase in the contact area, reducing the applied pressure and dissipating the compaction energy on the soil (Achat et al. 2015). At the other depths, penetration resistance on soil without residues (WR) was expected to be higher than in the other treatments with retention of residues (L and HR+L). However, soil moisture at the time of the evaluations was higher in the treatment without residues (Fig. 7), which reduced penetration resistance at the time of evaluation (Assis et al. 2009). The lower soil moisture content in the treatments L and HR+L can be attributed to the interception of rainwater by the residues (Du et al. 2019), causing a reduction in water infiltration.

Removing harvest residues is an alternative to increasing the operability of machines and implements during soil tillage, besides being an opportunity for generating extra revenue with bioenergy production, especially in the face of the growing global demand for the use of renewable sources (International Energy Agency 2019). However, the maintenance of harvest residues in the planting area increases nutrient cycling and organic matter content (Rocha et al. 2016), and contributes to mitigating soil physical deterioration under the traffic of increasingly robust machines.

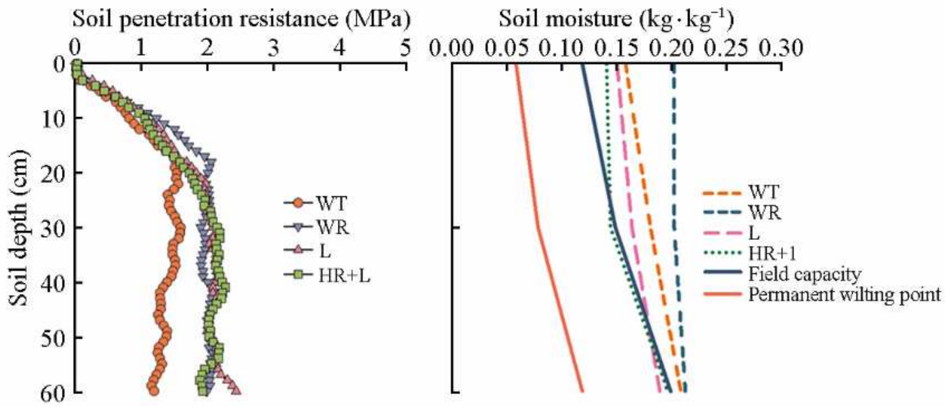

Fig. 7 Soil penetration resistance (MPa) and soil moisture (kg kg^{-1}) at the site where the D8T tractor pass on eucalyptus harvest residues and litter from the previous rotation (HR+L); only on the litter from the previous rotation (L); soil without residues (WR); and control, where tractor traffic did not occur (WT).

Conclusions

The harvesting operation resulted in an increase in soil bulk density in the inter-rows. Retention of harvest residues reduces the impacts of machines used in soil tillage, avoiding increases in soil bulk density and root penetration resistance.

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CO_2, N_2O and CH_4 emissions and C storage in eucalyptus forests with different managements of harvest residues

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.

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

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).

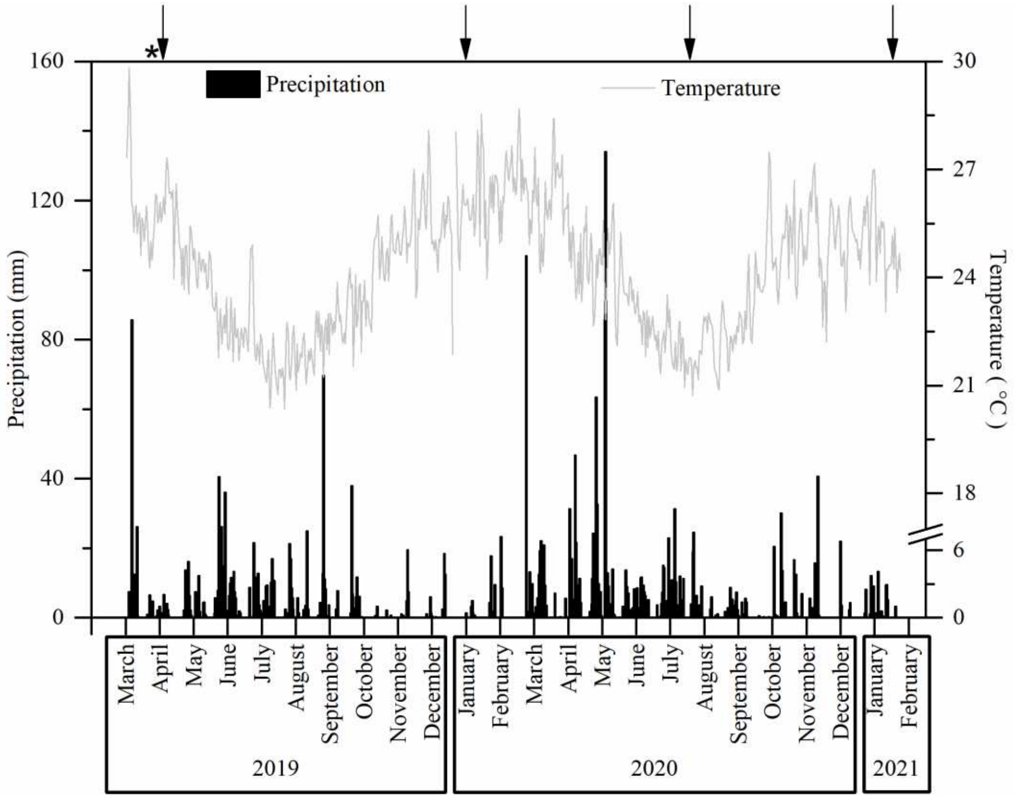

Figure 1. Precipitation and average temperature recorded during the experimental period. The data were obtained by a weather station located within a 7 km radius from the experimental site. Source: BRACELL. * indicates the start of evaluations (5 days before harvest) and ↓ indicates sampling times after harvest (0.3, 9.3, 15.8 and 22.3 months).

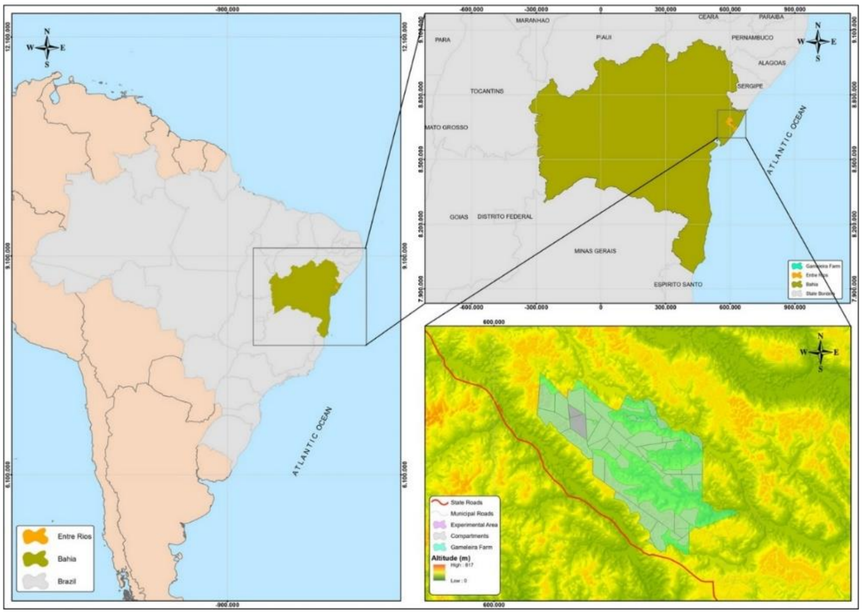

Figure 2. Location of the experimental area, in the municipality of Entre Rios - BA. Source: [18]

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 depths (0-10, 10-20, 20-40, 40-60 and 60-100 cm)

Position*	Soil layer	pH	TOC	P	K	Ca	Mg	S	Al	V	Sand	Silt	Clay	θ FC	θ PWP
	Cm		%	mg dm^{-3}	------------------- cmol$_c$ dm^{-3} ---------------------					%	-----------------kg kg^{-1}---------------				
R	0-10	$6.21^{\pm0.60}$	$1.27^{\pm0.23}$	$3.45^{\pm0.58}$	$53.25^{\pm6.74}$	$3.80^{\pm1.24}$	$0.43^{\pm0.07}$	$4.03^{\pm1.85}$	$0.00^{\pm0.00}$	$70.23^{\pm15.2}$	$0.75^{\pm0.02}$	$0.01^{\pm0.01}$	$0.24^{\pm0.02}$	$0.13^{\pm0.01}$	$0.07^{\pm0.01}$
	10-20	$5.93^{\pm0.67}$	$1.11^{\pm0.07}$	$2.55^{\pm0.58}$	$45.50\pm^{9.15}$	$3.21^{\pm0.97}$	$0.35^{\pm0.06}$	$4.28^{\pm2.35}$	$0.05^{\pm0.09}$	$61.60^{\pm17.4}$	$0.73^{\pm0.02}$	$0.01^{\pm0.01}$	$0.26^{\pm0.03}$	$0.15^{\pm0.01}$	$0.07^{\pm0.01}$
	20-40	$5.68^{\pm0.83}$	$0.89^{\pm0.04}$	$1.48^{\pm0.19}$	$52.75\pm^{12.54}$	$2.43^{\pm1.14}$	$0.27^{\pm0.07}$	$6.13^{\pm6.14}$	$0.17^{\pm0.22}$	$50.55^{\pm20.8}$	$0.66^{\pm0.04}$	$0.01^{\pm0.01}$	$0.33^{\pm0.04}$	$0.18^{\pm0.02}$	$0.10^{\pm0.01}$
	40-60	$5.25^{\pm0.63}$	$0.70^{\pm0.09}$	$0.60^{\pm0.44}$	$57.5\pm^{19.72}$	$1.46^{\pm0.70}$	$0.20^{\pm0.07}$	$19.6^{\pm11.10}$	$0.45^{\pm0.34}$	$36.58^{\pm15.2}$	$0.56^{\pm0.05}$	$0.01^{\pm0.01}$	$0.43^{\pm0.05}$	$0.20^{\pm0.02}$	$0.11^{\pm0.01}$
	60-100	$4.98^{\pm0.55}$	$0.48^{\pm0.09}$	$0.13^{\pm0.19}$	$30.00\pm^{12.89}$	$1.12^{\pm0.73}$	$0.18^{\pm0.07}$	$34.58^{\pm9.18}$	$0.57^{\pm0.41}$	$30.80^{\pm17.0}$	$0.49^{\pm0.03}$	$0.01^{\pm0.01}$	$0.50^{\pm0.02}$	$0.21^{\pm0.03}$	$0.13^{\pm0.02}$
IR	0-10	$6.04^{\pm0.20}$	$1.40^{\pm0.01}$	$4.55^{\pm1.67}$	$34.50\pm^{5.49}$	$3.83^{\pm0.30}$	$0.60^{\pm1.26}$	$3.33^{\pm0.45}$	$0.00^{\pm0.00}$	$68.03^{\pm6.91}$	$0.76^{\pm0.02}$	$0.01^{\pm0.01}$	$0.23^{\pm0.02}$	$0.12^{\pm0.01}$	$0.06^{\pm0.01}$
	10-20	$5.84^{\pm0.15}$	$1.13^{\pm0.13}$	$4.65^{\pm2.10}$	$27.00\pm^{4.90}$	$3.03^{\pm0.33}$	$0.49^{\pm0.19}$	$3.40^{\pm0.60}$	$0.00^{\pm0.00}$	$58.98^{\pm4.60}$	$0.70^{\pm0.03}$	$0.01^{\pm0.01}$	$0.28^{\pm0.03}$	$0.13^{\pm0.01}$	$0.07^{\pm0.01}$
	20-40	$5.29^{\pm0.20}$	$0.75^{\pm00.07}$	$2.95^{\pm3.41}$	$24.50^{\pm1.90}$	$1.70^{\pm0.03}$	$0.33^{\pm0.06}$	$11.78^{\pm2.60}$	$0.24^{\pm0.05}$	$41.40^{\pm4.86}$	$0.57^{\pm0.02}$	$0.01^{\pm0.01}$	$0.42^{\pm0.03}$	$0.15^{\pm0.01}$	$0.08^{\pm0.01}$
	40-60	$5.05^{\pm0.21}$	$0.58^{\pm0.20}$	$0.35^{\pm0.33}$	$30.50^{\pm19.28}$	$1.31^{\pm0.48}$	$0.26^{\pm0.04}$	$20.90^{\pm2.43}$	$0.52^{\pm0.25}$	$34.83^{\pm6.34}$	$0.49^{\pm0.03}$	$0.01^{\pm0.01}$	$0.50^{\pm0.04}$	$0.17^{\pm0.01}$	$0.10^{\pm0.02}$
	60-100	$4.90^{\pm0.21}$	$0.62^{\pm0.20}$	$0.25^{\pm0.24}$	$33.75^{\pm24.77}$	$1.28^{\pm0.89}$	$0.22^{\pm0.05}$	$32.68^{\pm5.25}$	$0.43^{\pm0.35}$	$30.50^{\pm11.5}$	$0.46^{\pm0.07}$	$0.01^{\pm0.01}$	$0.53^{\pm0.08}$	$0.20^{\pm0.03}$	$0.12^{\pm0.02}$

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; Particle-size analysis determined by 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 potential of -1500 KPa. Standard 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 m^2) 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].

$$Flux = \frac{\frac{\Delta Q}{\Delta t} \text{ x M x P x V}}{\text{R x Ts x A}} \qquad \textit{Equation 1}$$

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.

$$CO_2eq = (25 \text{ x } CH_4) + (298 \text{ x } N_2O) + (1 \text{ x } CO_2) \qquad \textit{Equation 2}$$

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).

$$\text{TOC or TN stock (Mg ha}^{-1}) = (\text{TOC or TN x Ds x h}) \text{ x } 10 \qquad \textit{Equation 3}$$

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.

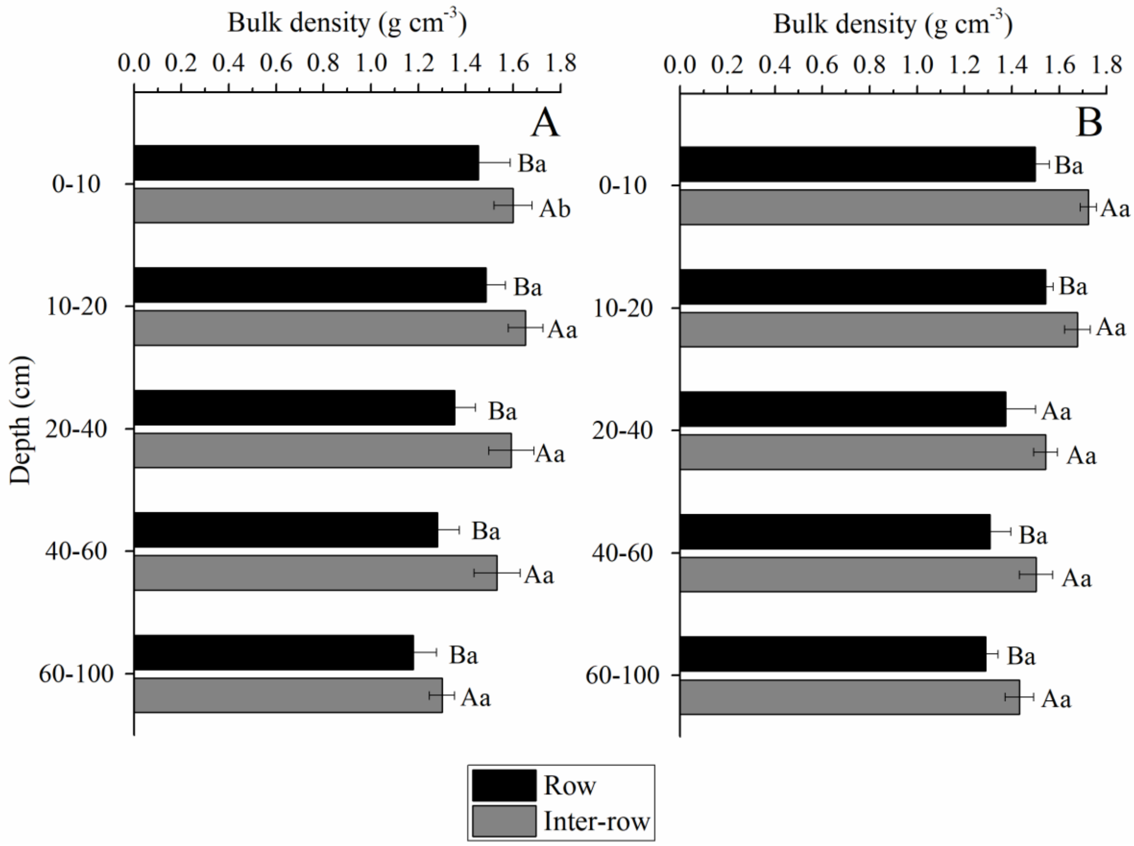

Figure 3. Bulk density (Ds; g cm^{-3}) in the rows (R) and inter-rows (IR) of eucalyptus plantation, before (A) and after (B) harvest. Means followed by equal uppercase letters do not differ between sampling positions (R and IR), within the same evaluation time by the F test ($p < 0.05$). Means followed 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].

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

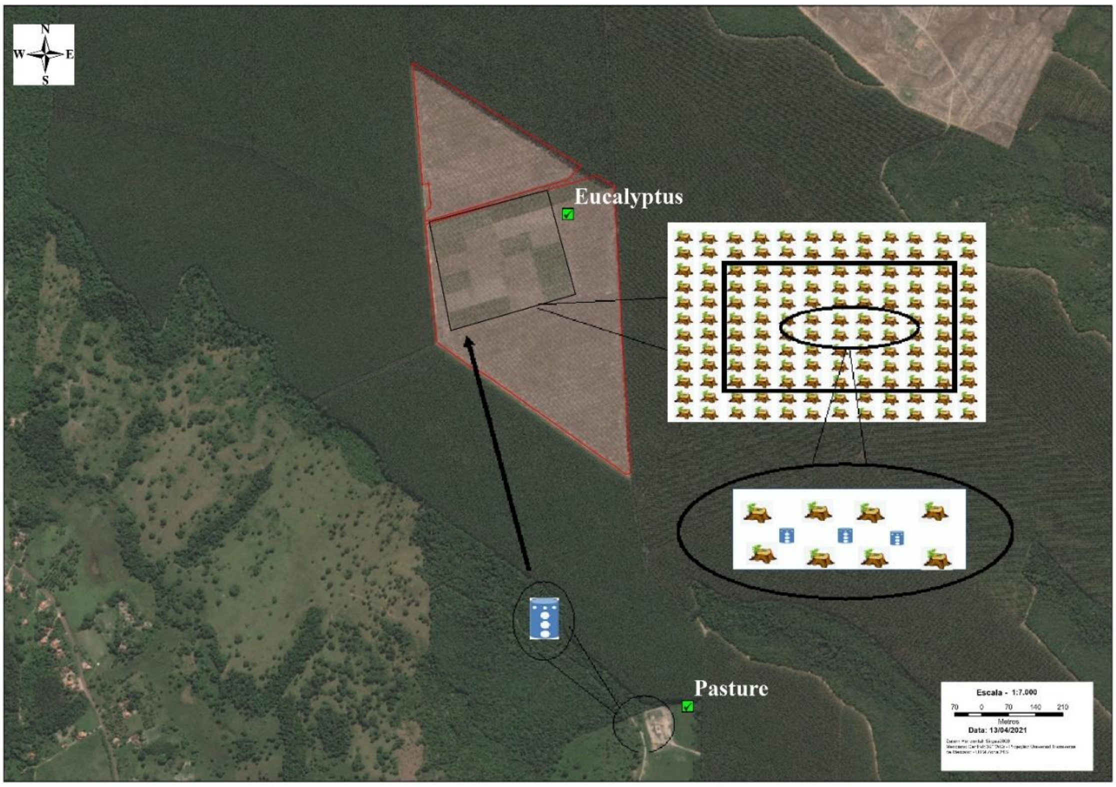

Figure 4. Installation scheme of the pipes used to measure the speed of decomposition of plant residues.

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 cm^3 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).

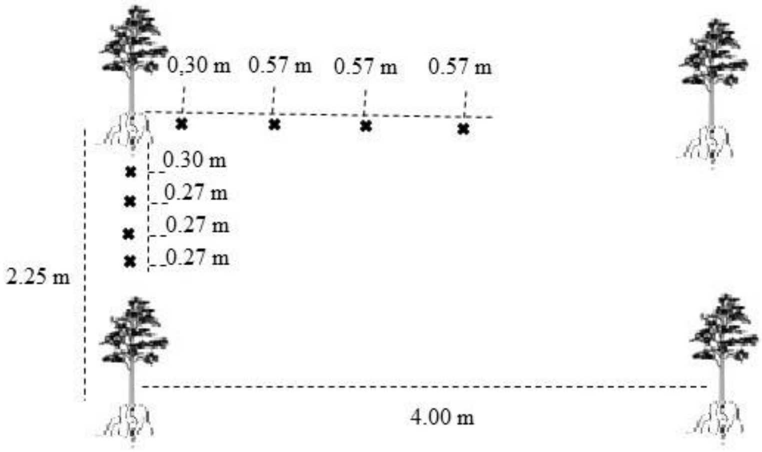

Figure 5. Sampling scheme used for root collection, in the rows and inter-rows. The area shown represents ¼ of the total tree area.

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.

$$\text{C emission (Mg ha}^{-1}) = \text{average } CO_2 \text{ equivalent (kg ha}^{-1}\text{ h}^{-1}) \times 675 \times 24 / 1000$$ *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 7 A1). 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 6 C1), 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 6 C1), 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 7 A2). 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 7 A1). 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 7 B2). 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.

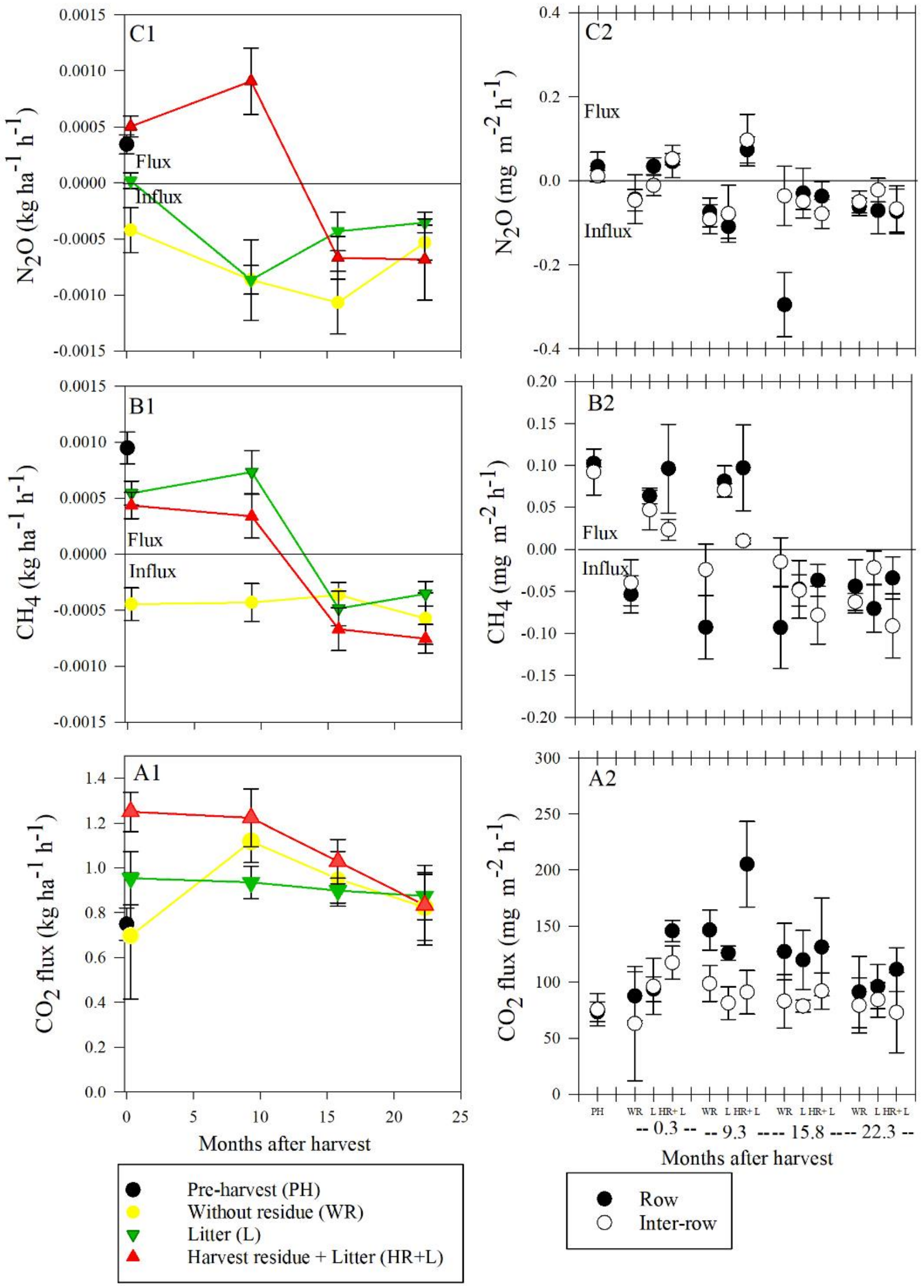

Figure 6. CO_2 (A1), CH_4 (B1), N_2O (C1) fluxes in pre-harvest (PH) and post-harvest without the presence of residues (WR), with litter from the previous rotation (L) and with harvest residues and litter from the previous rotation (HR+L) within each sampling season (at 0.3, 9.3, 15.8 and 22.3 months 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).

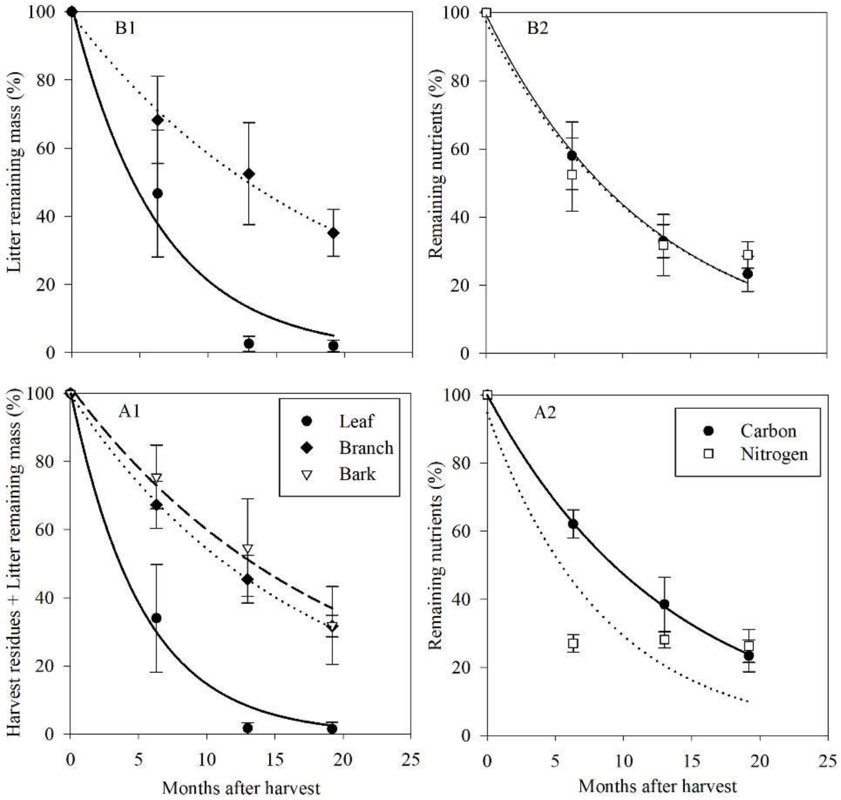

Figure 7. Mass loss of harvest residues + litter from the previous rotation (A1) and C and N release rates (A2). In B1, mass loss of litter from the previous rotation and, in B2, C and N release rates. Bars denote standard deviation around the mean (n=4).

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}).

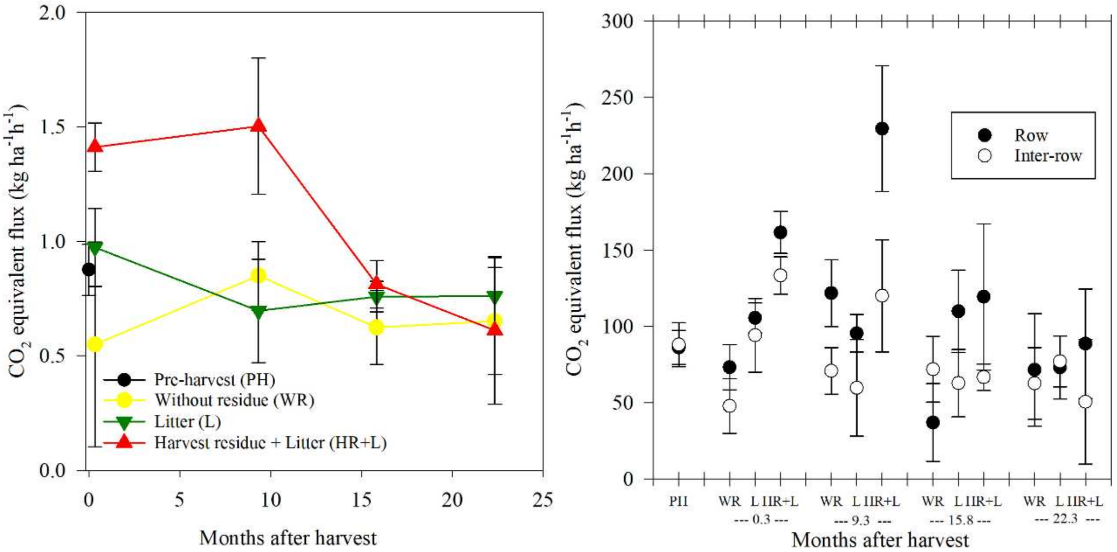

Figure 8. CO_2 equivalent flux (A) in pre-harvest (PH) and post-harvest without the presence of residues (WR), with litter from the previous rotation (L) and with harvest residues and litter from the previous rotation (HR+L) within each sampling season (pre-harvest and at 0.3, 9.3, 15.8 and 22.3 months 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).

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 6-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 6-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 10 A) and N (Figure 10 B) 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.

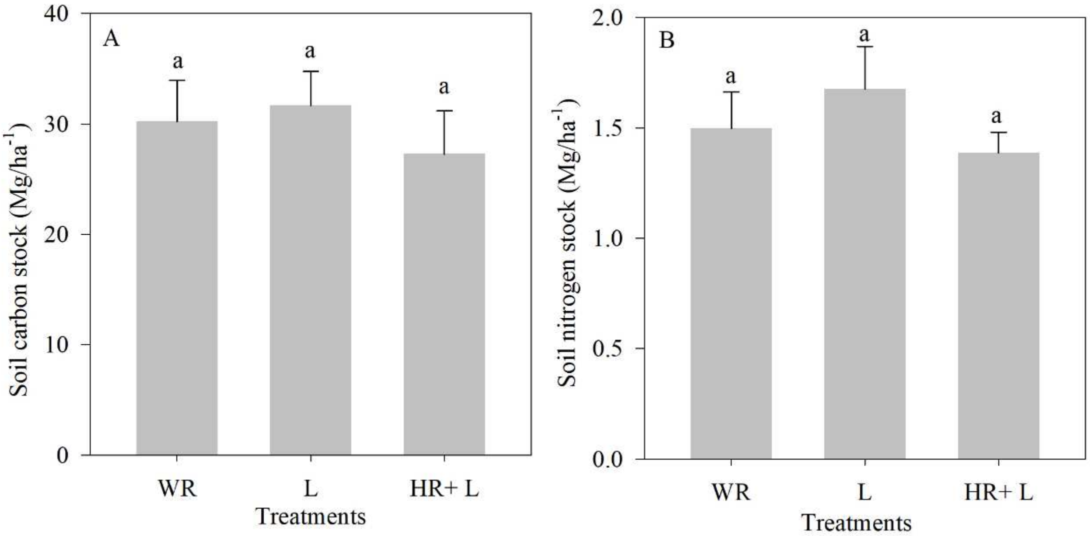

Figure 10. Stocks of organic carbon (A) and organic nitrogen (B) in the 0-10 cm soil layer, at 22.3 months after eucalyptus harvest, in the area without the presence of residues (WR), with litter from the previous rotation (L) and with harvest residues and litter from the previous rotation (HR+L). Bars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

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].

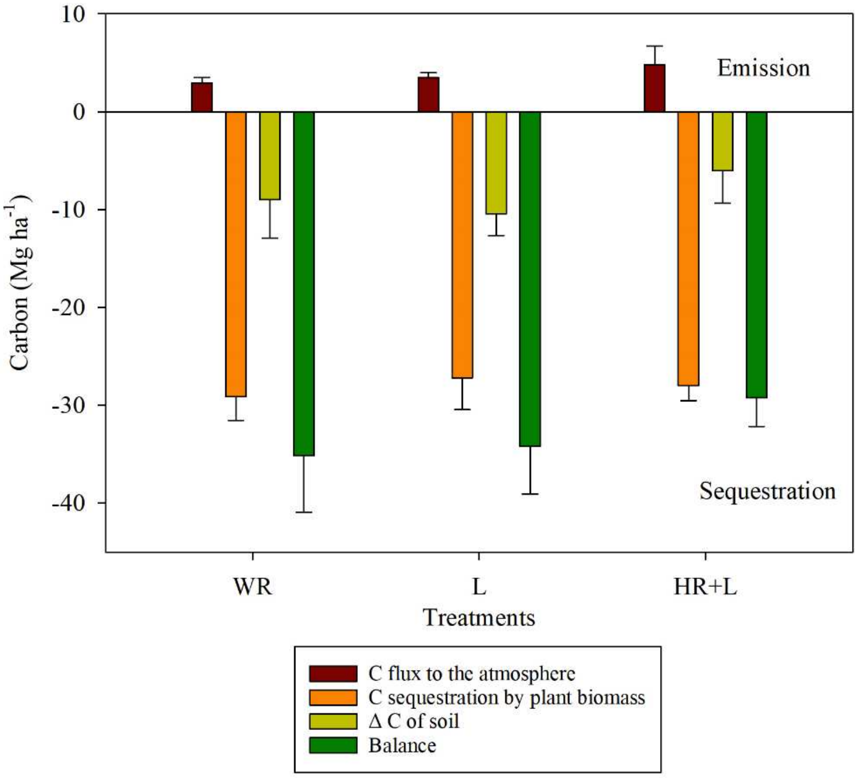

Figure 11. Net balance between C inputs (biomass + Δ C of soil in the 0-10 cm layer) and C outputs (CO_2 emission) in the different harvest residue managements during the initial growth cycle of eucalyptus (22.3 months).

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.

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Manejo dos resíduos da colheita e fertilização mineral do eucalipto influenciam atributos microbiológicos do solo

RESUMO

Os resíduos da colheita do eucalipto podem ser retirados da floresta e aproveitados para produção de energia. Isso causa a exportação de nutrientes minerais, havendo necessidade de compensação nutricional via aplicação de maiores doses de fertilizantes. Entre outros impactos dessa remoção, espera-se alteração significativa na atividade de microrganismos do solo. O objetivo do estudo foi o de avaliar a influência de diferentes manejos de resíduos florestais e a intensidade de fertilização mineral na biomassa e atividade microbiana do solo. Para isso, foi conduzido experimento utilizando-se um talhão no início da quarta rotação. A área foi colhida através do sistema *Harvester+ Forwarder*. Depois da colheita, as brotações foram conduzidas. Utilizou-se o delineamento de blocos ao acaso com parcelas subdivididas, alocando-se nas parcelas os seguintes tipos de manejo de resíduos: 1. Manutenção de todo resíduo da colheita e da serapilheira da rotação anterior (RC+S), 2. Manutenção da serapilheira da rotação anterior (S), 3. Retirada do resíduo da colheita e da serapilheira da rotação anterior (SR). As sub-parcelas foram constituídas por níveis de fertilização: 1. Sem adubação (A0); 2. Adubação convencional, composta de 60 kg ha^{-1} de N, 110 de P_2O_5 e 158 de K_2O (A1); 3. Adubação potencial, composta de 72 kg ha^{-1} de N, 133 de P_2O_5 e 188 de K_2O (A2). Para avaliar características microbiológicas foram efetuadas três amostragens do solo, na camada de 0-10 cm, aos 6, 13 e 19 meses, sendo as amostras submetidas às análises: C da biomassa microbiana (CBM), Respiração basal (RB), Quociente metabólico (qCO_2), atividade das enzimas β-glicosidade, fosfatase ácida, fosfatase alcalina e urease. A manutenção dos resíduos da colheita aumentou a RB e CBM, aos 6 e 13 meses respectivamente, independentemente dos níveis de fertilização. A fertilização reduziu atividade da urease, em todas as épocas de avaliação independentemente do manejo de resíduos. Houve interação entre o manejo de resíduos e níveis de fertilizantes para a atividade da fosfatase alcalina e qCO_2 aos 13 meses. A retirada dos resíduos da colheita da área cultivada e os consequentes aumentos nas doses de fertilizantes sintéticos acarreta redução da atividade microbiana do solo.

Palavras-Chave: *Eucalyptus;* sustentabilidade; manejo florestal, atividade microbiana do solo

Harvest residues management and mineral fertilization of eucalypt plantations affect soil microbial attributes

ABSTRACT

Eucalyptus harvest residues can be removed from the forest and utilized for energy production. This causes the export of mineral nutrients, requiring nutritional compensation through the application of higher doses of fertilizers. Among other impacts of this removal, a significant change in the activity of soil microorganisms is expected. The aim of this study was to evaluate the influence of different forest residue managements and intensity of mineral fertilization on soil microbiological characteristics. For this, an experiment was conducted using an eucalypt stand at the beginning of the fourth rotation. The area was harvested through the Harvester + Forwarder system. After harvest, the stand was conducted by the coppicing system. A randomized block design with split plots was used, with the following types of residue management in the plots: 1. Maintenance of all harvest residues and litter from the previous rotation (RC+S), 2. Maintenance of litter from the previous rotation (S), 3. Removal of harvest residue and litter from the previous rotation (SR). The subplots consisted of fertilization levels: 1. Without fertilization (A0); 2. Conventional fertilization, composed of 60 kg ha^{-1} of N, 110 of P_2O_5 and 158 of K_2O (A1); 3. Potential fertilization, composed of 72 kg ha^{-1} of N, 133 of P_2O_5 and 188 of K_2O (A2). To evaluate microbiological characteristics, three soil samplings were carried out in the 0-10 cm layer at 6, 13 and 19 months, and the samples were subjected to the following analyses: microbial biomass carbon (MBC), basal respiration (BR), metabolic quotient (qCO_2), activity of the enzymes β glycosidase, acid phosphatase, alkaline phosphatase and urease. Residue management increased BR and MBC at 6 and 13 months, respectively, regardless of fertilization levels. Fertilization reduced urease activity at all evaluation times regardless of residue management. There was interaction between residue management and fertilizer levels for alkaline phosphatase activity and qCO_2 at 13 months. Removal of harvest residues from the stand area with consequent increments in the doses of synthetic fertilizers results in reduction of soil microbial activity.

Keywords: *Eucalyptus*; sustainability; forest management, microbial activity.

1. Introdução

O Brasil possui atualmente a maior área plantada com eucalipto do mundo, com, aproximadamente, 7,5 milhões de hectares (IBGE 2019). Em decorrência da elevada produtividade dos plantios (Binkley et al., 2017; Gonçalves et al., 2013; Scolforo et al., 2019; Stape et al., 2010), elevadas quantidades de resíduos (folhas, cascas, galhos e serapilheira) são deixadas na área, fato que tem despertado o interesse para o uso desse material para produção de bioenergia. A adoção dessa técnica pode reduzir o retorno de carbono e de nutrientes ao solo com potencial consequências na atividade biológica do solo. e alterar a atividade da microbiota. Práticas de manejo que visem à melhoria dos atributos biológicos e as características físicas e químicas do solo podem ser consideradas potenciais ferramentas para o aumento da produtividade e sustentabilidade dos plantios de eucalipto (Valadares et al., 2020).

Durante a colheita florestal, grande quantidade de resíduos, compostos principalmente por galhos, cascas, folhas e serapilheira, é deixada no campo. Aproximadamente 20 % da biomassa dos plantios de eucalipto reverte-se em resíduos no momento da colheita (Daystar et al., 2014). Os resíduos vegetais são fontes de nutrientes para os microrganismos, além de propiciar abrigo e microclima favorável ao seu crescimento. Kumaraswamy et al. (2014) observaram que a retirada dos resíduos da colheita do eucalipto reduziu a biomassa microbiana do solo.

A retirada do resíduo da colheita causa grande exportação de nutrientes (Santana et al., 2008), demandando sua reposição por meio de fertilizantes para que a produtividade seja mantida. A fertilização mineral pode alterar a diversidade e a atividade microbiana do solo ao promover alterações no pH e desequilíbrios entre nutrientes no solo. Wang et al. (2008) observaram que adubações com N e P em eucalipto influenciam o C e o P da biomassa microbiana, respiração basal e atividade enzimática.

Dentre os efeitos benéficos dos microrganismos do solo na produtividade e sustentabilidade florestal, destacam-se os efeitos diretos como na nutrição e na fisiologia da planta (Trivedi et al., 2020; Valadares et al., 2020; Vergara et al., 2019; Oldroyd, 2013) e efeitos indiretos por meio da ciclagem de nutrientes, formação da matéria orgânica do solo e antagonismo a patógenos (Schlatter et al., 2017; Valadares et al., 2018). Os atributos microbianos do solo, tais como população e diversidade de microrganismos, taxa de respiração e atividade enzimática são indicadores sensíveis que podem auxiliar no monitoramento e na orientação da adoção de práticas e manejos como: preparo do solo, sistemas de plantio, utilização de insumos como fertilizantes, deposição de resíduos orgânicos, entre outros (Chaer & Tótola 2007; Wang et al., 2008; Guo et al., 2011; Kaschuk et al., 2011; Zhu et al., 2019)

Informações sobre a influência do manejo resíduos florestais e da fertilização mineral na atividade microbiana do solo em povoamentos de eucalipto são escassas, principalmente em ambientes tropicais. Neste estudo tivemos como hipótese que variações nas quantidades de resíduos da colheita do eucalipto que permanecem sob solo assim como, diferentes doses de fertilizantes minerais, afetam a biomassa e atividade da microbiana do solo. Assim, o objetivo deste estudo foi avaliar bioindicadores do solo em diferentes manejos de resíduos da colheita do eucalipto e diferentes intensidade de fertilização mineral.

2.Material e métodos

2.1. Desenho experimental

O experimento teve início em julho de 2019 e teve duração de 19 meses com a realização de três coletas de amostras (6, 13 e 19 meses) (Figura 1). O ensaio foi realizado em plantios comerciais de eucalipto da empresa BRACELL, situados no município de Entre Rios (BA), nas coordenadas geográficas de 38° 3' 36" S e 12° 1' 17" O a 180 m de altitude (Figura 2). O relevo da área é plano, o clima é predominantemente do tipo Af (tropical úmido), com precipitação média de 1.250 mm por ano, com inverno chuvoso e verão seco. Os valores de precipitação pluviométrica e temperatura média durante a condução do ensaio são apresentados na Figura 1. O solo da área experimental é classificado como Argissolo Amarelo coeso.

Foi selecionado um talhão do clone 1404 (*Eucalyptus urophylla* x *E. grandis*), no final da terceira rotação (5 anos), originalmente plantado no espaçamento de 4,0 x 2,4 m. Após a floresta ser cortada com *Harvester* e a madeira removida com *Forwarder*, montou-se o experimento em delineamento de blocos casualizados, com parcelas subdivididas e quatro repetições.

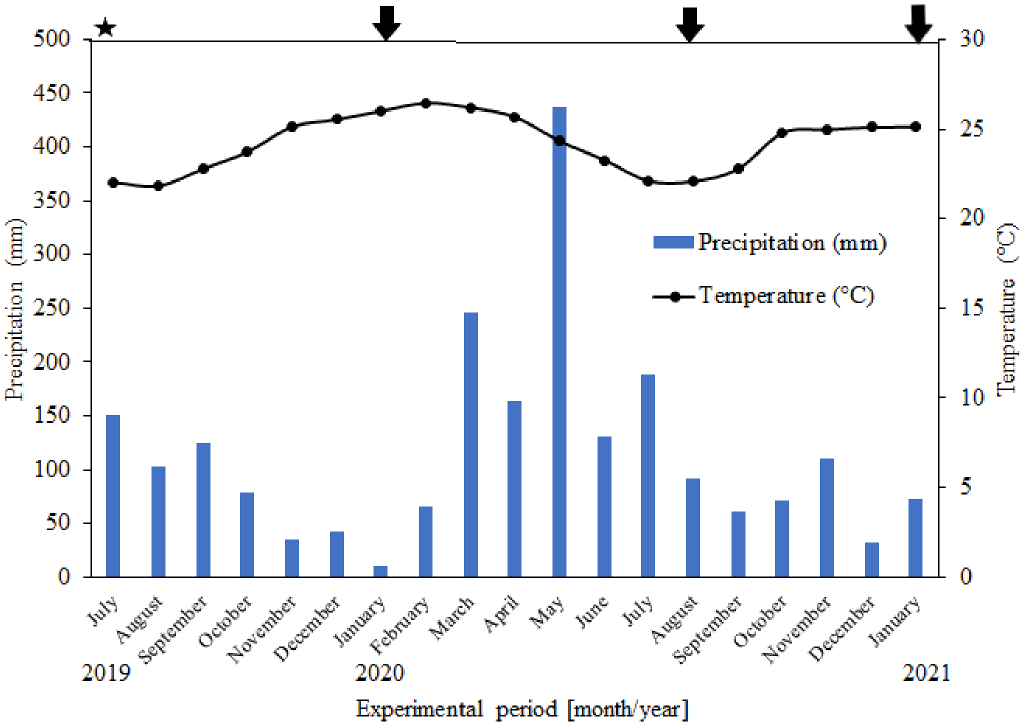

Figura 1. Precipitação e temperatura média registradas durante o período experimental. Os dados foram obtidos por uma estação meteorológica localizada em um raio de 7 km do local do experimento. Fonte: BRACELL. ★ Indica o início da imposição dos tratamentos sob experimentação; ↓ indica os tempos de amostragem após instalação (6; 13; e 19 meses).

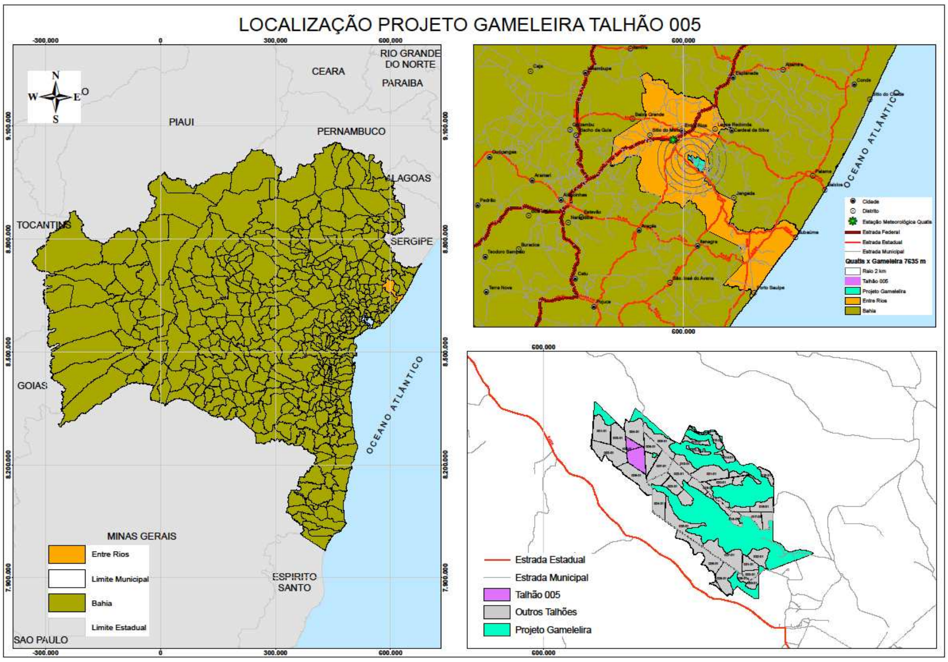

Figura 2: Localização da área experimental, no munícipio de Entre Rios – BA. (Fonte: BRACELL)

Nas parcelas foram adotados três manejos de resíduos: i) manutenção dos resíduos da colheita (RC: folhas, galhos, casca e ponteiras) e da serapilheira (S) da rotação anterior (RC+S); ii) manutenção apenas da serapilheira da rotação anterior (S) e iii) remoção de todos os resíduos da área (SR). Na condição RC+S foram mantidos sobre o solo 24,0 Mg ha^{-1} de matéria seca de RC (13, 34 e 53 % do peso corresponderam a folhas, galhos, casca, respectivamente) e 10,7 Mg ha^{-1} de matéria seca de S (35 e 65 % do peso corresponderam a folhas e galhos, respectivamente). A composição química e bioquímica dos componentes dos resíduos vegetais é apresentada na Tabela 1.

As sub-parcelas foram constituídas de três níveis de fertilização: i) Sem adubação NPK (A0), ii) Adubação convencional da empresa (A1), composta de 60 kg ha^{-1} de N, 110 de P_2O_5 e 158 de K_2O e iii) Adubação potencial (A2), composta de 72 kg ha^{-1} de N, 133 de P_2O_5 e 188 de K_2O, representando incremento de 30 % da adubação convencional, e definida para atingir a produtividade potencial estimada por Borges (2012) para a região do experimento. A adubação foi efetuada em filete contínuo na projeção da copa das árvores (brotações), três meses após as operações de colheita, em dose única, aplicando-se 600 e 720 kg da mistura NPK 10-08-22 para A1 e A2, respectivamente. A parcela estabelecida após a imposição dos tratamentos foi composta por 144 plantas (12 x 12 plantas), sendo consideradas como parcela útil as 64 plantas centrais (8 x 8 fileiras) (Figura 3).

Tabela 1: Composição química dos componentes dos resíduos florestais utilizados no estudo

Componentes	C	N	C:N	P	K	Ca	Mg	S
	---------------------- g kg^{-1} -------------------------							
Folhas	$480,6^{+/-12,2}$	$23,1^{+/-3,5}$	$20,8^{+/-3,6}$	$1,1^{+/-0,1}$	$8,0^{+/-0,1}$	$6,8^{+/-0,2}$	$2,7^{+/-0,1}$	$1,2^{+/-0,1}$
Galhos	$442,5^{+/-24,4}$	$6,2^{+/-1,3}$	$71,3^{+/-15,6}$	$0,5^{+/-0,2}$	$5,4^{+/-1,2}$	$8,7^{+/-1,4}$	$2,2^{+/-0,5}$	$0,3^{+/-0,1}$
Casca	$408,9^{+/-41,1}$	$4,1^{+/-0,3}$	$99,7^{+/-16,0}$	$0,3^{+/-0,1}$	$7,8^{+/-0,4}$	$16,1^{+/-1,2}$	$1,9^{+/-0,1}$	$0,2^{+/-0,1}$
Serapilheira (folhas)	$474,4^{+/-12,2}$	$11,5^{+/-1,1}$	$41,2^{+/-3,5}$	$0,4^{+/-0,1}$	$1,7^{+/-0,1}$	$13,1^{+/-1,5}$	$1,8^{+/-0,1}$	$0,9^{+/-0,1}$
Serapilheira (galhos)	$460,4^{+/-3,2}$	$4,3^{+/-0,8}$	$107,0^{+/-27,0}$	$0,2^{+/-0,1}$	$1,5^{+/-0,6}$	$11,1^{+/-2,6}$	$1,2^{+/-0,1}$	$0,4^{+/-0,1}$

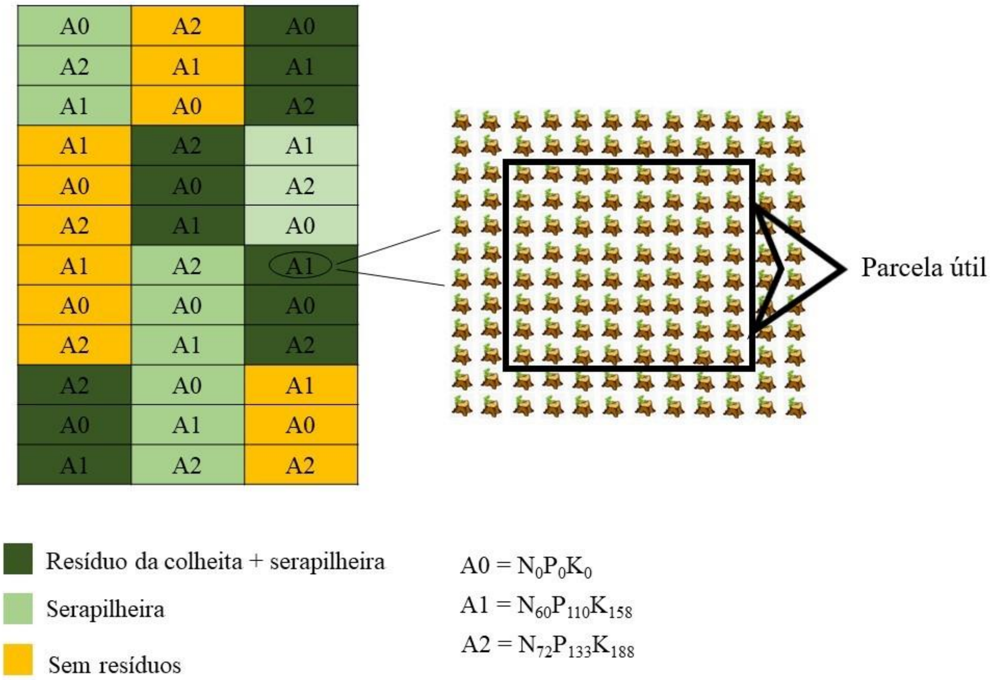

Figura 3: Representação esquemática das parcelas experimentais

2.2. Amostragens e análises experimentais

As amostragens foram feitas em microparcelas que consistiram em um tubo de PVC de 25 cm de altura e 10 cm de diâmetro, contendo nove furos com 5 cm de diâmetro e distribuídos na superfície lateral do tubo. Cada tubo foi recoberto com tela de aço, de malha de 2 mm, para permitir a entrada de raízes. Na parte superior do tubo foram abertos seis furos de 2 cm de diâmetro, localizados à 20 cm de altura, para permitir a entrada e saída da fauna do solo (Bradford et al., 2002; Blumfieldet al., 2004; Ferreira et al., 2016; Oliveira et al., 2021; Souza et al., 2016). O interior do tubo foi preenchido com solo indeformado, retirado da camada de 20 cm de uma área de pastagem natural adjacente ao experimento sem histórico de cultivos anteriores (Tabela 2). Os tubos foram transportados para área experimental, e inseridos no solo a 20 cm de profundidade, de modo que os furos laterais ficassem ao nível da superfície do solo (Figura 3).

Figura 4: Representação esquemática da montagem das microparcelas experimentais

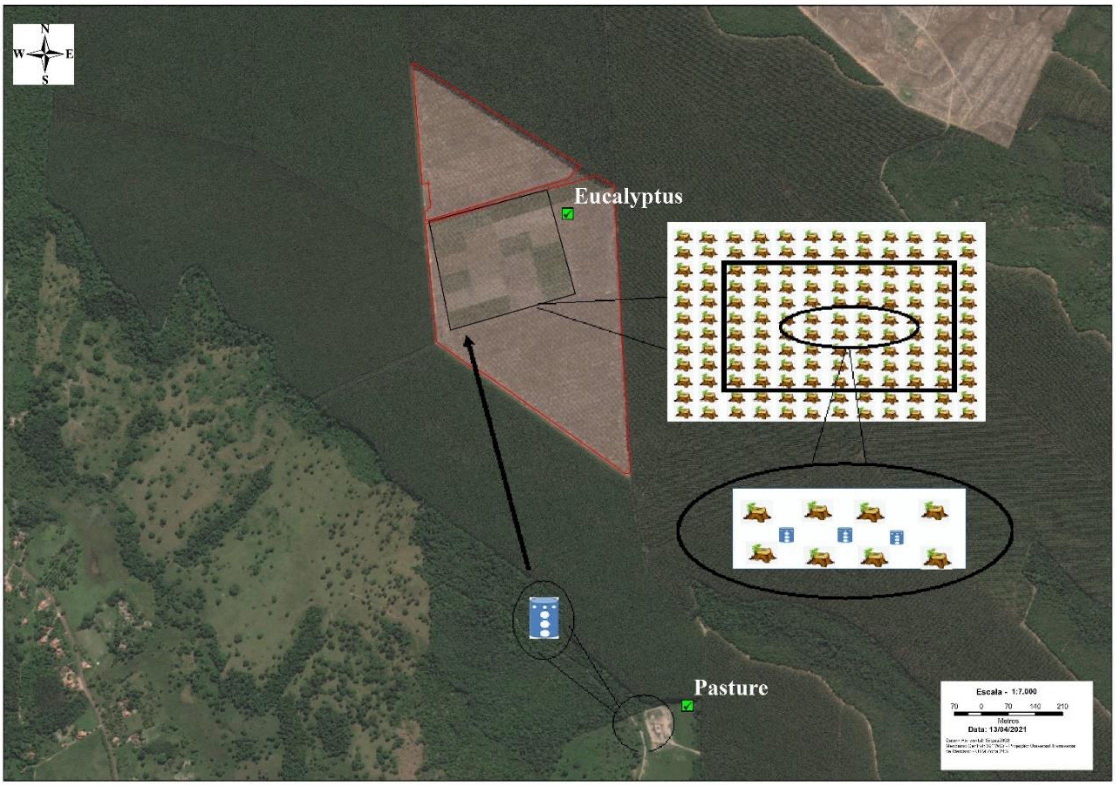

Tabela 2: Características químicas e físicas do solo utilizado nos tubos correspondentes às microparcelas

Camada do solo	pH	N	P	K	Ca	Mg	Al	(H+Al)	MOS	Areia	Silte	Argila
cm		dag kg^{-1}	mg dm^{-3}		---------cmol$_c$dm^{-3}----------				dag kg^{-1}	-------kg kg^{-1} --------		
0-10	5,11	0,05	4,24	60,75	1,51	0,53	0,05	2,36	1,15	0,82	0,02	0,16
10-20	4,90	0,03	3,40	47,50	1,08	0,31	0,18	2,55	0,98	0,78	0,02	0,20

pH em água (L:S 2,5 L kg^{-1}); N extraído pelo método de Kjeldahl; P e K disponíveis extraídos por Mehlich; Ca^{+2}, Mg^{+2} e Al^{3+} trocável em solução extratora de 1 mol L^{-1}KCl; H + Al extraído por solução de acetato de cálcio 0,5 mol L^{-1}$_{pH\ 7,0}$; Matéria orgânica = C.org x 1,724 – Walkley Black; Análise de partículas determinada pelo método da pipeta (Ruiz, 2005)

Nos 5 cm do tubo acima da superfície do solo foram depositadas as quantidades dos resíduos vegetais e do fertilizante referentes a cada parcela do tratamento. As quantidades foram calculadas com base em proporções de áreas (Tabela 3). Finalmente, a parte superior dos tubos foi coberta com tela plástica (com 1 x 1 cm de abertura), para prevenir a entrada de outro material que não constituísse os tratamentos.

Tabela 3: Massa (base seca) dos componentes dos resíduos e fertilizantes adicionados aos tubos (microparcelas), de acordo com o tratamento: SRA0 = sem resíduos e $N_0P_0K_0$; SRA1 = sem resíduos e $N_{60}P_{110}K_{158}$; SRA2 =sem resíduos e $N_{72}P_{133}K_{188}$; SA0 = serapilheira e $N_0P_0K_0$; SA1 = serapilheira e $N_{60}P_{110}K_{158}$; SRA2 =serapilheira e $N_{72}P_{133}K_{188}$; : RC+SA0 = resíduo da colheita + serapilheira e $N_0P_0K_0$; RC+SA1 = resíduo da colheita + serapilheira e $N_{60}P_{110}K_{158}$; RC+SA2 =resíduo da colheita + serapilheira e $N_{72}P_{133}K_{188}$

Tratamentos	Serapilheira		Resíduos da colheita			Dose de NPK (08-10-22)
	Folha	Galho	Folha	Casca	Galho	
	--------------------------------- g tubo^{-1} -------------------------					
SRA0	-	-	-	-	-	-
SRA1	-	-	-	-	-	24
SRA2	-	-	-	-	-	31,5
SA0	1,2	2,2	-	-	-	-
SA1	1,2	2,2	-	-	-	24
SA2	1,2	2,2	-	-	-	31,5
RC+SA0	1,2	2,2	1,0	4,0	2,5	-
RC+SA1	1,2	2,2	1,0	4,0	2,5	24
RC+SA2	1,2	2,2	1,0	4,0	2,5	31,5

Em cada parcela experimental foram instalados três tubos (Figuras 3 e 4). Coletou-se um tubo em cada tempo de avaliação após a imposição dos tratamentos: 6, 13 e 19 meses (Figura 1). No momento da coleta, os resíduos vegetais foram retirados dos tubos e seguiram para estufa de ventilação forçada a 65 °C. Antes da pesagem para determinação da decomposição por meio da perda de massa, os resíduos foram limpos com o auxílio de um pincel, para retirar o solo aderido. Além disso, foram retiradas amostras de solo da camada de 0-10 cm, utilizando uma sonda; as amostras foram transportadas e mantidas em refrigeração de 4 °C até a realização das análises microbiológicas.

No momento das análises, as amostras de solo foram peneiradas em malha de 2 mm. Após o processamento, as amostras foram submetidas às análises de C da biomassa microbiana (CBM), respiração basal (RB), quociente metabólico (qCO_2), atividade das enzimas βglicosidase (AβG), fosfatase ácida (AFACI), fosfatase alcalina (AFACA) e urease (AU).

Para a análise de CBM e RB, os teores de umidade das amostras foram ajustados para 80 % da capacidade de campo, obtendo-se equilíbrio com a tensão de 30 kPa. O CBM foi obtido pelo método da irradiação-extração (Mendonça & Matos, 2017), o qual consiste no uso de energia eletromagnética (micro-ondas), para rompimento celular dos microrganismos e liberação dos compostos de C intracelulares. Posteriormente, a extração foi realizada com sulfato de potássio 0,5 mol L^{-1}; a oxidação, com dicromato de potássio 0,066 mol L^{-1}; e a titulação, com sulfato ferroso amoniacal 0,033 mol L^{-1} conforme Tedesco et al. (1995).

O teor de C-CO_2 acumulado foi avaliado a partir de ensaio de respirometria (adaptado de Stotzky, 1965), conduzido sob condições controladas (25 ± 1 °C, no escuro). Foram incubados 30 g de solo por 5 dias em potes de vidro de 600 mL com tampas rosqueáveis contendo um septo central. Os gases produzidos foram coletados com seringas de 60 mL no início do ensaio e a 24, 72 e 120 horas depois. Após cada coleta, os potes foram abertos, ventilados e mantidos em ambiente arejado por 15 min. A determinação da concentração do CO_2 armazenado nas seringas foi realizada no *Cavity Ring-Down Spectroscopy* (CRDS). O carbono associado ao CO_2 acumulado (C-CO_2 acumulado) (mg kg^{-1} de solo) foi calculado pelo somatório dos teores de C-CO_2 (mg kg^{-1} de solo) obtidos em cada período.

As atividades das enzimas AβG, AFACI e AFACA foram determinadas de acordo com Tabatabai (1994), utilizando a determinação colorimétrica do p-nitrofenol liberado pelas enzimas após a incubação de1 g de solo a 37 ºC por 1 hora, na presença de seus substratos específicos: p-nitrofenil-β-D-glicosídeo (0,025 mol L^{-1}) em solução tampão pH (6,5) para AβG e p-nitrofenolfosfato (0,025 mol L^{-1}) em solução tampão pH (6,5 e 11,0) respectivamente para AFACI e AFACA. A AU foi determinada segundo método descrito por Kandeler & Gerber (1988), após a incubação de 5 g de solo a 37 ºC por 1 hora com solução aquosa de ureia (0,08 mol L^{-1}), extração do amônio com solução de KCl 1 mol L^{-1} contendo HCl 0,01 mol L^{-1} e dosagem colorimétrica do NH_4^+ em espectrofotômetro .

Na última coleta (19 meses), parte do solo coletado nas camadas 0-10 e 10-20 cm das microparcelas foi seca ao ar para a análise química (Tabela 4).

Os resultados obtidos foram submetidos à análise de variância utilizando-se o programa R. Quando o teste F indicou diferenças entre os tratamentos, bem como interações entre os tratamentos, as médias foram comparadas pelo teste de Tukey a 5% de probabilidade.

Tabela 4: Composição química do solo 19 meses após a imposição dos seguintes tratamentos: SRA0 = sem resíduos e $N_0P_0K_0$; SRA1 = sem resíduos e $N_{60}P_{110}K_{158}$; SRA2 =sem resíduos e $N_{72}P_{133}K_{188}$; SA0 = serapilheira e $N_0P_0K_0$; SA1 = serapilheira e $N_{60}P_{110}K_{158}$; SRA2 =serapilheira e $N_{72}P_{133}K_{188}$; : RC+SA0 = resíduo da colheita + serapilheira e $N_0P_0K_0$; RC+SA1 = resíduo da colheita + serapilheira e $N_{60}P_{110}K_{158}$; RC+SA2 =resíduo da colheita + serapilheira e $N_{72}P_{133}K_{188}$

Tratamento	pH	N	P	K	Ca	Mg	Al	MOS
		dag kg^{-1}	-- mg dm^{-3}--		---- cmol$_c$dm^{-3} ---			dag kg^{-1}
Camada de 0-10 cm								
SR A0	5,30	0,05	3,30	28,67	2,21	0,30	0,07	1,77
SR A1	4,55	0,06	101,05	28,50	2,01	0,63	0,46	1,47
SR A2	4,44	0,08	88,73	30,00	0,72	0,25	0,61	1,54
S A0	5,53	0,08	1,75	23,50	1,85	0,58	0,05	1,40
S A1	4,79	0,06	43,15	20,00	1,12	0,27	0,34	1,87
S A2	5,02	0,06	99,90	34,50	1,96	0,68	0,10	1,54
RC+S A0	5,20	0,06	2,43	34,50	1,02	0,27	0,03	1,86
RC+S A1	4,54	0,04	37,08	36,00	2,01	0,45	0,36	1,67
RC+S A2	4,74	0,06	135,13	33,00	2,98	0,56	0,34	1,60
Camada de 10-20 cm								
SR A0	5,27	0,04	2,23	22,00	1,59	0,30	0,12	1,40
SR A1	4,52	0,05	37,28	13,00	0,80	0,23	0,51	1,04
SR A2	4,75	0,06	26,75	18,50	1,00	0,29	0,39	1,14
S A0	5,32	0,06	1,20	11,50	1,20	0,31	0,17	1,11
S A1	5,06	0,05	17,75	20,50	1,22	0,31	0,27	1,51
S A2	5,16	0,05	36,20	25,00	1,12	0,37	0,19	1,35
RC+S A0	5,11	0,05	1,68	25,50	1,13	0,35	0,17	1,44
RC+S A1	4,72	0,04	28,70	24,00	0,89	0,26	0,41	1,47
RC+S A2	4,37	0,05	55,38	15,00	0,57	0,22	0,46	1,15

pH em água (L:S 2,5 L kg^{-1}); N extraído pelo método de Kjeldahl; P e K (Extrator Mehlich-1) Ca^{+2}, Mg^{+2} e Al^{3+} trocável em solução extratora de 1 mol L^{-1}KCl; ^{4}Matéria orgânica = C.org x 1,724 – Walkley Black;

3. Resultados

3.1 Carbono da biomassa microbiana (CBM)

Os teores de CBM do solo foram afetados pelos manejos de resíduos 13 meses após o início do experimento (Tabela 5). Foi constatado maior teor de CBM onde havia deposição de resíduos florestais sobre o solo, independentemente dos níveis de fertilização. O teor de CBM nos locais com apenas com serapilheira da rotação anterior (S) foi maior comparado aos das áreas onde houve remoção completa dos resíduos (SR). No mesmo período de avaliação, os teores de CBM nas áreas onde havia o resíduo da colheita e serapilheira da rotação anterior (RC+S) não diferiram daqueles correspondentes aos dos tratamentos S e SR.

3.2. Respiração basal (RB)

A respiração basal apresentou diferenças apenas na primeira coleta (6,3 meses) após a imposição dos manejos de resíduos e níveis de adubação (Tabela 5). Foi constatado maior RBS onde havia deposição de resíduos florestais sobre o solo, independentemente dos níveis de fertilização. A RB dos locais apenas com serapilheira da rotação anterior (S) foi maior na área onde houve a remoção completa dos resíduos (SR). No mesmo período de avaliação, o resultado referente ao tratamento no qual havia o resíduo da colheita e serapilheira da rotação anterior (RC+S) foi semelhante aos dos tratamentos S e SR.

3.3. Quociente metabólico (qCO_2)

O *q*CO2 apresentou variações em decorrência dos tratamentos aplicados (Tabela 5). Houve interação entre o manejo de resíduos e níveis de fertilização (Tabela 5; Figura 5). Foi observado maior qCO_2 no local onde havia serapilheira da rotação anterior (S) combinada a não aplicação de fertilizantes (A0).

3.4. Atividade da Beta glicosidase (AβG)

A atividade de enzima Beta glicosidase também sofreu modificações aos 13 meses após a imposição dos tratamentos (Tabela 5). Foi constatado maior AβG nas parcelas que receberam fertilização, independentemente do manejo de resíduos florestais.

Tabela 5: Carbono da biomassa microbiana (CBM), Respiração basal (RB), Quociente metabólico (qCO_2), atividade das enzimas βglicosidase (AβG), fosfatase ácida (AFACI), fosfatase alcalina (AFACA) e Urease (AU) aos 6, 13 e 19 meses após a imposição dos seguintes tratamentos: retirada de todos os resíduos (SR); manutenção da serapilheira da rotação anterior (S) e manutenção de resíduos da colheita e serapilheira da rotação anterior (RC+S) combinados da ausência da aplicação de fertilizantes (A0) ou aplicação de $N_{60}P_{110}K_{158}$ (A1) ou $N_{72}P_{133}K_{188}$; (A2)

6 meses							
Tratamento	CBM	RBS	qCO_2	AβG	AFACI	AFACA	AU
	μg g^{-1}	(μg CO^2-C g^{-1} h^{-1})	μg CO^2-C/ mg Cmic $^{-1}$ h^{-1}		------ μg pnp g^{-1} h^{-1} ------		μg N-NH^{4+} g^{-1} h^{-1}
SR	58,6 a	0,048 b	1,56 a	28,7 a	108,4 a	26,5 a	6,3 a
S	73,9 a	0,069 a	1,41 a	28,1 a	112,4 a	16,2 a	4,7 a
RC+S	51,1 a	0,058 ab	1,33 a	30,5 a	133,2 a	21,0 a	3,1 a
CV (%)	48,8	19,2	81,4	27,9	20,2	30,8	30,8
A0	69,9 a	0,059 a	1,77 a	26,5 a	114,1 a	19,1 a	8,2 a
A1	53,9 a	0,058 a	1,31 a	30,6 a	112,7 a	24,8 a	2,5 b
A2	59,9 a	0,057 a	1,23 a	30,2 a	127,1 a	19,8 a	2,7 b
CV (%)	68,0	21,9	87,5	27,1	13,1	47,5	47,5
MR x MF (1)	ns	Ns	ns	ns	ns	ns	ns
13 meses							
SR	57,6 b	0,124 a	2,57	36,8 a	120,0 a	43,1	10,2 a
S	73,3 a	0,121 a	2,71	36,4 a	103,4 a	41,2	7,5 a
RC+S	66,2 ab	0,107 a	2,20	43,1 a	111,6 a	47,3	5,2 a
CV (%)	15,2	16,2	42,2	45,5	16,9	29,8	54,3
A0	61,7 a	0,131 a	2,73	29,6 b	93,3 a	58,5	10,6 a
A1	79,3 a	0,108 a	1,83	42,9 a	124,5 a	30,3	5,7 b
A2	56,1 a	0,112 a	2,92	43,8 a	117,3 a	40,1	6,9 b
CV (%)	64,7	21,1	56,4	25,9	28,9	25,1	46,2
MR x MF (1)	ns	ns	*	ns	ns	*	ns
19 meses							
SR	98,6 a	0,095 a	1,09 a	44,5 a	150,8 a	25,4 a	11,7 a
S	99,0 a	0,114 a	1,25 a	39,4 a	145,2 a	30,0 a	10,2 a
RC+S	83,2 a	0,099 a	1,41 a	37,7 a	128,9 a	31,5 a	8,9 a
CV (%)	40,8	38,6	50,7	24,3	22,2	36,4	38,4
A0	96,5 a	0,093 a	1,10 a	43,6 a	151,6 a	32,9 a	13,8 a
A1	93,9 a	0,092 a	1,13 a	39,1 a	141,6 a	27,6 a	7,9 b
A2	90,3 a	0,123 a	1,52 a	36,5 a	131,7 a	26,6 a	8,9 b
CV (%)	39,2	28,9	43,2	30,3	21,0	28,4	34,9
MR x MF (1)	ns	ns	ns	ns	ns	ns	ns

(1) Interação entre manejo de resíduos (MR) e manejo de fertilizantes (MF), * demonstra significância da interação pelo teste F a 5% de probabilidade e ns, demonstra ausência de significância. Médias seguidas de letras iguais não diferem pelo teste Tukey, a 5% de probabilidade; CV = coeficiente de variação.

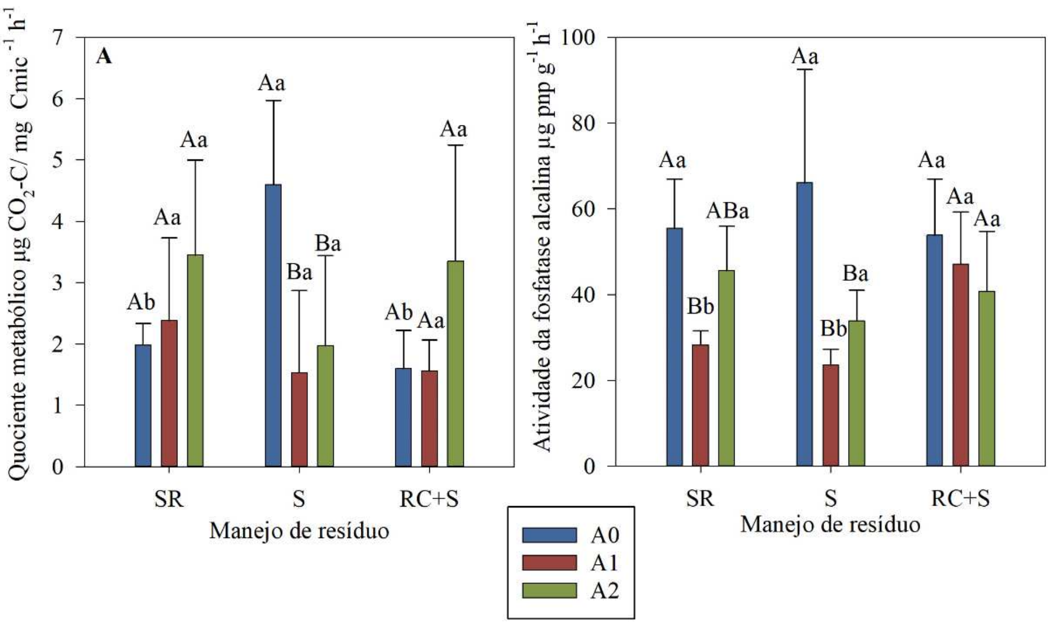

Figura 5: Valores do quociente metabólico e da atividade da fosfatase alcalina influenciados pelo manejo de resíduos: retirada de todos os resíduos (SR); manutenção da serapilheira da rotação anterior (S) e manutenção de resíduos da colheita e serapilheira da rotação anterior (RC+S) com os níveis de fertilização: ausência da aplicação de fertilizantes (A0) ou aplicação de $N_{60}P_{110}K_{158}$ (A1) ou $N_{72}P_{133}K_{188}$; (A2), aos 13 meses após o início do experimento. Letras maiúsculas comparam níveis de fertilização, minúsculas comparam manejo de resíduos.

3.5. Atividade da fosfatase ácida (FACI)

Não foram observadas diferenças na FACI durante o período experimental (Tabela 5).

3.6. Atividade da fosfatase alcalina (FACA)

Aos 13 meses após a imposição dos tratamentos, a atividade de FACA foi influenciada pela interação do manejo de resíduos com os níveis de fertilização (Tabela 5; Figura 5). Foram observados maiores valores da atividade da FACA quando não houve a aplicação de fertilizantes (A0) nos tratamentos onde houve remoção completa (SR) ou parcial (S) dos resíduos. Nas áreas onde foram mantidos os resíduos da colheita e a serapilheira da rotação anterior (RC+S) a atividade da FACA não foi influenciada pelos níveis de fertilização.

3.7. Atividade da urease (AU)

A atividade da urease diferiu entre os níveis de fertilização em todas as épocas de amostragem (Tabela 5). Foi constatada maior AU nas áreas onde não houve a aplicação de fertilizantes (A0), independentemente do manejo de resíduos empregado.

4. Discussão

4.1. Carbono da biomassa microbiana (CBM)

O maior teor de CBM do solo aos 13 meses após a manutenção dos resíduos nos tratamentos RC+S e S pode estar relacionado ao somatório de condições favoráveis para o solo: a presença de resíduos propicia fontes de C para fauna e microrganismos do solo, além de aumentar a proteção contra a perda de água por evaporação e reduzir a exposição do solo aos raios solares, com consequente aumento na temperatura (Gasparim et al., 2005). Rocha et al. (2018), comparando área em que houve retirada de resíduos, observaram maior teor de CBM na camada 0-5 cm, 19 meses após a manutenção de resíduos da colheita do eucalipto e serapilheira da rotação anterior, ou em área onde foi deixada apenas serapilheira.

Os efeitos da deposição de resíduos vegetais sobre o solo no aumento do teor de CBM são mais perceptíveis nas fases iniciais de decomposição. A fração prontamente decomponível, como as folhas, fornece mais prontamente C e N para a biomassa microbiana (Moreira & Siqueira, 2006). Após a utilização da fração solúvel, a biomassa de microrganismos sofre limitação de C e inicia a fase de morte (Cochran et al., 1998). O teor de CBM possuí natureza dinâmica, sendo facilmente alterado por fatores bióticos e abióticos (Powlson et al., 1987). Mendham et al. (2002) observaram aumento no teor de CBM da camada 0-5 cm de solo um ano após a retenção dos resíduos da colheita do eucalipto, no entanto, não observaram diferenças cinco anos após a colheita. Esses resultados divergem do estudo de Zhu et al. (2020) que observaram maior teor de CBM, na camada 0-20 cm, com um mês, um e cinco anos após a retenção de resíduos da colheita do eucalipto. A ausência de diferença no teor CBM entre os diferentes manejos de resíduos nas amostragens feitas aos 6 e 19 meses, pode estar atrelada ao fato dessas coletas terem sido realizadas na estação seca (Figura 1). Maiores teores de água no solo, como ocorre durante a estação chuvosa, beneficiam a atividade da microbiota do solo e aumentam o teor de CBM (Moura et al., 2015); esse fato pode aumentar a diferença entre os tratamentos.

A aplicação de fertilizantes não afetou o teor de CBM em todos os tempos de avaliação (Tabela 5). Assim como no presente estudo, há vários trabalhos que relatam que adição de fertilizantes químicos não altera o teor de CBM em solos cultivados com eucalipto. Wang et al. (2008) aplicaram 75 ou 150 kg ha^{-1} de P via superfosfato triplo e não notaram diferenças no teor de CBM da área sem aplicação de fertilizantes. Zhao et al. (2013) não observaram diferenças no teor de CBM com aplicação de 100 kg ha^{-1} de N na forma de nitrato de amônio. Por outro lado, Wang et al. (2008) relataram redução do teor decorrente da aplicação de 100 ou 200 kg ha^{-1} de N via ureia comparativamente à não adição de fertilizantes.

4.2. Respiração basal (RB)

A RB tem relação direta com a quantidade de resíduos decomponíveis (Moreira & Siqueira, 2006), como visto nos tratamentos RC+S e S, onde constatou-se maior RB em comparação à situação SR (Tabela 5). A RB aumenta com retenção de resíduos na área até certo limite, o que justifica a inexistência de diferenças nas áreas com RC+S e S (Tabela 5). Estudos similares a esse, como os de Versini et al. (2013) e Epron et al. (2015), apontam que incremento de 50 e 36 % na quantidade de resíduos da colheita em uma área produtiva não altera RB; porém, a remoção de todos os resíduos do eucalipto em florestas comerciais diminuiu a respiração microbiana (Oliveira et al., 2021; Rocha et al., 2018; Epron et al., 2015; Versini et al., 2013).

A RB foi mais intensa nos solos com a presença de resíduos apenas nos primeiros 6 meses de decomposição (Tabela 5). Com o avanço da decomposição, o conteúdo de formas mais lábeis de C e N do resíduo, principalmente aquelas associadas às folhas, diminui, pois são consumidas pelos microrganismos nos primeiros meses (Silva, 2008). Uma alta taxa de RB pode ser interpretada como característica agronômica desejável, uma vez que com a decomposição dos resíduos orgânicos haverá disponibilização de nutrientes para as plantas (Moreira & Siqueira, 2006). Oliveira et al. (2021) realizaram experimento com micro parcelas análogas às deste experimento (Figura 4), e observaram, aos 6 meses de experimento, que a RB era 62 % maior quando compararam as parcelas com e sem resíduos de colheita do eucalipto; após 12 meses de condução, as diferenças reduziram para 36 %. Segundo Harborne (1997), a eficiência de utilização do C pela biomassa microbiana de frações lábeis (açúcares) e recalcitrantes (celulose, polifenóis e lignina), está na ordem de 60 e 10 %, respectivamente.

A aplicação de fertilizantes não resultou em efeito na RB em qualquer tempo de avaliação (Tabela 5). Zeng et al. (2018) observaram que não houve diferença na respiração do solo quando houve aplicação de $N_{50}P_{115}K_{60}$ em florestas de pinus na China. Os nutrientes N, P e K influenciam de modo distinto a atividade microbiana e, consequentemente, a RB; além disso, na literatura os resultados da influência dos nutrientes na RB são controversos. A fertilização de N em solos florestais com alta disponibilidade desse nutriente, desestimula a respiração microbiana do solo (Janssens et al., 2010; Wang et al., 2008; Knorr et al., 2005). Kang et al. (2016) observaram que a influência de fertilizantes químicos com N na RB depende da fertilidade do solo, sugerindo que a adição de N via fertilizantes em solos que possuem limitação do nutriente, como o do experimento (Tabela 2), não reduz RB. Estudando o efeito do P sobre a RB, utilizando metanálise de 102 publicações, Feng & Zhu (2019) apontam que adição de P via fertilizantes sintéticos aumenta a RB em florestas tropicais. Os autores creditam isso ao fato de o P aumentar a atividade microbiana, tendo em vista a limitação deste nutriente nesses ambientes. A adição de K na forma de KCl reduz RB, sobretudo com o aumento da dose aplicada, visto que o íon Cl^- e o aumento da condutividade elétrica do solo afetam a atividade dos microrganismos do solo (Pereira et al., 2019).

4.3. Quociente metabólico (qCO_2)

Os resultados de qCO_2 variaram entre os tratamentos apenas aos 13 meses de iniciado o experimento (Tabela 5). Foi observado maior qCO_2 onde havia serapilheira da rotação anterior (S) combinada com a não aplicação de fertilizantes (A0) (Figura 5 A). A diminuição de teores de C e N solúveis da serapilheira, aos 13 meses, combinada ao não com o suprimento de nutrientes via fertilização provavelmente afetou a atividade da biomassa microbiana. De acordo com Anderson & Domsch (1993), qCO_2 elevado é indicativo de comunidades microbianas em estágio iniciais de desenvolvimento, com maior proporção de microrganismos ativos em relação aos inativos, ou, ainda, um indicativo de populações sob algum tipo de estresse metabólico. A serapilheira apresenta grande quantidade de materiais com elevado grau de decomposição, com altas proporções de materiais lignificados (Pegoraro *et al.,* 2013). A lignina tem forte influência sobre a decomposição da serapilheira, diminuindo sua taxa (Aber & Melillo, 1991). O qCO_2 aumenta na presença de resíduos florestais com muita celulose e polifenóis e com alta relação C:N, acarretando condição de estresse para a biomassa microbiana (Monteiro & Gama Rodrigues, 2004). Barreto-García et al. (2020) observaram maiores valores de qCO_2 em resíduos florestais com maiores quantidades de galhos, que por sua vez possuem maior relação C:N.

4.4. Atividade da Beta glicosidase (AβG)

A AβG não foi alterada em resposta ao manejo de resíduos da colheita do eucalipto, independentemente da fertilização (Tabela 5). A retenção de resíduos de culturas agrícolas no solo aumenta a AβG (Adetunji et al., 2017; Perucci et al., 1997), o que está relacionado ao teor de C prontamente mineralizável, uma vez que a enzima atua na fase final da decomposição da celulose formando o açúcar simples β-D-glucose (Tabatabai, 1994). Os resíduos da colheita do eucalipto possuem características bioquímicas distintas da maioria dos resíduos vegetais gerado por culturas de interesse agrícola, pois apresentam maior relação C:N, bem como maiores teores de lignina e compostos fenólicos (Pegoraro et al., 2013).

São poucos os trabalhos encontrados que avaliaram a AβG na decomposição de resíduos florestais. Maillard et al. (2018) não observaram diferenças na AβG nas camadas de solo de 0-5 e 5-10 cm de profundidade, quatro anos após a retirada resíduos gerados na colheita do eucalipto; no entanto, encontraram maior AβG na camada 10-20 cm. Kim et al. (2018) não observaram diferenças na AβG na camada 0-10 cm do solo com diferentes quantidades de resíduos provenientes do desbaste de pinus, sete anos após a deposição dos mesmos no solo.

No experimento foram observadas maiores AβG 13 meses após a fertilização independentemente do manejo de resíduos (Tabela 5). A influência da adubação na atividade da enzima pode estar ligada à disponibilidade ou limitação do nutriente no solo (Turner & Wrigth. 2014). Na literatura há relatos da ausência de resposta ou aumento da AβG após adubação química de N, P e K em solos florestais. Turner & Wrigth. (2014) não encontraram diferença na AβG com a aplicação isolada de N, P e K ou combinada (NPK) em florestas nativas tropicais. Zeng et al. (2018) observaram que não houve diferença na atividade da enzima quando houve aplicação do de $N_{50}P_{115}K_{60}$ em florestas de pinus, nas quais as avaliações foram feitas na camada de 0-10 cm por 4 anos consecutivos. Por outro lado, Cusack et al. (2010), em florestas tropicais, e Carreiro et al. (2000), em florestas temperadas, constaram maiores AβG com adubação de N.

De maneira geral AβG aumentou em todos os tratamentos ao longo dos tempos de amostragem (Tabela 5). Outros autores também relataram o mesmo comportamento da AβG experimentos que envolveram manejos de resíduos, atribuindo esse fato a acumulação dessa enzima em partículas de argila e matéria orgânica, que por sua vez são mais protegidas a ação de proteases (Mendes et al., 2019; Lopes et al., 2018)

4.5. Atividade da fosfatase ácida (AFACI) e fosfatase alcalina (AFACA)

A presença de resíduos vegetais no solo aumenta atividade das fosfatases ácidas e alcalinas em função do aumento de P orgânico no solo (Adetunji et al., 2017). No entanto, há de se considerar que, além da quantidade, a qualidade dos resíduos vegetais também influencia na atividade das enzimas (Mendes e Reis Jr., 2004; Mendes et al., 2009). Perucci & Scarpon (1985) testaram o efeito da aplicação de diferentes resíduos vegetais de plantas de interesse agrícola e observaram que nem todos os resíduos agrícolas acarretam o aumento da atividade das fosfatases, referindo esses efeitos à qualidade dos materiais.

São escassos os trabalhos que testam a influência da presença de resíduos de eucalipto na atividade das fosfatases. Maillard et al. (2018) não observaram diferenças na atividade das fosfatases ácidas na camada de 0-10 cm de solo com a retirada de resíduo da colheita, mas não avaliaram a atividade das fosfatases alcalinas. Por outro lado, diferentes dos nossos resultados, Rocha et al. (2019) observaram que a retirada de resíduos da colheita do eucalipto reduz a atividade das fosfatases ácidas nos dez primeiros centímetros de solo, em plantios de aproximadamente 15 anos e duas rotações consecutivas. Isso pode explicar a diferença nos resultados, pois, no presente estudo, os dados referem-se a plantios em uma única rotação, estando os resíduos apenas dois anos na área do estudo.

Os nossos resultados (Tabela 5) mostraram não ter havido efeito da adubação NPK na AFACI, mas redução da AFACA quando houve retirada completa (SR) ou parcial dos resíduos (S) na coleta feita com 13 meses. Resultados semelhantes foram observados por Rocha et al. (2019) para as fosfatases ácidas, pelos quais a adubação mineral com P reduziu a atividade da enzima no tratamento com a retirada parcial de resíduos florestais. No entanto, assim como o nosso trabalho, a fertilização não afetou a AFACA na área onde foram mantidos todos os resíduos (RC+S).

A atividade das fosfatases é fortemente influenciada pelos teores de fósforo solúvel solo, tendendo a aumentar sob deficiência do nutriente (Oberson et al., 1996). Por conseguinte, a adição de P nesses solos reduzem as fosfatases (Wang et al., 2020; Turner & Wrigth., 2014). Do ponto de vista energético não é vantajoso para os microrganismos mineralizar fósforo quando há abundância de fósforo inorgânico (Marklein & Houlton, 2012).

Apesar da adubação fosfatada e da elevação dos teores de P no solo observada 19 meses após a operação (Tabela 4), a adubação com N em solos com baixos teores de matéria orgânica estimula a atividade microbiana aumentando a demanda de P e consequentemente intensifica a atividade da fosfatase (Bonnie et al., 2008; Houlton, 2012; Turner & Wrigth, 2014). O efeito da presença do N na fertilização na atividade da enzima fosfatase ácida é maior em comparação com a presença do P (Marklein e Houlton, 2012). Fertilização mineral com N e P aumenta a atividade da fosfatase ácida, principalmente em função da presença do N (Olander & Vitousek, 2000).

A ausência de diferença de resultados da atividade AFACA entre os manejos de resíduos e níveis de adubação nas amostragens feitas aos 6 e 19 meses pode estar atrelada ao fato de essas coletas terem sido feitas na estação seca (Figura 1). As fosfatases alcalinas são sensíveis a variações sazonais, apresentando menores atividades no período seco, devido à redução do metabolismo dos microrganismos com consequente diminuição no requerimento por nutrientes (Ahmed et., 2019; Baldrian et al., 2008), esse fato pode reduzido o contraste entre os tratamentos nesta época de avaliação.

4.6. Atividade da urease (AU)

A atividade da urease é insensível ao aumento da carga de deposição de resíduos vegetais sobre o solo (Rajashekhara Rao & Siddaramappa, 2008). A retenção de certos resíduos vegetais é conhecida por aumentar a AU, principalmente os que apresentam baixa relação C:N e pouca recalcitrância na liberação de N durante a decomposição (Perucci et al., 1984). Há poucos estudos que demonstram se a retenção de resíduos florestais aumenta a atividade da urease. Zhu et al. (2020) observaram maior AU na camada de 0-20 de solo com a retenção de resíduos da colheita do eucalipto na China. Em florestas plantadas em ambientes tropicais não foram encontrados trabalhos mostrando a relação da AU e manejo de resíduos.

Assim como este trabalho, vários estudos apontam que a atividade da enzima urease diminuí com a aplicação de fertilizantes minerais, principalmente o nitrogênio (Da Silva et al., 2014; Bautista-Cruz & Ortiz-Hernández, 2015; Meysner et al., 2006; Mohammadi, 2011). Também são relatadas reduções da atividade da enzima após a aplicação de P mineral (Wang et al., 2008). A fertilização nitrogenada reduz a quantidade da comunidade de fungos (Allison et al., 2007) e bactérias diazotróficas em plantios de eucalipto (da Silva et al., 2015).

Atividade enzimática também está relacionada com pH do solo, sendo menor com a acidificação (Sinsabaugh et al., 2008). Neste trabalho, a fertilização, em ambas as doses, reduziu o pH do solo e aumentou a disponibilidade de Al^{3+} (Tabela 4). A aplicação de altas doses de fertilizantes minerais, ou sua aplicação continua, a longo prazo, abaixa o pH do solo (Geisseler & Scow, 2014; Schroder et al., 2011; Barak et al., 1997).

Os resultados desse estudo ajudam compreender a baixa resposta do eucalipto à adubação nitrogenada (Barros et al., 1990; Santos, 2001). Alguns autores atribuem essa baixa resposta à alta eficiência da planta em absorver o N da matéria orgânica do solo (Jesus et al., 2012; Barreto-García et al., 2010; Gonçalves et al., 2001). Mas, além disso, atualmente, há relatos demonstrando a capacidade do eucalipto em estabelecer relações simbióticas com bactérias fixadoras de nitrogênio atmosférico (Da Silva et al., 2014; Fonseca et al., 2017).

5. Conclusões

A retirada de resíduos da área do plantio reduz a biomassa e a atividade microbiana do solo.

A aplicação de fertilizantes sintéticos, em altas doses, altera a composição química do solo reduzindo a atividade microbiana do solo.

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