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Litterfall production, decomposition and litter nutrient contents in a mined area revegetated with different forest species

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ABSTRACT: Afforestation of sites disturbed after bauxite mining is the favorite technique to restore all ecosystem functions. The nature of the tree species used for revegetation of post-mining land can accelerate the recovery of soil organic matter and nutrient cycles. This study aimed to determine the litterfall production, decomposition rate and nutrient content from three types of forest cover (*Eucalyptus*, *Anadenanthera peregrina*, mixed plantation of 16 native species) planted in a bauxite mining area in recovery. Litterfall production was evaluated monthly over 30 months, and the litter mass was assessed twice a year (dry and rainy periods). Total nutrient content was determined from samples grouped by period (dry and rainy). The annual average values for litterfall dry mass and litter mass were higher in *Eucalyptus* and mixed native. The period (dry or rainy) did not influence litterfall rates in *A. peregrina*, but *Eucalyptus* and mixed native presented higher amounts for litterfall during the rainy and dry periods, respectively. Litter accumulation in *Eucalyptus* was not affected by the season of the year, but mixed native and *A. peregrina* presented higher litter accumulation in the dry season. Apparent decomposition rates of *A. peregrina* and mixed native were higher in the rainy season, highlighting the *A. peregrina* with the highest values compared with the other forest covers. The mixed native presented the highest leaf content of P, K, Ca and Mg in both the litterfall and litter mass, while *Eucalyptus* had the lowest P, K, Ca, S and N content and the highest C content in the litterfall. Litterfall production is important in degraded areas to ensure the nutrient return to the soil. The data obtained suggest that the cultivation of a mixed of 16 native trees contribute for produce the higher annual litterfall yields, besides produces leaf litterfall of better nutritional quality in relation to P, K, Ca, Mg and S. Therefore, mixed of native trees can be a promising option for reactivation of nutrient cycling and organic matter formation in mined area of bauxite in the Brazilian Atlantic Forest.

Keywords: land reclamation, litter, *Eucalyptus*, Brazilian Atlantic Forest.

INTRODUCTION

Mining activities result in loss of soil and plant cover and ecosystem malfunction (Shrestha and Lal, 2011; Borges et al., 2019) leading to the degradation of thousands of hectares worldwide (Machado et al., 2013). In degraded environments, the removal of the superficial soil layer eliminates the litter and also the natural seed bank, resulting in a reduction of the biogeochemical cycling of nutrients and loss of the soil quality and efficient mechanisms for the natural regeneration of plant cover (Celentano et al., 2011; Machado et al., 2016).

Recovery of physicochemical and biological soil properties in mined sites is challenging. Furthermore, the high incidence of erosion, combined with poor soil fertility and low organic matter content, often limit vegetation growth and delay the restoration of ecosystems (Wantzen and Mol, 2013; Ahirwal and Maiti, 2021; Valente et al., 2023). An alternative for restoring the soil quality in degraded areas is establishing forest cover using native or exotic species that promote fast revegetation of the area (Lanuza et al., 2018). However, information about the potential of exotic and forest species to apport litter and nutrient to the soil in mining areas are still scarce.

The input and decomposition of litter from forest species are fundamental for reactivating the biogeochemical cycling and increase the soil fertility in terrestrial ecosystems (Celentano et al., 2011; León and Osorio, 2014; Agus et al., 2016; Silva et al., 2018; Feng et al., 2019; Giweta, 2020), especially in tropical soils with a low level of nutrients (Tang et al., 2010; Ge et al., 2013). Therefore, quantifying the litter production, chemical quality and decomposition is useful for evaluating and monitoring rehabilitated forests (Silva et al., 2018; Giweta, 2020), which can increase the chances of success in the recovery process of mined areas. Notwithstanding all other factors, sustainable rehabilitation partly depends on establishing and maintaining a supply of plant-available macronutrients (N, P, and K) that are deficient in disturbed sites after bauxite mining. For instance, Worlanyo and Jiangfeng (2021) indicated that during the early stages of rehabilitation (<5 years of age), the vegetation might be P limited, while in older rehabilitation, N limitation may be manifesting, especially for the non-legume species.

In Brazil, mining is an important economic activity, but it can also negatively affect the environment and society. For instance, the recent dan collapse in Minas Gerais State, in 2019, resulted in the loss of 133 ha of native vegetation and 71 ha of permanent protection areas along with watercourses in the Atlantic Forest biome, the 5th hotspot of biodiversity in the world (Myers et al., 2000; Thompson et al., 2020). This fact reinforces the need to identify forest species and practices that can foster the recovery of areas degraded by mining activity that improve soil recovery and reactivate natural nutrient cycling. This study aimed to evaluate the litterfall production and decomposition rate, as well as nutrient return to the soil, in plantations of *Eucalyptus*, *Anandenthera peregrina,* and the mixed native species planted to cover an area of bauxite mining in the Brazilian Atlantic Forest.

MATERIALS AND METHODS

Study area and experimental design

The study was carried out in São Sebastião da Vargem Alegre, Minas Gerais, Brazil (21° 1′ 58″ S and 42° 35′ 8″ W, 780 m altitude), in an area of bauxite extraction. The predominant climate is Cwa (Köppen Classification System), with hot and rainy summers and a well-defined dry season. The average annual precipitation and temperature are 1,287 mm and 20.3 °C, respectively (Instituto Nacional de Meteorologia - Inmet, 2016). The soils were classified as *Latossolo Vermelho Amarelo distrófico típico* (Santos et al., 2018), which corresponds to a Ferralsols Orthidystric (IUSS Working Group WRB, 2015). After mining, the soil surface layer (0.00-0.20 m) was stored for approximately one year. Then, it was returned to the area during topographic reconfiguration, followed by decompaction with a subsoiler at 0.60 m soil depth.

The experiment was installed in March 2011 using a randomized block design with split plots and three replicates with different forest species (Table 1). The plots (40 × 18 m) comprised three different forest cover treatments: (1) monoculture of *Anadenanthera peregrina* (L.) Speg (*A. peregrina*); (2) monoculture of *Eucalyptus*; and (3) mixed plantation with 16 species, including pioneer and non-pioneer native species from Atlantic forest biome (mixed native). The *Eucalyptus* and *A. peregrina* species were planted by 3 × 2 m, and the mixed native species in Quincunx (4 pioneers rounding a climax specie in the center) spaced 2.0 × 1.5 m. The mixed native seedlings were produced from seeds collected in fragments of Atlantic Forest (Woodland). In this study, we used two subplots (10 × 18 m) with different fertilization treatments: (*i*) standard fertilization (SF) used by the company in their rehabilitation activities of mined areas; and (*ii*) a combination of SF with organic fertilization (OF) and chemical fertilization (CF).

Litterfall interception and litter mass accumulation on the ground

To evaluate the litterfall production, we installed suspended collectors above the ground in October 2013, when the plants were 31 months old. We installed three collectors of nylon (1 mm mesh) between the planting rows in each subplot (54 collectors in total), with each collector presenting an 8 × 0.5 m (4 m^2) area at the height of 0.5 m from the ground. The large area of the collectors aimed to better represent the different trees species in the study. We collected the litter production monthly for 30 consecutive months, and the litterfall collected was weighed and homogenized and then separated into leaves+reproductive structures (leaf litterfall) and twigs. Each component was weighed before and after oven drying at 65 °C for 48 h to determine the dry weight, and then stored for chemical characterization.

We also estimated the litter remaining and accumulated on the ground at the end of the dry period (September 2014 and September 2015) and the rainy period (March 2014, March 2015, and March 2016). To do this, we randomly threw five times a frame (0.5 × 0.5 m) on the soil and collected the litter deposited inside the frame. The litter mass was weighed, and all five samples were mixed and homogenized. From this material, we collected a composed sample that was further separated into leaves reproductive structures (leaf litter) and twigs (twig litter), and weighed before and after oven drying at 65 °C for 48 h to determine the dry matter weight chemical characterization.

The apparent decomposition ratio of the litter was estimated by the ratio of litter production and litter mass on the ground at the end of the dry and rainy periods (Olson, 1963; Sales et al., 2020), according to equation 1.

$$k = Mt/Mr \qquad \text{Eq. 1}$$

in which: k is the decomposition rate in kg $year^{-1}$; Mt is the sum of the mean monthly weight in kg ha^{-1} of the litterfall in the collectors during the dry or rainy period; and Mr is the mean weight in kg ha^{-1} of the litter mass remaining on the ground at the end of the dry or rainy period. The annual litter production and litter mass (kg ha^{-1} yr^{-1}) were calculated as the ratio of the sum of monthly litterfall or litter mass by the period of 2.5 years (equivalent to the 30 months of experimental evaluation). We also calculated the average litterfall production and litter mass for the rainy and dry seasons, considering three rainy and two dry seasons, each one with six months during the experimental evaluation period.

Table 1. Description of the plots identifying the monocultures composed of *A. peregrina* and *Eucalyptus* and a mixed plantation of 16 native species (mixed native) and subplots with standard fertilization (SF) and a combination of SF with organic fertilization (OF) and chemical fertilization (CF)

Treatments/Plots		Forest species	Phenology
A. peregrina		*Anadenanthera peregrina* (L.) Speg	Deciduous
Eucalyptus		*Eucalyptus urophylla x Eucalyptus grandis*	Evergreen
Mixed native	Pioneer	*Anadenanthera peregrina* (L.) Speg	Deciduous
		Ficus insipida Willd – Fi	Semi-deciduous
		Inga edulis Mart. – Ie	Semi-deciduous
		Piptadenia gonoacantha (Mart.) JF Macbr. - Pg	Semi-deciduous
		Enterolobium contortisiliquum (Vell.) Morong.- Ec	Deciduous
		Ceiba speciosa (A. St.-Hil.) Ravenna - Cs	Deciduous
		Sapindus saponaria L. – Ss	Evergreen or semi-deciduous
		Pera glabrata (Schott) Poepp. Ex Baill.- Pgl	Evergreen
	Non-pioneer	*Trichilia* sp – Tsp	Semi-deciduous
		Cupania oblongifolia Mart. – Co	Evergreen or semi-deciduous
		Apuleia leiocarpa (Vogel) JF Macbr. - Al,	Deciduous
		Handroanthus chrysotrichus (Mart. Ex A. DC.) Mattos – Hc	Deciduous
		Hymenaea courbaril var. *stilbocarpa* (Hayne) YT Lee and Langenh – Hcs	Semi-deciduous
		Lecythis sp – Ls	Semi-deciduous
		Paubrasilia echinata Lam. – Pe	Semi-deciduous
		Annona squamosa L. – As.	Deciduous
Subplots		Fertilization, place and proportion of application	
SF		2.0 Mg ha^{-1} dolomitic limestone: *Eucalyptus* and *A. peregrina*: 25 % - planting holes and 75 % between the rows; and mixed native: 50 % - planting hole and 50 % between the rows. 30.0 Mg ha^{-1} poultry litter (fresh, 30 % moisture): *Eucalyptus* and *A. peregrina* - 22 % in the planting hole and 78 % between the rows; and mixed native - 44 % in the planting hole and 56 % between the rows).	
SF+(OF+CF)		5.0 Mg ha^{-1} dolomitic limestone: *Eucalyptus* and *A. peregrina*: 25 % - planting holes and 75 % between the rows; and mixed native: 50 % - planting hole and 50 % between the rows). 60.0 Mg ha^{-1} poultry litter (fresh, 30 % moisture). *Eucalyptus* and *A. peregrina* - 22 % in the planting hole and 78 % between the rows; and mixed native - 44 % in the planting hole and 56 % between the rows. 0.75 Mg ha^{-1} (*Eucalyptus* and *A. peregrina*) or 1.5 t ha^{-1} (mixed native) of Bayovar natural reactive phosphate (100 % in the planting holes). 1st top-dressing fertilization (1 month before planting): *Eucalyptus* and *A. peregrina*: 10 kg ha^{-1} of N, 22 kg ha^{-1} of P, and 8 kg ha^{-1}; and mixed native: 20 kg ha^{-1} of N, 44 kg ha^{-1} of P, and 16 kg ha^{-1} of K). 2nd top-dressing fertilization (10 months before planting): *Eucalyptus* and *A. peregrina* - 67 kg ha^{-1} of N, 17 kg ha^{-1} of P, and 67 kg ha^{-1} of K +1.7 kg ha^{-1} of B, 0.8 kg ha^{-1} of Zn, 0.8 kg ha^{-1} of Cu; and mixed native - 134 kg ha^{-1} of N, 34 kg ha^{-1} of P, and 134 kg ha^{-1} of K to the mixed native + (3.4 kg ha^{-1} of B, 1.6 kg ha^{-1} of Zn, 1.6 kg ha^{-1} of Cu).	

Chemical characterization of the litterfall and litter mass

For the chemical characterization, we grouped the litterfall components by season (dry or rainy), considering the proportion of monthly litterfall contribution in the collectors. All samples were ground in a Wiley-type mill and then submitted to nitric-perchloric digestion to determine the K content (flame photometry); P content (colorimetry, by the vitamin C method, modified by Braga and Defelipo (Braga and Defelipo, 1974); and Ca, Mg and S content (atomic absorption spectroscopy). We determined the total nutrient content (kg ha^{-1}) of leaf and twig from litterfall and litter mass by multiplying the total nutrient content from each component by the dry mass in the rainy and dry seasons (Vitousek and Sanford, 1986; Tang et al., 2010).

Statistical analysis of the data consisted of the Shapiro-Wilk test to verify the normality, Bartlett test to verify the homogeneity of variances, and the analysis of variance (ANOVA). When statistical significance was reached ($p<0.05$), the means were compared by Tukey's test at 10 % probability to analyse the effect of fertilization and forest cover litterfall production and litter mass from the different components, as well the total nutrient content. All statistical analyses were carried out using the Statistica 7.0 software (Statsoft 2012).

RESULTS

Litterfall production and litter mass on the ground

A. peregrina presented the lowest litterfall production (3,950 ± 593 kg ha^{-1} yr^{-1}) and differed significantly from *Eucalyptus* (8,324 ± 1,979 kg ha^{-1} yr^{-1}) and mixed native (6,322 ± 608 kg ha^{-1} yr^{-1}, $p<0.10$) (Figure 1a). Leaves were the main component of litterfall in *A. peregrina* (77 %), *Eucalyptus* (67 %), and mixed native (84 %) with a similar pattern over the studied period (Figures 1b and 1c).

Total litterfall production and the influence of precipitation are shown in figure 1. The rainy season in the state of Minas Gerais comprises the months from October to March and the dry season from April to September. While the seasons influenced the litterfall production in *Eucalyptus* and mixed native, this pattern was not found for *A. peregrina*. The highest litterfall production occurred in the rainy season for *Eucalyptus*, while mixed native achieved the same values only in the dry period (Figures 1a, 1d and 1e). The leaves followed a similar pattern during the dry and rainy seasons compared with the total litterfall, with and *A. peregrina* presenting the lowest values for both periods. Although mixed native and *Eucalyptus* showed similar patterns concerning leaf production across the year, twigs presented higher quantities during the wet season for *Eucalyptus* and the *A. peregrina* and mixed native did not differ as regards the quantity of twig litterfall. The ANOVA showed no significant effects ($p>0.10$) on the interaction between types of fertilization and litter production from the different forest covers. Therefore, we used the mean values of litter production from the treatments SF and OF+CF.

Annual mean value for litter mass in *A. peregrina* (5,717.12 ± 811.37 kg ha^{-1} yr^{-1}) was significantly lower ($p<0.10$) than in *Eucalyptus* (15,658.46 ± 3209.51 kg ha^{-1} yr^{-1}) and mixed native (12,508.69 ± 721.57 kg ha^{-1} yr^{-1}) (Figure 2a), with no difference between *Eucalyptus* and mixed native. Leaf litter was the main component in *A. peregrina* (62 %) and mixed native (79 %), and 50 % in *Eucalyptus*, which also presented the highest percentage of twig litter in each sampling (Figures 2a, 2b, and 2c). There was no difference in litter mass in *Eucalyptus* considering seasonality (Figures 2d and 2e), whereas *A. peregrina* and mixed native showed higher values during the dry period. Nevertheless, *Eucalyptus* had the highest accumulation of litter mass in the rainy period, followed by mixed native and *A. peregrina*. During the dry period, there was no difference between *Eucalyptus* and mixed native. The forest cover *A. peregrina* presented the smallest accumulation of litter

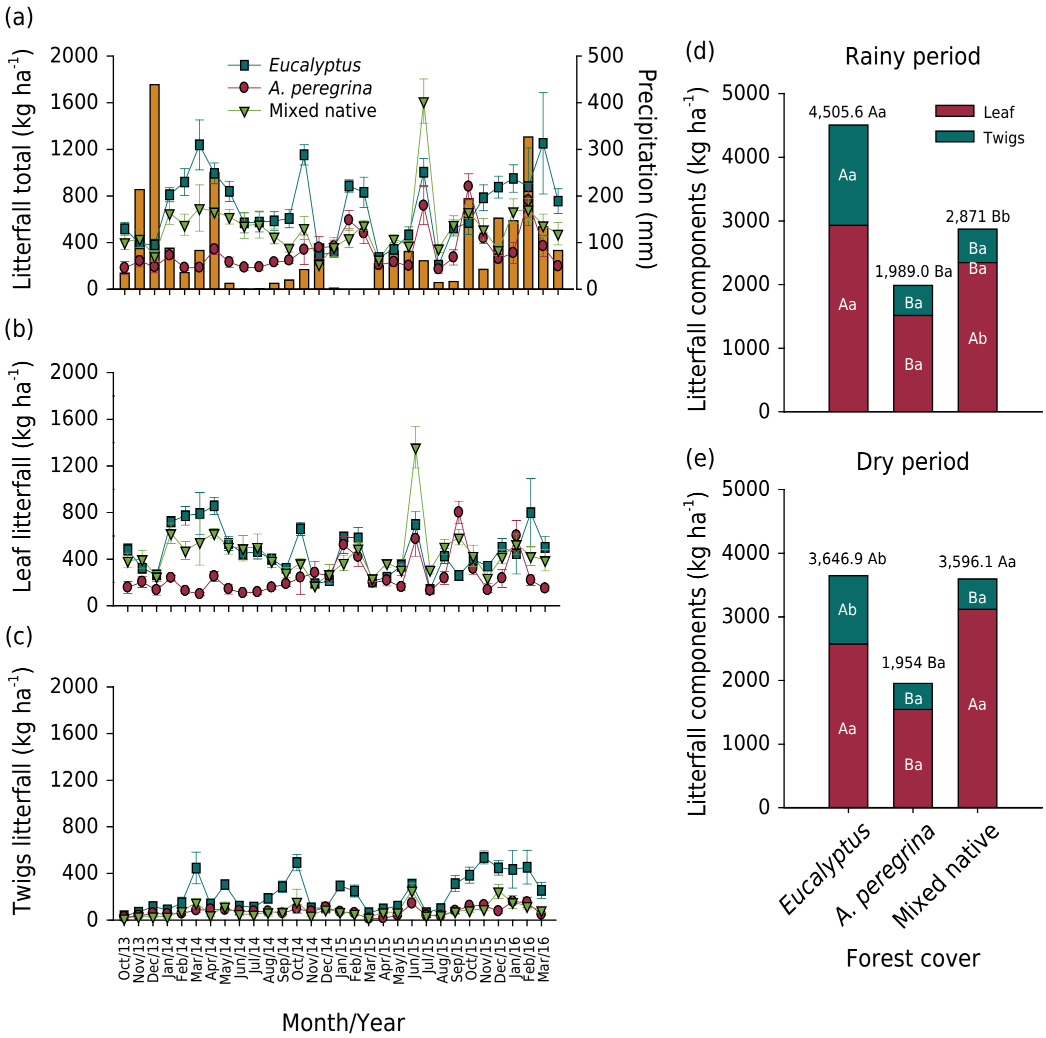

Figure 1. Total monthly interception of litterfall (a), leaves(b), twigs (c), litterfall components (leaf and twigs) (d and e) at the rainy and dry periods from *Eucalyptus*, *A. peregrina* and from a mixed plantation of native species (mixed native), during 30 months, in an area of bauxite mining in rehabilitation. Bars indicate the standard error of the mean. Uppercase letters compare different types of cover for each period (dry or rainy), while lowercase letters compare each type of forest cover in the dry and rainy periods, and when similar, indicate no significant differences by Tukey's test at 10 %. Values above the bars indicate litterfall quantities.

mass all year. Analysing the litter components, we found that *A. peregrina* and mixed native produce the highest accumulation of leaves during the dry season, while *Eucalyptus* had the highest values for twigs, differing from *A. peregrina* and mixed native during both periods.

Decomposition of the litter mass and its components

A. peregrina showed the highest apparent decomposition rate (k: 0.7 kg yr^{-1}) during the rainy period (Figure 3), around three times bigger than the other species studied. Nevertheless, no differences were observed between *A. peregrina* and the other types of cover in the dry period. We also did not identify differences in the decomposition rate of litter, leaf-litter and twigs in *Eucalyptus* did between seasons. Moreover, the decomposition rate of twigs did not vary with the forest cover and period of the year.

Total nutrient content of the litterfall and the litter mass

Native forest species (mixed native) presented the higher total content of P, K, Ca, Mg and S in the leaves of the litterfall in both seasons, with the higher values in the

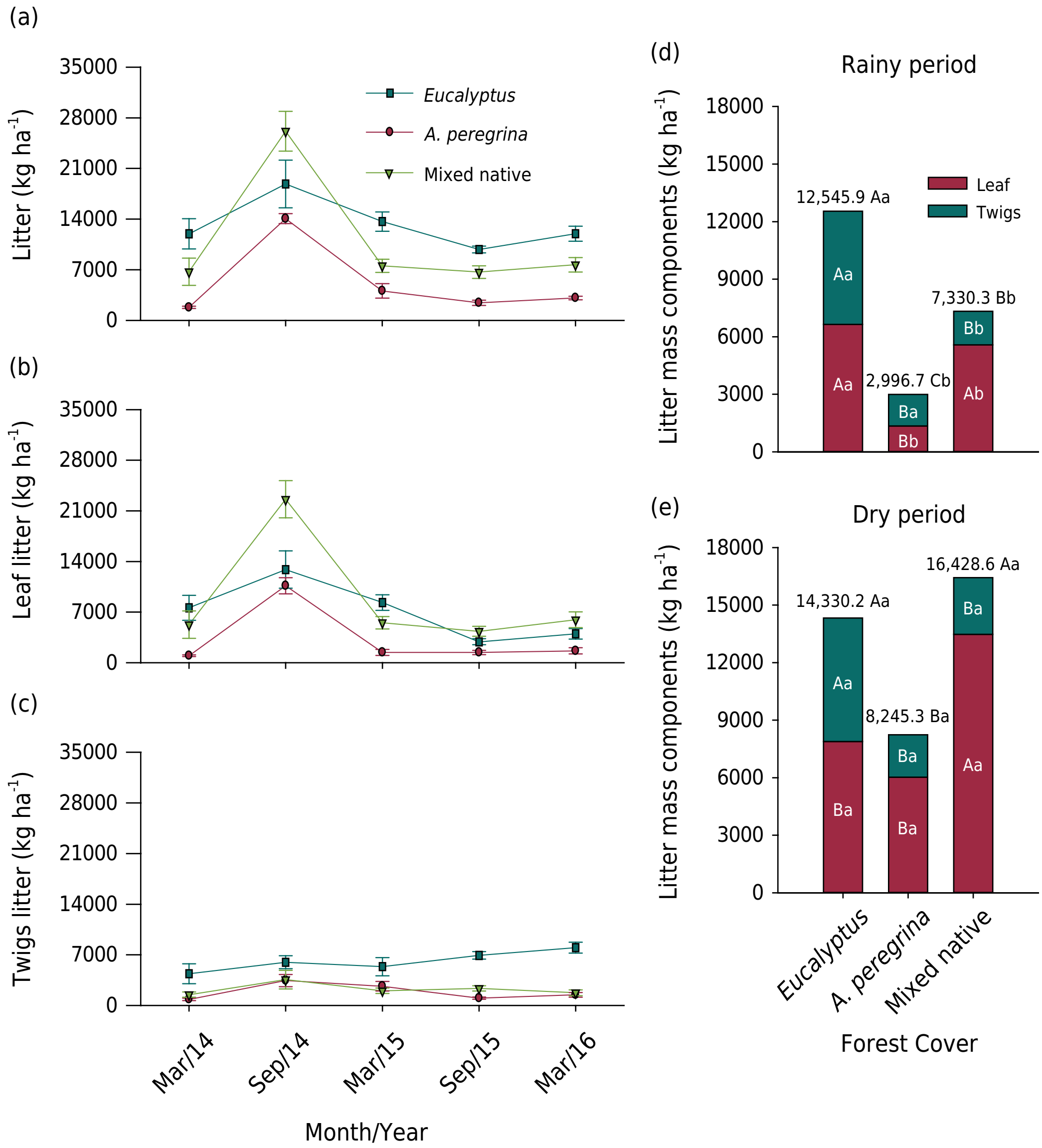

Figure 2. Total l litter mass (a), leaf (b) and twigs (c) at the dry and rainy months, litter components (leaf and twigs) (d and e) during the dry and rainy periods from *Eucalyptus*, *A. peregrina* and a mixed plantation of native species (mixed native), during 30 months, in an area of bauxite mining in rehabilitation. Bars indicate the standard error of the mean (n = 3). Uppercase letters compare the different types of cover for each period (dry or rainy), while lowercase letters compare forest cover between the dry and rainy periods, and when similar, indicate no significant differences by Tukey's test at 10 %. Values above the bars indicate total litter.

dry period (Table 2). *A. peregrina* and *Eucalyptus* did not present differences in the content of P and S of the litterfall leaf, but *A. peregrina* had the lowest values of K and Ca in the rainy season and Mg in both seasons. We found the highest C/N ratio of the litterfall leaf in *Eucalyptus* and the lowest in *A. peregrina*. The highest content of P, K, Ca, Mg, S and C in twigs were observed in the rainy season for *Eucalyptus*, while *A. peregrina* and mixed native presented similar values. The three forest covers presented similar N contents from litterfall twigs in the rainy season, but mixed native presented the highest N values in the driest period. Similar to leaf litterfall, the twigs of the *Eucalyptus* litterfall showed the highest C/N ratio among the forest cover studied, followed by mixed native.

Native forest cover (mixed native) presented the highest nutrient content of leaf litter mass in the dry season for all nutrients studied. There was no difference in the nutrient content of the leaf litter mass during the rainy period between *Eucalyptus* and mixed

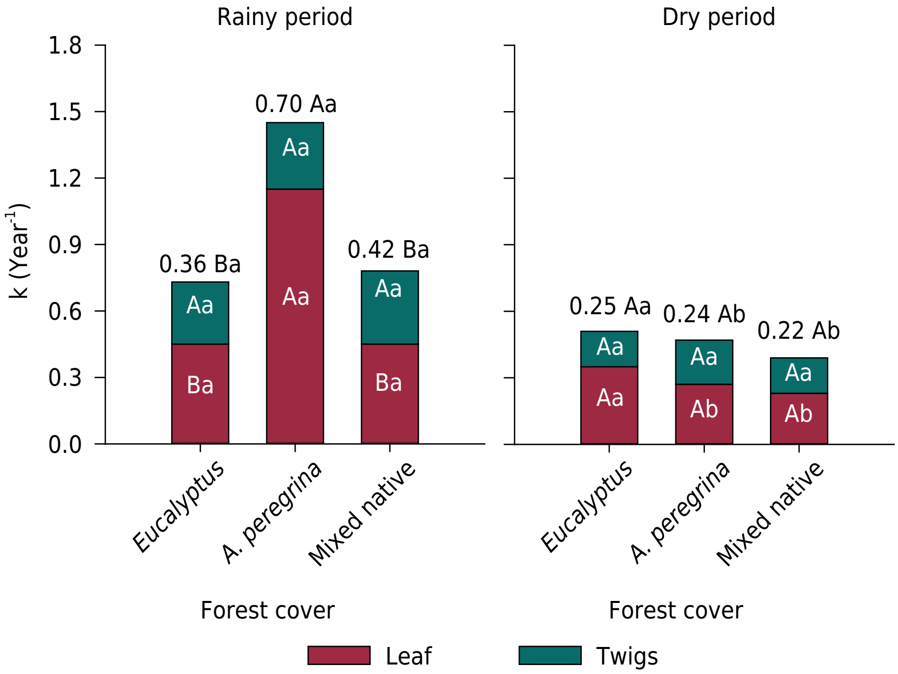

Figure 3. Apparent decomposition rates for litter, leaf litter and twigs during the dry and rainy periods from *Eucalyptus*, *A. peregrina,* and a mixed plantation of native species (mixed native), during 30 months, in an area of bauxite mining in rehabilitation. Uppercase letters compare the different types of cover for each of the seasons (dry or rainy), while lowercase letters compare each type of forest cover between the dry and rainy seasons, and when similar, indicate no significant differences by Tukey's test at 10 %. Values above the bars indicate the total decomposition rate.

native, and *Eucalyptus* showed the highest C/N ratio in the leaf litter mass (Table 2). The P and N contents in the twigs-litter mass did not differ between the forest covers throughout the year, but the season influenced the nutrient content of the twig litter mass in mixed native, which presented the highest values of P, Ca, Mg, S, C and N in the dry season. The C/N ratio of the twig litter was higher for *Eucalyptus*, not being influenced by the time of year.

DISCUSSION

Litterfall and litter mass by type of forest cover

Growth rate and productivity of forests influence the production of litterfall (Wang et al., 2008; Barliza et al., 2019; Feng et al., 2019). The mixed with native species has a slow growth with a diameter at the ground level varying from 8.66 to 10.41 cm and a mean base area from 0.0092 to 0.0118 m^2 compared with *Eucalyptus*. However, it presented litter production similar to *Eucalyptus*, which can be explained by its higher diversity of species (pioneer and no-pioneer) with different phenology (Valente et al., 2021). Several studies report that species diversity in forest plantations is associated with higher annual litterfall production (Gama-Rodrigues et al., 2007; Wang et al., 2007; Tang et al., 2010). These results agree with Miranda Neto et al. (2015), who studied litterfall production in a mining area in recovery with native forest species in Minas Gerais, Brazil. After nine years, these authors found an annual litterfall production of 6772 ± 1940 kg ha^{-1}. The leaf litterfall represented 67 to 84 % of total litterfall production, similar to results also found in planted forests in Brazil by Silva et al. (2018) and Souza et al. (2019) and worldwide by Agus et al. (2016).

Trees with a larger diameter, height and basal area tend to present a greater contribution of litter as *Eucalyptus* (a fast-growing three) and some other native species with different annual growth rates, especially in the early stages of succession (Souza et al.,

Table 2. Total nutrient content of the leaves and twigs from litterfall and litter mass in *A. peregrina*, *Eucalyptus* and a mixed plantation of native species (mixed native), at the dry and rainy periods in an area of bauxite mining in rehabilitation

Forest Cover	Season	P	K	Ca	Mg	S	C	N	C/N
		kg ha^{-1}							
				Leaf litterfall					
A. peregrina	Rainy	1.9 Ba	8.3 Ca	12.9 Ca	2.2 Ca	1.7 Bb	723.2 Ba	36.4 Aa	19.9 Ca
	Dry	1.3 Bb	8.5 Ba	16.6 Ba	2.3 Ca	1.9 Ba	724.2 Ba	37.0 Ba	19.8 Ca
Eucalyptus	Rainy	2.0 Ba	12.0 Ba	22.4 Ba	4.5 Ba	1.7 Ba	1369.9 Aa	24.6 Ba	55.1 Aa
	Dry	1.5 Bb	11.1 Ba	23.4 Ba	4.2 Ba	1.6 Bb	1192.3 Aa	22.8 Ca	52.6 Ab
Mixed native species	Rainy	2.7 Ab	15.3 Ab	31.9 Ab	6.1 Ab	2.9 Ab	1020.8 ABb	41.9 Ab	24.4 Ba
	Dry	3.0 Aa	24.1 Aa	45.0 Aa	8.2 Aa	3.6 Aa	1348.0 Aa	58.1 Aa	23.2 Ba
				Twig litterfall					
A. peregrina	Rainy	0.4 Ba	3.2 Ba	7.5 Ba	0.7 Ba	0.4 Ba	206.9 Ba	7.5 Aa	29.6 Ba
	Dry	0.2 Ab	3.2 Aa	7.6 ABa	0.5 Ba	0.3 Ba	178.0 Ba	6.9 Aa	26.3 Ca
Eucalyptus	Rainy	0.5 Aa	5.1 Aa	14.2 Aa	1.7 Aa	0.7 Aa	692.9 Aa	6.2 Aa	111.6 Ab
	Dry	0.2 Ab	3.1 Ab	9.2 Aa	1.4 Aa	0.4 ABb	470.2 Ab	4.7 Ba	100.9 Aa
Mixed native species	Rainy	0.3 Ba	3.0 Ba	8.2 Ba	1.4 Ba	0.5 Ba	221.5 Ba	6.6 Aa	33.4 Ba
	Dry	0.2 Ab	2.3 Aa	6.0 Ba	1.1 ABa	0.5 Aa	200.9 Ba	5.6 ABa	36.7 Ba
				Leaf litter mass					
A. peregrina	Rainy	0.8 Bb	3.9 Bb	19.8 Bb	1.8 Bb	1.2 Ba	531.1 Bb	24.7 Bb	21.7 Ba
	Dry	3.2 Ba	28.7 Ba	95.7 Ba	10.0 Ba	4.6 Ba	2585.7 Ba	106.6 Ba	24.1 Ba
Eucalyptus	Rainy	4.0 Aa	7.0 ABb	73.6 Aa	10.4 Aa	5.8 Aa	2959.5 Aa	80.4 Aa	37.2 Ab
	Dry	4.2 Ba	14.1 Ca	82.6 Ba	12.3 Ba	5.0 Ba	3518.0 Ba	79.3 Ba	44.6 Aa
Mixed native species	Rainy	3.9 Ab	12.9 Ab	98.6 Ab	11.7 Ab	6.7 Ab	1871.8 Ab	99.5 Ab	18.8 Ba
	Dry	10.0 Aa	43.6 Aa	296.1 Aa	29.5 Aa	18.2 Aa	6005.4 Aa	293.6 Aa	20.6 Ca
				Twig litter mass					
A. peregrina	Rainy	0.5 Aa	4.2 Ba	24.2 ABa	2.4 Ba	1.2 Aa	647.5 Ba	27.0 Aa	24.7 Ba
	Dry	0.7 Aa	5.9 Ba	35.8 Aa	3.1 Ba	1.6 Ba	957.1 Ba	40.3 Aa	24.2 Ba
Eucalyptus	Rainy	1.0 Aa	8.0 Aa	35.9 Aa	6.0 Aa	2.0 Aa	2163.0 Aa	35.3 Aa	59.5 Aa
	Dry	1.1 Aa	10.3 Aa	40.7 Aa	6.2 Aa	2.1 Aba	2720.0 Aa	38.0 Aa	77.3 Aa
Mixed native species	Rainy	0.6 Ab	4.3 Ba	21.7 Bb	3.1 Bb	1.5 Ab	353.4 Bb	11.6 Ab	29.5 Ba
	Dry	1.2 Aa	7.2 ABa	37.8 Aa	5.3 Aa	2.7 Aa	1362.0 Ba	37.6 Aa	37.0 Ba

Upper case letters in a column compare between the different types of forest cover for each of the seasons, while lowercase letters compare each type of cover between the dry and rainy seasons, and when similar, indicate no significant differences by Tukey's test at 10 %.

2019). The mixed of native species includes some pioneering, fast-growing species (such as *Ceiba speciosa*, *Enterolobium contortisiliquum* and *Piptadenia gonoacantha*), which resemble *Eucalyptus* in their base area, and lose a large part of their leaves during the dry season. So, the fast litterfall production (Valente et al., 2021) with higher growth rates in the *Eucalyptus* treatment could be compensated by the plant density (3,333 trees per hectare) and biodiversity of the mixed native treatment, as commented by some authors already cited. *Eucalyptus* trees increased from 16.63 to 19.76 cm and from 0.0221 to 0.0313 m^2 in diameter at ground level and mean base area, respectively, after 2.5 years of the study period, considering a density of 120 individuals in the study area (Valente et al., 2021).

The smaller litter production of *A. peregrina* treatment can be attributed to its phenology, characterized by leaflets of small sizes. Also, the slow growth of only 2.26 cm in diameter at the ground during the period of litterfall production evaluation could be attributed to the results obtained (Valente et al., 2021).

The higher litterfall production of native species and, especially, *Eucalyptus* can improve the rehabilitation of degraded areas. The rapid surface cover can enhance the soil cover, reduce soil erosion and improve the soil structure by trees' roots and the formation of soil organic matter (Borges et al., 2019; Cavalcante et al., 2019).

The total litter mass is the result of litterfall production and the decomposition rate (Martius et al., 2004; León and Osorio, 2014), and can be influenced by litterfall and soil chemical composition (Parsons et al., 2014), as well by the season of the year (Souza et al., 2019). *Eucalyptus* and mixed native presented higher annual litterfall production and litter mass accumulation in soil. Although there is a predominance of leaves litterfall, the concentration of twigs increased in the litter mass due to its low decomposition rates compared with the leaves.

Seasonality of litterfall production

Environmental variables such as temperature and radiation are limiting factors to litterfall production, which response can vary according to the forest cover in tropical regions (Zhang et al., 2014). *Eucalyptus* presented the highest value of litterfall production during the rainy period (October to March of the years studied), which may be related to water availability that leads to more vegetative growth the internal translocation of nutrients from the older tissue to the younger, and consequently higher discarding of leaves and other older components of the tree. This can be pronounced by the young age of the population when the study was started (31 months). However, the increase of litterfall in the rainy season can be attributed to the increase in twigs litterfall due to the physical impact of rain on the trees (Zhang et al., 2014).

The increase of litterfall production of native species found in this study during the dry season (April to September of the years studied) has also been reported by Miranda Neto et al. (2015) in an area of bauxite mining in the process of recovery with native Atlantic Forest species, and in other studies of litterfall production in tropical forests in Brazil (Smith et al., 1998; Barlow et al., 2007) and worldwide (Tang et al., 2010; Zhang et al., 2014). During the dry period, leaf abscission occurs as a mechanism of plant adaptation to water stress, increasing the mean litterfall production in this period (Jha and Prasad Mohapatra, 2010). Litterfall production by forest species may be related to the perennial or deciduous characteristics of the trees (Souza et al., 2019). The phenology of the species used in the mixed plantation of forest species (mixed native) in this study has a predominance of deciduous and semi-deciduous species of the Atlantic Forest (Table 1) that lose their leaves during the dry period. This explains the higher leave litterfall production during this period (Souza et al., 2019). Soils of mined areas impose physical barriers to the root growth of trees and also stimulate leaf fall, limiting the access to water and nutrients (Sheoran et al., 2010). This effect is more evident on the species most susceptible to loss of (deciduous) leaves, which makes the mixture of deciduous, semi-deciduous and perennial species essential for success in programs for the recovery of degraded areas as proposed in the present study.

The production and decomposition rate of the litter influence the accumulation of litter mass. In this study, *Eucalyptus* was the forest cover that most accumulated litter mass during the rainy period (12,545 kg ha^{-1}), followed by mixed native (7,330 kg ha^{-1}) and *A. peregrina* (2,297 kg ha^{-1}). Souza and Davide (2001) found an accumulation of around 63,320 kg ha^{-1} in plantations of *Eucalyptus saligna* with 12 years of age in an area of bauxite mining values in the same study region. In the dry period, mixed native and *Eucalyptus* showed similar values of accumulated litter in the soil, since they also produced similar amounts of litterfall in the same period of the year and presented similar rates of decomposition. The period of less water availability in the soil leads to leaf abscission, increasing the supply of litterfall to the soil, which is common to perennial species such as *Eucalyptus* and also, the majority of deciduous and semi-deciduous. Besides the higher contribution to the soil, the decomposition rate also influences the accumulation of litter on the ground (Martius et al., 2004; Sales et al., 2020).

Apparent decomposition rate and seasonality

Litter decomposition is the main factor that controls the accumulation of litter mass and nutrient cycling in forest ecosystems (Krishna and Mohan, 2017; Feng et al., 2019; Souza et al., 2019). In our study, we found that seasonality affected the decomposition rate, with higher values in the rainy season, as also observed by Miranda Neto et al. (2015). The favorable conditions of temperature and humidity in the rainy season stimulate soil microbial activity and, consequently, increase the decomposition rate (Pandey et al., 2007; Krishna and Mohan, 2017). The higher decomposition rate of the leaf litter in *A. peregrina* compared to the other types of cover in the rainy season may be related to the small size of leaflets and nutrient content, which facilitate the process of decomposition by soil microorganisms (Krishna and Mohan, 2017; Sousa-Neto et al., 2017). A litter with a higher content of lignin and C/N ratio tends to present a lower decomposition rate (Bachega et al., 2016; Cotrufo and Lavallee, 2022). The *A. peregrina* litter has a high concentration of N and a lower C/N ratio compared to other types of cover, which contributes to an increase in the decomposition rate.

The decomposition rate of *Eucalyptus* in the rainy season (0.37 yr^{-1}) and dry season (0.25 yr^{-1}) was higher than the value of 0.11 yr^{-1} found by Souza and Davide (2001), but smaller than 0.54 yr^{-1} for *E. urophylla* x *E. globulus maideni* (Schumacher et al., 2013), and 0.51, 0.59 and 1.0 yr^{-1} for *E. pelita, E. camaldulensis* and *E. grandis* respectively (Zaia and Gama-Rodrigues, 2004). The low N content in the leaf litter from *Eucalyptus* is one of the factors that limit its decomposition (Krishna and Mohan, 2017).

Although the mixed native species present a higher diversity, we did not found differences in the decomposition rates compared with *Eucalyptus*, highlighting the importance of the litterfall quality over the species diversity in affecting the decomposition rate (Meier and Bowman, 2008; Tang et al., 2010; Cizungu et al., 2014). Under the same condition, mass loss is directly proportional to the C/N lignin/N ratios (Cotrufo and Lavallee, 2022) and C/P ratios. The composition of litterfall is strongly related to their recalcitrance and, consequently, so higher or lower rates of decomposition (Barlow et al., 2007; Duarte et al., 2013; Cizungu et al., 2014; Sales et al., 2020). The process of decomposition can also be influenced by the microbial composition community (Yang et al., 2014), soil fertility (Cotrufo et al., 2010), especially N, and the soil structure, which is intensively modified in mining areas (Miranda Neto et al., 2015). However, rehabilitation strategies that increase the soil nutrients by poultry litter and chemical fertilizers (Table 1) and, consequently, the composition of litter favor the microorganism's activity and the decomposition should be not limited by nutrients. Most of the native species' litterfall was produced in the dry season, while *Eucalyptus* was in the wet season, with much more twigs than leaves. So, the decomposition rates reflect a situation where the native species litterfall already are in an advanced stage of physical decomposition by environment components such as arthropods when the wet season starts, while the *Eucalyptus* litterfall is not (it is higher during the wet season). Accumulating lignin in litter over time, factors controlling the microbial degradation of lignin become a key quality parameter (Cotrufo et al., 2010), and as twigs (the size and thickness are bigger than leaves) have proportionally much more lignin than leaves. Leaves are the most abundant and fastest decomposing part of the litter, and improving our understanding about its production and decomposition rate becomes a key factor in forest restoration programs (León and Osorio, 2014).

Nutrient input

Improving our understanding of the dynamics of nutrients between soil and plant can contribute to improving the restoration processes of degraded forest environments (Quichimbo et al., 2020). The return of C and nutrients to the soil via litterfall input and decomposition play an important role in activating the biogeochemical cycling in forest ecosystems, especially in the recovery of highly degraded or low fertility soils (Pandey et al., 2007; Tang et al., 2010; León and Osorio, 2014; Zhou et al., 2015). However, litter production and decomposition are dependent on the climate (Souza et al., 2019; Sales et al., 2020) and the type of forest cover.

The mix of native species (mixed native) provided the highest content of nutrients (P, K, Ca, Mg and S) to the soil via leaf litterfall. This was expected since mixed native had the highest contents of these nutrients in its leaves and a high mass leaf litterfall. The diversity of species in mixed native may be responsible for the higher total nutrient content of the leaf litter produced and added to the soil compared to the *A. peregrina* and *Eucalyptus* monocultures (Celentano et al., 2011; Cizungu et al., 2014). Planting deciduous and semi-deciduous species in the same also improves nutrient cycling, with the disposal of leaves occurring before the internal nutrient retranslocation and thus discarding nutritionally richer components compared to non-deciduous or perennial phenological groups (Machado et al., 2016). Moreover, mixed forests containing N-fixing species tend to increase and improve nutrient cycling through litterfall when compared to monocultures (Forrester et al., 2006; Forrester and Bauhus, 2016), increasing C and N contents in the soil. This process enhances the formation of soil organic matter, being an efficient alternative to accelerate the recovery processes of degraded areas, especially after mining (Chaer et al., 2011). This reinforces the hypothesis that the introduction of N-fixing species such as *Anadenthera peregrina*, *Enterolobium contortisiliquum*, *Piptadenia gonoacantha* and *Ingá sp*, to mix of natives was a correct procedure for the proposed recovery of the studied degraded area.

The *A. peregrina* monoculture presented higher contents of C and N compared to *Eucalyptus* and mixed native. However, this did not result in higher contents of these elements in the litterfall due to the small size of its leaflets and the lower mass of leaf litterfall. Moreover, the *A. peregrina* monoculture presented the lowest C/N ratio among the coverages studied in the present work, which is an intrinsic characteristic of species belonging to the legume family (Chaer et al., 2011). Rapidly growing species such as *Eucalyptus* tend to have low contents of nutrients in senescent components, such as litterfall, due to their efficient internal relocation of nutrients, mainly in low fertility soils (Laclau, 2003). Our results show that *Eucalyptus* with the smallest content of N of all the cover types, and the highest C/N ratio in its leaves and twigs. Although the total nutrient content input to the soil is lower in *Eucalyptus*, the higher litterfall production can constitute an important source of nutrients and protection for the soil surface.

The contents of nutrients in the leaflet tend to be higher than in other components of the litterfall (Chave et al., 2010). In our study, we found that the leaves presented high nutrient concentrations and total content to the soil for all forest covers. The litter accumulated on the soil surface is a store of nutrients, which is gradually released through decomposition and mineralization (Gautam and Mandal, 2018). The nutrient content of the litter mass leaf was higher in mixed native for most of the studied nutrients (P, Ca, Mg, S and N). Phosphorus and S had the smallest concentrations in the leaves, reflecting the low concentrations of these elements in tropical soils and their efficient internal translocation to young tissues with a consequent decrease in senescent tissues discarded from plants.

Seasonal variations influenced the nutrient content of leaf litterfall and litter mass differently for forest covers, with mixed native being the cover with the highest influence.

This cover had the highest content of all the nutrients during the dry season when there was a higher contribution of litterfall. For *Eucalyptus* and *A. peregrina*, only P and S were influenced by seasons, with the highest content observed in the rainy season. The nutrients accumulated in the leaves of the litter mass were also more concentrated in the dry season. During this period, the litter accumulates more in the soil and the decomposition rate tends to be lower, resulting in a decrease in leaching and a higher accumulation of nutrients. Therefore, our results indicate the contribution of litterfall to the reactivation of nutrient cycling and organic matter formation in degraded areas under recovery with forest species. Moreover, the increase of litterfall can also be an important factor in maintaining essential ecological processes, such as soil formation and soil erosion control in post-mining areas (González-Rodríguez et al., 2011).

CONCLUSIONS

The mixed planting of forest species and the monoculture of *Eucalyptus* produce the higher annual litterfall yields compared to the monoculture of *A. peregrina* in a mined area of bauxite undergoing recovery.

Seasonality affects the litter production and decomposition rates of forest species. While the mix of native plants (mixed native) produces higher amounts of litter during the dry season, the higher litterfall production in the *Eucalyptus* occurs in the rainy season. Moreover, higher decomposition rates for mixed native and *A. peregrina* occurs during the rainy season.

Planting forest cover is important for depositing nutrients to the soil by litterfall, and the mixed plantation of native species (mixed native) produces leaf litterfall of better nutritional quality in relation to P, K, Ca, Mg and S.

Eucalyptus, *A. peregrina,* and the mixed native species presented good litterfall production, litter mass and nutrient return to the soil under the conditions of the study, and are efficient in the recovery process of areas degraded by bauxite mining, since they presented values similar to those of unmined areas, whether planted or of natural regeneration.

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