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Decomposition and nutrient release of eucalyptus harvest residues in southeast Brazil

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SILVICULTURE

ABSTRACT

Background: Eucalypt harvest residues are critical to nutrient balances and forest soil productivity mainly in areas with consecutive forest rotations. However, nutrient release and their relations over decomposition are still poorly understood in tropical sites. We aimed to understand how nutrients are released from leaves, branches, and bark (as harvest residues), and how nutrient concentrations could be limiting the decomposition of each fraction. We measured mass loss and nutrient release of *Eucalyptus urophylla* x *Eucalyptus grandis* harvest residues for 365 days in Southeast Brazil.

Results: Leaves fraction showed a faster decomposition rate than branches and bark, but nutrient accumulation was observed for all harvest residues, especially bark and branches at later stages of the decomposition. Decomposition of all harvest residues seemed to be P-limited with a stronger limitation occurring for leaf litter decomposers. The decomposition of more lignified residues such as bark and branches was less influenced by climatic variables than leaf decomposition.

Conclusion: Eucalypt harvest residues had a great contribution to soil fertility, and retaining them in the soil systems will enhance soil fertility in the short (leaves) and long-term (branches and bark) and can partially supply the nutrients for the next rotation.

Keywords: Ecological stoichiometry, Harvest residues, Nutrient cycling, Tree plantations, Tropical forests.

HIGHLIGHTS

Slower decomposition was observed for eucalypt barks than branches and leaves.
Eucalypt harvest residues decomposition was mainly P-limited.
Air temperature played a major role in leaves decomposition only.
Eucalypt harvest residues can partially supply soil fertility for the next rotation.

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INTRODUCTION

The area covered by eucalypt plantations in Brazil increased 43% between 2011 and 2020 (from 4.87 to 6.97 million hectares), currently representing 81% of the total area planted with forest species (Ibá, 2020). Brazilian forest sector has high productivity and short cultivation cycles between planting and harvesting, and this performance is attributed mainly to favorable climate conditions (Gonçalves et al., 2013; Ibá, 2020). However, higher growth rates and short rotations of eucalypt stands can remove large amounts of nutrients from the soil system (Guo and Sims, 1999), and depending on the harvest system and the maturity of the stand, the amount of exported nutrients through harvest processes can be three times greater in more intensive systems (Santos et al., 2020).

Several studies have reported that successive removal of harvest residues causes a significant reduction in productivity and soil fertility (Mendham et al., 2014; Achat et al., 2015; Souza et al., 2020), even after high rates of fertilizer supplementation (Rocha et al., 2018). According to Laclau et al. (2003), the sustainability of the site depends on the maintenance of available nutrients in the soil over successive rotations, especially in tropical regions where soils have natural low fertility due to rapid weathering (Sayer, 2006). Therefore, information on the processes driving biogeochemical cycles of nutrients in fast-growing forest plantations is essential to combine fertilization regimes along with trees' demands and availability of nutrients (da Silva et al., 2011).

Maintaining harvest residues in forest stands can influence soil physical properties, nutrient stock, carbon cycle, plant growth, microbial communities, and soil fauna (Achat et al., 2015; Souza et al., 2020), and nutrients released from harvest residues are crucial for tree growth in tropical nutrient-poor sites (Laclau et al., 2010; Versini et al., 2014b). These nutrients are even more important in commercial forest crops as eucalypt due to their rapid growth and greater nutritional demand (Versini et al., 2014a), acting as an important sink of nutrients (Hernández et al., 2009).

Litter decomposition can be controlled by litter quality and climate conditions and both influence soil decomposer organisms (Bradford et al., 2016). However, in some cases, decay rates seem to be more influenced by chemical composition than climatic variables (Ferreira et al., 2016; Siqueira et al., 2021). Even so, higher temperatures and precipitation can favor biological activity and consequently decomposition (Zhang et al., 2008).

Nutrient concentration and its stoichiometry should not be neglected when investigating influencing factors over decomposition processes such as lignin:N ratios that are associated with slower decomposition rates (Mungai and Motavalli, 2006; Sánchez et al., 2018), especially in the later stages of decomposition (Berg and McClaugherty, 2003). Among harvest residues, branches and bark fractions present a lower rate of decomposition when compared to the leaf fraction and this result is mainly attributed to the high C:N and lignin:N ratios (Zhang et al., 2008; Sánchez et al., 2018). Nutrient stoichiometric relations during litter decomposition are indicative of each nutrient is limiting soil decomposer community (Lanuza et al., 2018; Siqueira et al., 2021), but the literature lacks information on eucalypt harvest residues decomposition and its nutrient relations over decomposition.

Understanding the factors that affect the decomposition of eucalypt harvest residues and their effects on soil fertility are relevant to the management of forest plantations. Thus, this study aimed to evaluate the influence of the chemical composition of eucalypt harvest residues and climatic variables on the decomposition rates and nutrient release from eucalypt harvest residues (leaves, branches, and bark fractions).

MATERIAL AND METHODS

Study site description

The study site is located within the Aracruz municipality, Espirito Santo State (19º 48' S, 40º 17' W). The altitude is 34 m a.s.l. and the land has flat topography. The soil is well-drained and with a clayey texture. The climate in the region is mild, with the annual average temperature around 23 °C and precipitation around 1200 mm (Alvares et al., 2013). However, we monitored the climate data during the experiment and the weather station was located ± 2 km from our plots (Figure 1).

The area was previously an unmanaged forest, and the first *Eucalyptus* plantations were started in the `80s. The area belongs to Suzano S.A (pulp and paper manufacturer) which has been cultivating the site with *Eucalyptus* since then. We selected a 9-year-old (to collect harvest residues) and a 1.5-year-old (to incubate the litterbags) *Eucalyptus urophylla* x *Eucalyptus grandis* plantations.

For both areas (9- and 1.5-year-old), soil preparation was done tilling the soil up to 80 cm and fertilizers were added along (162 kg ha-1 of N-P-K (06:30:06) supplemented with 0.7% Cu and 1% Zn). The plants were also fertilized at 180 days after planting using 229 kg ha-1 of N-P-K (12:00:20) with 0.7% of B. The plants were spaced at 3x3 m. Chemical control for ants and weed growth was done before and after *Eucalyptus urophylla* x *Eucalyptus grandis* outplanting.

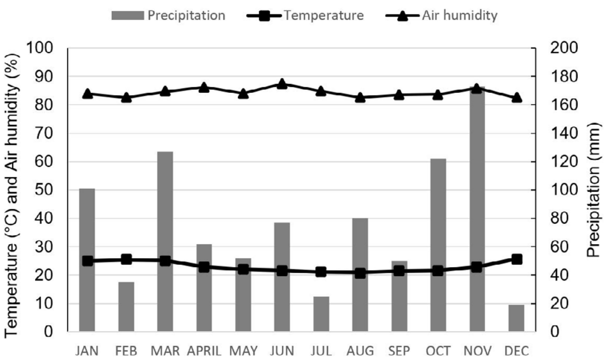

Figure 1. Monthly precipitation (mm), air temperature (°C) and relative humidity (%) in Aracruz, Espírito Santo state, Southeast Brazil. Vertical bars represent monthly precipitation, black squares represent relative humidity, and black triangles represent air temperature.

Harvest residues decomposition

We selected three trees from the 9-year-old plantation that had height and diameter at breast height close to the average of all plants within a 540 m2 plot. Then, we cut down these trees, detached branches, leaves, and bark on a black plastic and hand-sorted them into each respective fraction. Each fraction was oven-dried at 65º C for 72 hours. The harvest residues of each fraction from the oldest plantation were incubated in the youngest (1.5-year-old) for 365 days and the decomposition was evaluated based on the litterbags methodology as proposed by Bocock and Gilbert (1957). Litterbags (2 mm mesh size) sized 20 x 20 cm containing 30 g of each fraction of the harvest residues were randomly incubated in the soil. We limited branch size up to 15 cm in length and to 2 cm in diameter.

We randomly placed the litterbags within six plots (30 x 30 m each), and we had 6 litterbags per fraction of harvest residue in each sampling time (0, 30, 90, 180, and 365 days). After collection, the litterbags were cleaned by eliminating insects, soil particles, and other undefined materials. Then, the samples were oven-dried for 72 h at 65°C, weighed (0.01 g), and ground (to pass through 1 mm mesh) to determine chemical concentrations over time.

For chemical analysis, samples from the six plots were grouped into three composite samples (samples from every two plots were combined according to each harvest residue fraction, N=3). The N, P, K, Ca, Mg, Mn, Zn and Fe concentrations were determined according to the method described by Malavolta and Oliveira (1997). Lignin, cellulose, and hemicellulose were measured only at times 0 and 365 days and determined using the acid detergent fiber method (Van Soest and Wine, 1967).

The mass loss data and remaining lignin, cellulose, and hemicellulose (expressed as a percentage) were calculated as proposed by Olson (1963) as follows:

$$MSR\%=(MS \times 100)/MSI$$

Where MSR is percentage of remaining mass, MS is remaining dry mass of the litterbags at each sampling time (g), MSI is initial dry mass of the litterbags (g).

We calculated the decomposition rate constant (k) based on the model proposed by Olson (1963):

$$Wt/Wo = exp^{(-kt)}$$

Where Wo is initial mass of the litter, Wt is mass remaining after a period of time (t; in days), and k is a decomposition constant.

Half-life was calculated as t1/2 = ln (2)/k, where t1/2 is half-life (days) for dry matter, time required for half of these residues to disappear. We also estimated time required for 95% of the harvest residues to disappear as follows:

$$T_{0,95}= (3)/k.$$

Calculations and data analysis

Mass loss data of each harvest residue was submitted to local polynomial regression fitting models using "loess" function in ggplot2 package (Wickham, 2016). Predicted fitting models were determined by one or more numerical predictors using local fitting. The confidence intervals ($P <$ 0.05) of the predicted adjusted models were calculated.

Nutrient release for all harvest residues was calculated as the percentage loss for each nutrient at each sampling time based on the original content (nutrient concentration multiplied by dry mass at each sampling time and multiplied by 100). When investigating the ecological stoichiometry relationships as a function of mass loss over the decomposition period, we tested for either linear or non-linear adjusted models and we test the significance of each model through analysis of variance (ANOVA). To verify whether the data met ANOVA assumptions, they were submitted to diagnostic plots (normality, linearity, and homoscedasticity of residuals) and maximum likelihood function (Box-Cox test) using the MASS package (Venables and Ripley, 2002).

Spearman's correlation ($P < 0.05$) between harvest residue decomposition rates and nutrient concentrations was analyzed and the heatmap was plotted using corrplot package (Wei and Simko, 2021). Principal component analysis (PCA) was conducted to evaluate variability among the nutrient concentrations and litter decay of each harvest residue fractions. For this, data was standardized through z-scale transformation to avoid scale influence and plotted using the ggbiplot package (Vu, 2011). The data analyses were performed in R environment (R Core Team, 2019).

RESULTS

Litterbags with leaves had higher annual decomposition rate (k) while bark had lower values for both half-life time (50% of the residue had disappeared) and 95% of residence time. Half-life time of the harvest residues was 0,8, 1.5, and 1.7 years for leaves, branches, and bark, respectively (Table 1).

Table 1. Decomposition rates of *Eucalyptus urophylla* x *Eucalyptus grandis* harvest residues (leaves, branches, and bark) in Southeast Brazil.

Harvest residues	k	$t_{0,5}$	$t_{0,95}$
	(day^{-1})	(days)	
Leaves	0.0024	289	1250
Branches	0.0013	533	2308
Bark	0.0011	630	2727

k = decomposition constant; $t_{0,5}$ = time required for half of the residues to disappear; $t_{0,95}$ = time required for 95% of the residues to disappear.

Similar decay rates were observed between branches and bark fractions, supported by the overlapped confidence intervals of the adjusted models (Figure 2), with a steady mass loss since the beginning of the incubation period. However, leaf litter decay showed a faster decomposition mostly in the first 90 days followed by a slower decomposition until the end of the experiment. We observed that 44%, 63%, and 67% of the leaves, branches, and bark, respectively, remained after 365 of incubation in the soil.

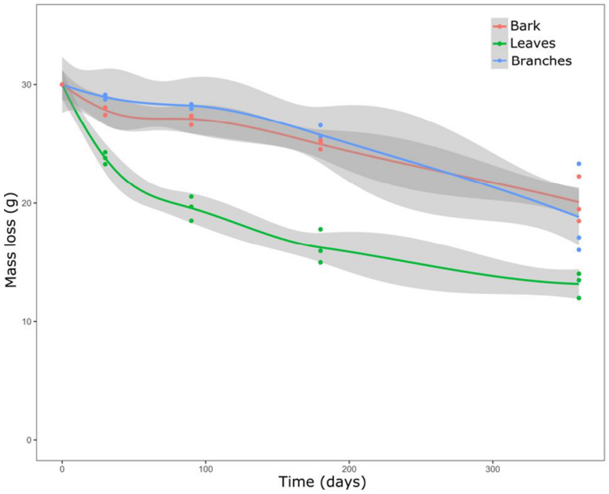

Figure 2. Remaining mass of leaves, branches, and bark from *Eucalyptus urophylla* x *Eucalyptus grandis* plantation over 365 days in Southeast Brazil. Predicted confidence intervals applying local polynomial regression fitting models are represented by the smooth grey curves ($P < 0.05$).

We observed nutrient accumulation in leaves residues in the first 100 days after incubation of the litterbags whereas a stronger immobilization of nutrients occurred in bark and branches harvest residues at the later stages of incubation period (Figure 3). Lignin concentration decreased over time for all harvest residues, but a more robust decrease was observed for leaves and bark. Likewise, hemicellulose decreased for branches, but increases were observed for leaves and bark harvest residues. Cellulose concentration increased over decomposition time across all harvest residues (Figure 3). Initial lignin:N concentration varied from 4.58 to 6.13 for branches and bark litters, respectively, whereas leaf litter showed 0.60.

Nutrient relations in litter showed a nonlinear adjustment for N and P and a negative linear trend for K and Mg for the leaves fraction, which means these nutrients were released over the decomposition period. We observed increases in N concentration for branches and bark fractions when plotted against mass loss of each fraction with a linear trend, where initial N in the leaves fraction was almost fivefold when compared to branches and bark fractions. Yet, higher initial P and K were observed in the leaves fraction. Ca, Mg, and Mn did not display a clear pattern among harvest residues, but Mg concentration decreased for the leaves fraction (Figure 4).

Leaf litter decomposition was positively correlated with air temperature, whereas bark and branches residues were only marginally positively correlated to minimum air temperature. On the other hand, all residues were negatively associated with air humidity, but not statistically significant. Regardless of the harvest residue, the total precipitation was not correlated with decomposition rates (Figure 5).

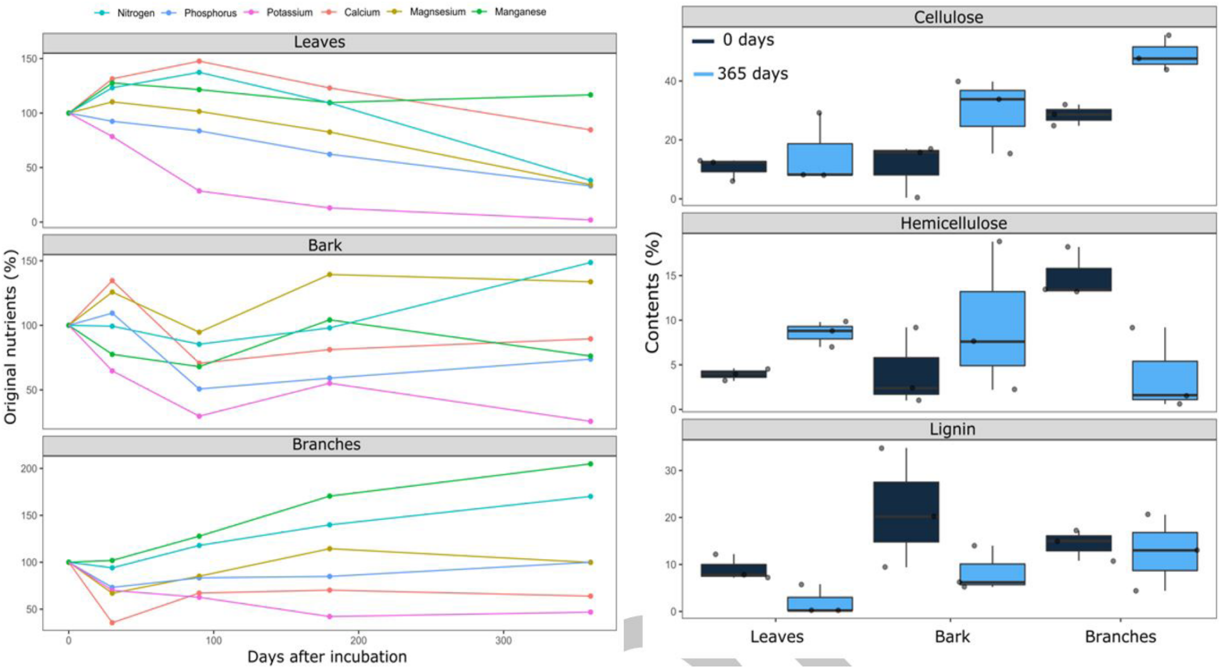

Figure 3. Percentage of original nutrient content (%) and initial and final lignin, cellulose, and hemicellulose contents as a function of time during the decomposition of leaves, branches, and bark (harvest residues) of *Eucalyptus urophylla* x *Eucalyptus grandis* over 365 days in Southeast Brazil.

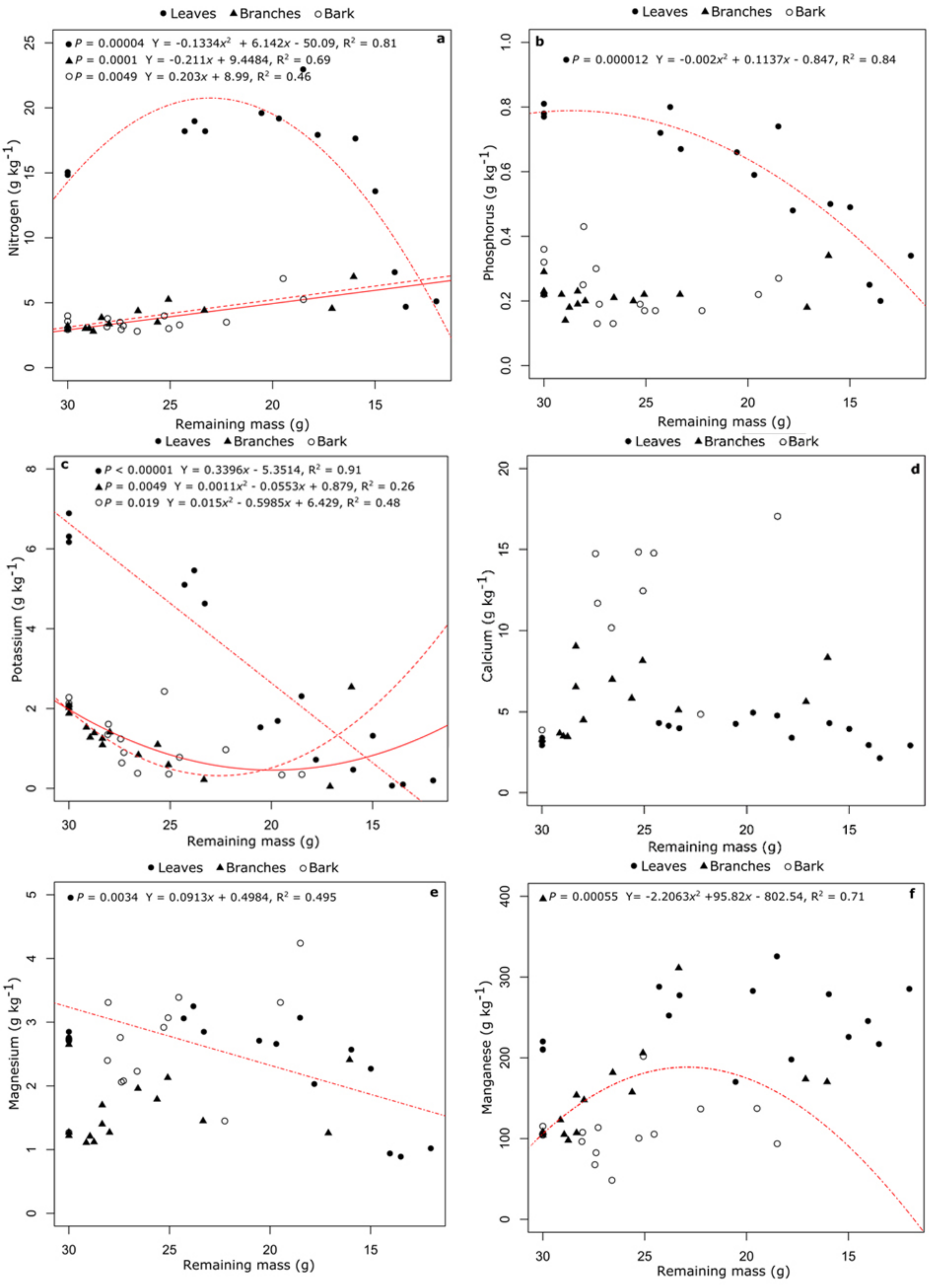

Figure 4. Changes in the concentration of N, P, K, Ca, Mg, and Mn as a function of the mass loss during the decomposition of *Eucalyptus urophylla* x *Eucalyptus grandis* harvest residues in Southeast Brazil. Solid lines – bark adjusted models; dot-dashed lines – leaves adjusted models; dotted lines – branches adjusted models.

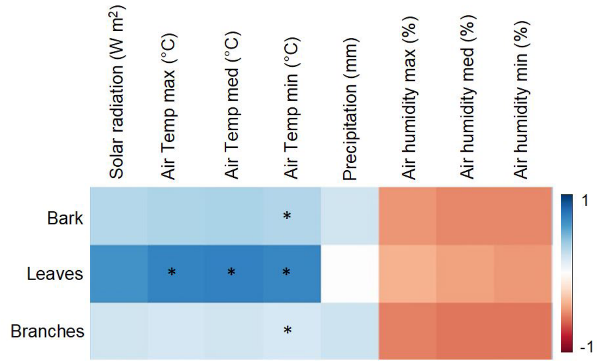

Figure 5. Spearman correlation ($P < 0.05$) heatmap between harvest residue fractions and climatic variables over decomposition time. Color represents the value of Spearman correlation coefficient. Blue indicates positive correlation, and orange indicates negative correlation.

The first two axes of the PCA – PC1 and PC2 (accounting for 69.3% of the data variability) showed a direct association between litter decay rates and Ca concentrations with PC1, and both had a positive correlation to PC1. Nitrogen, P, K, and Mg showed a positive correlation to PC2 (Figure 6). With respect to the relation of harvest residues decay rates with nutrient concentrations, the residues were organized in different groups in the PCA, where bark and branches were grouped and more associated with Ca and decay rates.

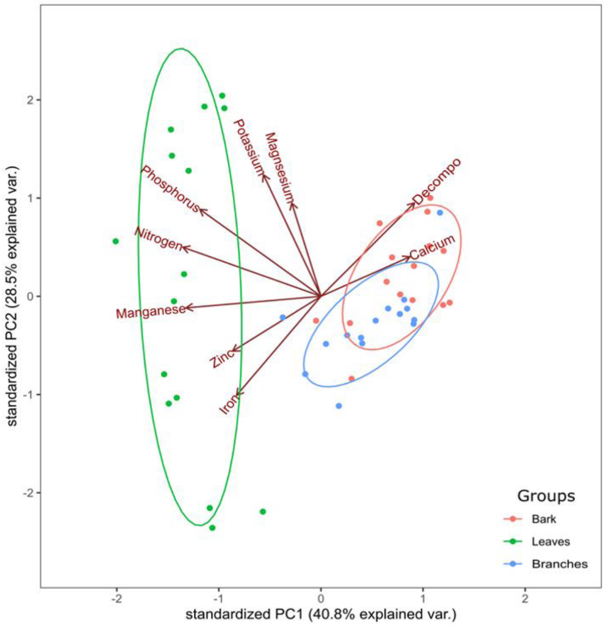

Figure 6. Principal component analysis of the litter decay, C, N, P, K, Ca, Mg, Mn, Zn, and Fe concentrations for *Eucalyptus urophylla* x *Eucalyptus grandis* harvest residues in Southeast Brazil. The area of the ellipses was calculated as one standard deviation distance from center of each ellipse and comprised 68% of data variation.

DISCUSSION

Leaf litter displayed a faster decomposition when compared to branches and bark residues and this was reported also by Laclau et al., (2010) and Pinto et al., (2016). Overall, we observed a greater initial concentration of nutrients in the leaves and lower lignin concentration which explains the faster decomposition. Moreover, leaves have a higher specific surface area and are tenderers which facilitates decomposers to degrade this residue in comparison to branches and bark (Paré and Thiffault, 2016; Siqueira et al., 2021).

Lignin plays an important role in the decomposition process due to its recalcitrance, but few organisms can degrade such as some groups of fungi (Sigoillot et al., 2012). For leaf litter decomposition, easily degradable compounds are released first, and a faster decomposition is expected in the first days (Duarte et al., 2013). However, when recalcitrant compounds regulate the process more, the decay rates are slower or almost stopped (Marchante et al., 2019), and we observed this tendency from 90 days onward for leaves fraction where more recalcitrant compounds are likely regulating the decomposition process. For branches and bark residues, a slightly faster decomposition up to 90 days and at the end of the incubation period which corroborates Duarte et al. (2013) and Fioretto et al. (2005) findings regarding lignin compounds decomposition.

Furthermore, leaf N concentration increased in the first 90 days after incubation, at the same time when leaf litter decomposition was faster. It suggests that N was not limiting the decomposer community, but N accumulation in leaf litter may be due to decomposers that absorb N and remain stuck in the leaves (Guo and Sims, 2001; Siqueira et al., 2021). Yet, in some cases N can remain associated with lignin or lignin-like substances where lignin can protect cell wall proteins from microbial attack (Fioretto et al., 2005).

Regarding lignin degradation, Mn is an important player as it is part of the enzyme manganese peroxidase which oxides Mn^{2+} ions present in litter and soils (Berg et al., 2015; Chowdhary et al., 2019), but still poorly studied in forest ecosystems. We observed that only branches showed a significant non-linear trend for Mn concentrations over decomposition, showing Mn accumulation followed by decreases at the end of the incubation period. Yet, Mn is reported to facilitate N release (Vivanco and Austin, 2019), but it seems that Mn did not exert an important role in any of the harvest residues decomposition as its concentration varied broadly over the incubation period.

The fast K decrease, also reported by others (Osono et al., 2008; Lanuza et al., 2018), can be explained by its high solubility. Regarding Ca release, it occurs mainly in the late decomposition phases because it is a major component of cell structures, which are degraded last (Osono and Takeda, 2004). Ca concentration was almost constant for leaves and branches which suggests that its concentration decreased following mass loss.

However, Ca and decay rates are associated with bark and branches residues (Figure 6) both with higher initial Ca concentration than leaves, which suggested that they are grouped together (slower decomposition) while leaves fraction are nutrient richer (faster decomposition).

The critical role exerted by N and P in litter decomposition can commonly lead to co-limitation of these elements during the process (Fanin et al., 2013; Siqueira et al., 2021), and tropical sites are commonly associated with P-limitation (Cassart et al., 2020). Nutrient stoichiometry such as N:P ratio can reveal which nutrient could be limiting litter decomposition: N-limited when litter has a low N:P ratio (< 14), and P-limited when high N:P ratio (> 16) (Tessier and Raynal, 2003). Leaf litter had a higher N:P ratio (~26) than both branches and bark (~17.5), but all harvest residues seem to be P limited with a stronger P limitation occurring for leaf litter soil decomposers. Apart from that, the high lignin:N ratio values observed for branches and bark contributed to slower decay rates for those harvest residues. P limitation was also reported by Siqueira et al. (2021) for tropical N-fixing species. Nutrient limitation may vary depending on soil microbial community which warrants further studies.

Apart from the chemical composition of each harvest residue, climatic variations may also determine changes in litter decomposition and nutrient release rates (Bradford et al., 2016). Leaf litter decomposition was positively correlated with air temperature, but their effects on branches and bark decomposition were less important. It suggests that more recalcitrant substrates such as bark and branches are less influenced by climatic variables than leaf litter decomposition (Davidson and Janssens, 2006). Surprisingly, precipitation did not correlate to any harvest residue. Greater monthly precipitations were observed at the end of the incubation period when the decomposition process slowed down. The well distributed rainfall events could explain the lack of correlation with the decomposition rates over time.

Leaf as a harvest residue represents 40% of the total volume, but higher nutrient contents of N (63-75%) and P (55-65%) are found in leaf litter (Mendham et al., 2003). It shows the crucial role for nutrient release and soil fertility (nutritional management of forest plantations) played by leaf litter, especially when rapid decay rates are observed.

CONCLUSION

Eucalyptus harvest residues displayed a great contribution to soil fertility, and retaining them in the soil systems will enhance soil fertility in the short (leaves fraction) and long term (branches and bark fractions) and can partially supply the nutrients for the next rotation. However, all harvest residues' decomposition seemed to be P-limited with a stronger P limitation occurring for leaf litter decomposers.

AUTHORSHIP CONTRIBUTION

Project Idea: RRM, MVWC
Database: RRM
Processing: DPS, DGB, DRM
Analysis: DPS, DGB, DRM
Writing: DPS, DGB, DRM
Review: MVWC, DPS, DRM, DGB, RG, FSO

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