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Biomass and carbon stocks in *Eucalyptus* spp. litterfall in an integrated production system

Reservas de biomasa y carbono en hojarasca de Eucalyptus *spp. en un sistema de producción integrado*

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ABSTRACT

Litter has fundamental carbon values accumulated in its biomass, with an essential participation in the whole forest system for both carbon sequestration and for the benefits to the biogeochemical cycle in supplying the soil's nutritional demand. This study aimed to evaluate the litter characteristics of eucalyptus clones regarding the contribution of biomass, carbon, and nutrients in each of its forming fractions in an integrated production system at 10 years of age. The accumulated litterfall production of two hybrids, *Eucalyptus urophylla* x *E. grandis* (AAC 645) and *E. urophylla* x *E. camaldulensis* (AAC 33), was evaluated. The collection was carried out in 1 m^2 plots for each clone, and the accumulated litter biomass, carbon content, nutrient content, and stock of each litter component were evaluated. Clone AAC 645 had the highest litter biomass and carbon stock. The branch fraction in both clones showed higher biomass accumulated carbon averages, and nutritional support. Clone AAC 645 had higher total nutrient content, except for Ca, Mg, and S.

Keywords: Forest nutrition; Nutrient cycling; ICLF.

RESUMEN

La hojarasca tiene valores fundamentales de carbono acumulado en su biomasa, con una participación esencial en todo el sistema forestal, tanto, para la captura de carbono como para los beneficios al ciclo biogeoquímico en el suministro de la demanda nutricional del suelo. El objetivo de este estudio fue evaluar las características de la hojarasca de clones de eucalipto en relación con el aporte de biomasa, carbono y nutrientes en cada una de sus fracciones formadoras en un sistema de producción integrado a los 10 años de edad. Se evaluó la producción acumulada de hojarasca de dos híbridos, Eucalyptus urophylla x E. grandis *(AAC 645) y* E. urophylla *x* E. camaldulensis *(AAC 33). La colecta se realizó en áreas de 1* m^2 *para cada clon y se evaluó la biomasa de hojarasca acumulada, el contenido de carbono, el contenido de nutrientes y el stock de cada componente de la hojarasca. El clon AAC 645 tuvo la biomasa de hojarasca y el stock de carbono más altos. La fracción de ramas en ambos clones mostró mayores promedios de biomasa y carbono acumulado, así como soporte nutricional. El clon AAC 645 presentó mayor contenido de nutrientes totales, excepto Ca, Mg y S.*

Palabras claves*: Nutrición forestal; Ciclo de nutrientes; SICGB.*

Introduction

The difficulty in finding information about the behavior of unconventional genetic materials in the Cerrado biome with an emphasis on biomass and litter production is still significant. The vast majority of works characterize clones of species and hybrids of *E. urophylla*, *E. grandis,* and *E. urophylla* x *E. grandis* (Valadão *et al*., 2020). Additionally, there is also a lack of information related to the behavior of these clones when deployed in integrated systems.

Integrated systems have been gaining more and more space in agriculture due to the possibilities of adoption, benefits, and complexity identified through years of study, and estimates claim that Brazil will expand around 33 million hectares in integrated agricultural systems, livestock, and forestry areas by 2050 (Sá *et al*., 2017). The characteristic integrating agricultural, forestry,

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and animal species in the same space makes local development sustainable, promoting highly diversified production, environmental conservation, and ecological and economic interactions (Martinelli *et al.*, 2019). In addition to attenuating the effects of degradation caused by inadequate management, increasing microporosity in deeper layers through the fine roots of eucalyptus, the forest component inserted in this type of system also acts in carbon sequestration and increased productivity due to better use of environmental resources (Kim *et al.*, 2016; Borges *et al.*, 2019).

In addition, litter formed by leaves, branches, bark, and reproductive material that comes from these trees makes up a rich layer of organic matter and nutrients, which promote an increase in nutrition in these areas, especially in soils with low natural fertility (Schumacher *et al.*, 2013). Litter promotes enrichment in soil chemistry and also influences its physical and biological parts.

Factors such as soil, climate, species, quality of genetic material, and food preferences of organisms in the soil can influence the fall and decomposition rate of the litter layer (Moretti *et al.*, 2020). This variation will predict the greater or lesser release of nutrients for plant availability and use. The litterfall and decomposition in agroforestry systems play an important role in maintaining soil fertility due to the constant release of nutrients in the soil and the consequent regulation of the nutrient cycle, being able to provide nutrients in sufficient quantities to maintain the fertility of the system itself. This especially occurs in systems where there is total biomass removal in the harvesting process, in which litter is even more important in maintaining soil sustainability (Abreu *et al.*, 2020).

Planted forests are also one of the most effective strategies for mitigating climate change, as they have great potential to store carbon in biomass. Regarding the agroforestry system, it has the capacity to sequester 7.2 t C ha^{-1} year^{-1}, with approximately 70% of this value attributed to biomass (Kim *et al.*, 2016).

The litter layer is the main nutrient transfer route and precursor of organic carbon in the soil; thus, its characterization is essential for understanding the soil's C dynamics in and the nutrients' biogeochemical cycle. For example, *Eucalyptus urograndis* litter presents values ranging from 3 to 7.5 t C ha^{-1} accumulated over 20 to 240 months of age (Wink *et al.*, 2013). It constitutes a study that has become increasingly necessary given the critical and recent decisions in the context of reducing the emission of greenhouse gases (GHG). Litter is; therefore, essential to maintaining a forest system, whether integrated or not. Thus, this study aimed to evaluate the litter characteristics of Eucalyptus clones in an integrated production system regarding the contribution of biomass, carbon and nutrients.

Material and methods

Study area

The material was collected from a commercial plantation on private property in the municipality of Cachoeira Dourada, south of Goiás, Brazil, 240 kilometers from the state capital, Goiânia.

The municipality is located at the geographic coordinates of 18°29'30" S and 49°28'30" W, with an average altitude of 459 m. The climate is classified as humid tropical according to Köppen, with two well-defined seasons, dry in winter and wet in summer. The average annual temperature is 25.05 ºC, and the average annual rainfall for the period evaluated ranged from 1,252 to 2,049 mm with an average of 1,604 mm (Agritempo, 2019). The predominate soil in the region is classified as dark red latosol with a clayey texture, very weathered, and having low natural fertility (Embrapa, 2013).

An area of 18 hectares with the Crop-Livestock-Forest integration system (ICLF) was established in 2010 using two hybrids of commercial clones, the *Eucalyptus urophylla* ST Blake x *E. grandis* W. Hill ex Maiden (AAC 645) and *E. urophylla* ST Blake x *E. camaldulensis* Dehnh. (AAC 33). The forest planting was initially associated with soybean cultivation in the first year, and the Santa Fé system was implemented the following year with corn planting associated with the forage crop *Urochloa brizantha* cv. Marandu (synonym - *Brachiaria brizantha*). Animals were inserted into the system after the trees developed.

Trees were planted in four rows (3 x 2 m) spaced 22 m apart, totaling 645 trees per hectare, representing 35.5% of the area occupied by forest. Soil preparation was carried out based on chemical analysis, with the application of 300 kg ha^{-1} of mono-ammonium-phosphate (MAP) (formulation 11-52-00 (N- P_2O_5– K_2O)). After seedling establishment, the top dressing was carried out in May 2011, with 120 g of 20-00-20 (N - P205 - K20) per plant. Phytosanitary management, such as control of ants and weeds, was performed in the entire experimental area during the entire period when necessary.

Sample collection and preparation

The accumulated litter sampling was carried out at 10 years of age. Litter biomass was determined by randomly demarcating four 1 m^2 plots for each clone and collecting all litter accumulated until total soil exposure.

Samples were stored in paper bags and adequately identified. The samples were dried in the laboratory until weight stabilized in a circulation and air renewal oven at 65 ºC, separated into leaves, branches, bark, and miscellaneous (reproductive material, grass residues, and highly decomposed material that is difficult to identify). After separation, the fractions were individually weighed on a digital scale (precision 0.001g).

The calculation to estimate the accumulated litter biomass (AL, kg ha^{-1}) is performed based on the collected dry mass (DM, kg) as a function of the collection area (CA, m²), extrapolating the result to one hectare (Equation 1).

$$AL = ((DM \times 10.000) / CA) \quad (1)$$

The conversion of biomass into carbon stock (CS, kg ha^{-1}) followed the method presented by the IPCC (2006), based on accumulated litter (AL, kg ha^{-1}) and the value corresponding to the total C content contained in the litter of 43% (Equation 2).

$$CS = (AL \times 0{,}43) \quad (2)$$

The samples were crushed and ground in a 60 mesh Wiley blade mill and mixed, forming a composite sample of each compartment per clone. The material was sent to analyze the nutrients in the laboratory chemically, and the levels of macro (N, P, K, Ca, Mg, and S) and micronutrients (B, Cu, Mn, and Zn) in the plant tissue were determined. Nitrogen was determined by sulphuric digestion; phosphorus, potassium, calcium, magnesium, sulfur, manganese and zinc by nitroperchloric digestion, with sulfur and phosphorus being read by flame emission spectrophotometry and calcium and magnesium by reading by atomic absorption spectrophotometry (Embrapa, 2009).

The nutrient stock in the accumulated litter was calculated through the product between the stock of each litter component fractions and the concentration of each of the nutrients in them.

Statistical analysis

Analysis of variance for dry biomass, carbon stock, nutrient content, and stock was performed by comparing clones, compartments, and their interaction. The variance model (GLM) with 95% significance was used for each data set, followed by Tukey's multiple comparisons with the same significance level. A multivariate principal component (PCA) analysis was also performed using a correlation matrix for nutrient content. The variance percentage of axes 1 and 2 was observed to verify the effect of this analysis. A correlation analysis was performed between the nutritional attributes to verify the correlation coefficient and statistical significance of at least 95%.

Results

It is observed that the component with the most significant biomass accumulation in the litter is the branches, composing an average of 57% of the total among the clones (Table 1). The AAC 645 clone had the most litter, leaves, bark, and branch buildup and, consequently, the highest carbon accumulation. The clones produced an average of 14,839.8 and 6,381.11 kg ha^{-1} of dry biomass and carbon stock, respectively.

The macronutrient concentration gradient of the compartments followed a similar pattern for both clones for the four nutrients with the highest concentration, being N > Ca > Mg > K, except for the AAC 645 leaves with N > Ca > K > Mg and the Miscellaneous of AAC 33 with N > Ca > Mg > S being observed (Table 2). P and S nutrients alternated at the lowest concentrations in all compartments. The concentration gradient for micronutrients followed the order of Mn> B> Cu> Zn, except Leaf and Miscellaneous of the AAC 645 clone, in which Cu was the nutrient with the lowest content.

Anova did not show significance for the isolated treatments and interaction. However, comparing branches for the Ca and Mg nutrients ($p = 0.014$ and $p = 0.036$, respectively) and the miscellaneous for S ($p = 0.0196$) between the clones was significant, being that the AAC 33 clone was superior in the content of these nutrients. The N, K, Ca, Mg, and S macronutrients compartments differed statistically, but the same did not occur for P and micronutrients.

Table 1. Biomass and total carbon stock and by compartment (leaf, bark, branches and miscellaneous) of litter with an interaction effect of *E. urophylla* x *E. grandis* (AAC 645) and *E. urophylla* x *E. camaldulensis* (AAC 33) clones in an integrated production system.

Compartments (Co)	Clones (C)	Dry biomass (kg ha^{-1})	Carbon stock (kg ha^{-1})
Leaf	AAC 645	2,454.64aB	1,055.50aB
	AAC 33	2,355.48aA	1,012.86aA
Bark	AAC 645	2,102.98aB	904.28aB
	AAC 33	1,358.15aA	584.00aA
Branch	AAC 645	10,010.31aA	4,304.43aA
	AAC 33	6,139.59aA	2,640.02aA
Miscellaneous	AAC 645	2,550.69aB	1,096.79aB
	AAC 33	2,707.76aA	1,164.34aA
Total	AAC 645	17,118.61a	7,361.00a
	AAC 33	12,560.99a	5,401.22a
		Prob (>F)	
C		0.020*	0.020*
Co		<.0001*	<.0001*
C x Co		0.158^{ns}	0.158^{ns}

Notes: Values followed by ns are not significant with p-value greater than 0.05 and followed by * are significant with p-value less than 0.05. Different lowercase letters indicate difference between clones within each compartment and uppercase letters indicate difference between compartments of the same clone by Tukey's test (p ≥ 0.05). The total only compares the clones to each other.

Table 2. Mean nutrient content in litter compartments of *E. urophylla* x *E. grandis* (AAC 645) and *E. urophylla* x *E. camaldulensis* (AAC 33) clones in an integrated production system.

Compartments (Co)	Clones (C)	N	P	K	Ca	Mg	S	B	Cu	Mn	Zn
		(g kg^{-1})						(mg kg^{-1})			
Leaf	AAC 645	52aAB	0.36aA	2.9aA	6.85aA	2aA	0.3aB	46.34aA	8.72aA	606aA	11.78aA
	AAC 33	38.7aAB	0.09aA	1.4aA	5.47aB	1.95aB	0.4aA	42.31aA	2.89aA	229aA	1.62aA
Bark	AAC 645	34.05aBC	0.26aA	0.6aB	7.05aA	2.35aA	0.19aB	24.06aA	7.83aA	239aA	3.88aA
	AAC 33	30.8aB	0.25aA	1.1aA	6.85aB	2.9aA	0.14aA	29.06aA	12.1aA	237.5aA	6.55aA
Branch	AAC 645	24.35aC	0.09aA	0.9aB	6.31bA	2.15bA	0.09aB	41.36aA	7.09aA	114.65aA	3.71aA
	AAC 33	26.95aB	0.35aA	1.1aA	13.85aA	3.15aA	0.16aA	21.17aA	12.45aA	352.5aA	11.2aA
Miscellaneous	AAC 645	60.3aA	0.15aA	0.9aB	9.59aA	2.5aA	0.85bA	34.76aA	16.7aA	317.5aA	21.45aA
	AAC 33	51.1aA	0.08aA	0.7aA	5.57aB	2aAB	0.9aA	44.59aA	6.775aA	60.5aA	5.22aA
Total	AAC 645	170.7a	0.84a	5.3a	29.795a	9a	1.415a	1465.15a	403.3a	12771.5a	408.15a
	AAC 33	147.55a	0.76a	4.3a	31.735a	10a	1.59a	1371.1a	342.15a	8795a	245.8a
Prob (>F)											
C		0.357^{ns}	0.674^{ns}	0.578^{ns}	0.372^{ns}	0.057^{ns}	0.203^{ns}	0.796^{ns}	0.600^{ns}	0.798^{ns}	0.703^{ns}
Co		0.004*	0.848^{ns}	0.066^{ns}	0.198^{ns}	0.109^{ns}	0.005^{*}	0.245^{ns}	0.452^{ns}	0.511^{ns}	0.415^{ns}
C x Co			0.198^{ns}	0.225^{ns}	0.093^{ns}	0.368^{ns}	0.130^{ns}	0.330^{ns}	0.582^{ns}	0.317^{ns}	0.647^{ns}

Notes: Values followed by ^{ns} are not significant with p-value greater than 0.05 and followed by * are significant with p-value less than 0.05. Different lowercase letters indicate difference between clones within each compartment and uppercase letters indicate difference between compartments of the same clone by Tukey's test (p ≥ 0.05). The total only compares the clones to each other.

It can be observed in the multivariate analysis that the miscellaneous of the AAC 645 clone had higher Zn and Cu contents (Figure 1), while the AAC 33 clone had higher B and S contents. On the one hand, the AAC 645 clone showed higher N, K and Mg levels for the leaves. On the other hand, the bark, and branch of the AAC 33 clone had higher P, Mg, and Ca levels.

The nutrients that present a significant directly proportional relationship are Ca and Mg; Mn and P; Mn and K; S and N; Cu and Zn (R = 0.71, p = 0.04; R = 0.78, p = 0.02; R = 0.84, p=0.009; R = 0.84, p = 0.008; R = 0.87, p = 0.005, respectively), meaning that the higher the content of one, the higher the content of the other.

Nutrient stock is related to the biomass stock of each compartment (Table 3). Therefore, the branch compartment has the highest mass accumulation and has the highest nutrient input, except for S, which has the greatest accumulation in the miscellaneous compartment. Regarding the clones, the litter from the AAC 645 clone has greater nutritional accumulation in its biomass on the soil surface.

The accumulation order for macronutrients was Branch>Miscellaneous>Leaf>Bark, while the order for micronutrients followed Branch>Leaf>Miscellaneous>Bark. The nutrient storage magnitude gradient follows the order N>Ca>Mg>K>P>S for all compartments, except the mix of both clones, in which P takes the last position. The order for micronutrients follows Mn>B>Cu>Zn for all compartments and clones except the leaf and the miscellaneous of the AAC 645 clone, in which Cu becomes the nutrient with the lowest accumulation.

According to the analysis of variance, the clones showed differences among themselves for branch, leaf, and miscellaneous. The AAC 33 clone had statistically higher stock in the branch for P, Mn, and Zn (p = 0.00023, p = 0.0061, p = 0.00014, respectively), while the AAC 645 clone was higher for B (p = 0.00015). The AAC 645 clone was statistically superior in the leaf compartment for K, Mn, and Zn (p = 0.034, p = 0.0119, p = 0.040, respectively), and in miscellaneous for Zn (p = 0.00037).

Discussion

Over the 10 years of forest development in which the litter accumulation took place, it was observed that the AAC 645 clone obtained the highest total carbon storage than the AAC 33 clone, with 7,361 and 5,401.22 kg ha^{-1}, respectively. This accumulation implies the superiority of the AAC 645 clone over AAC 33 when the main criterion is carbon capture. Viera and Rodríguez-Soalleiro (2019) found 8,340 kg ha^{-1} of litter carbon in a 10-year-old *Eucalyptus urophylla* × *E. globulus* stand, which is higher than the value found in the present study; these variations may be associated with different characteristics of the material and also with edaphoclimatic issues.

Tree biomass is normally the largest carbon reservoir due to mass accumulation in its

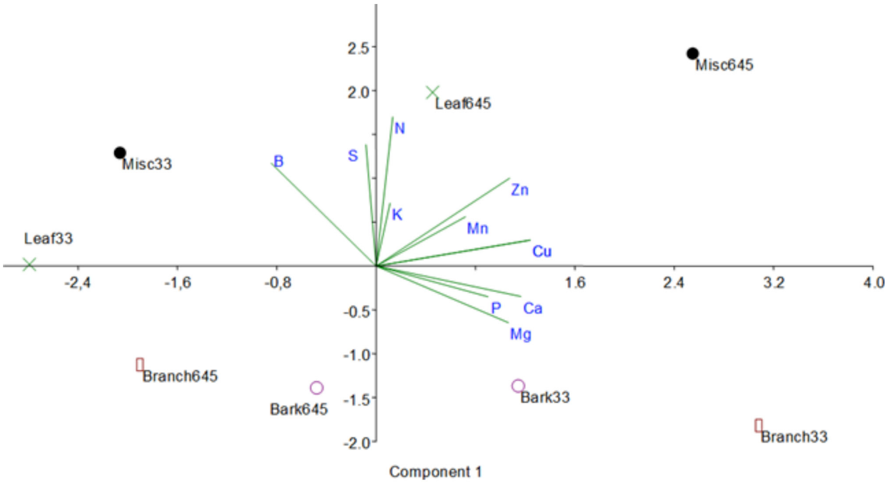

Figure 1. Principal components analysis of the nutritional contents of eucalyptus litter (Letter X - Leaf; Empty circle - Bark; Empty rectangle - Branch; Full circle - Miscellaneous).

Table 3. Total nutrient stock in litter compartments of *E. urophylla* x *E. grandis* (AAC 645) and *E. urophylla* x *E. camaldulensis* (AAC 33) clones in an integrated production system.

Compartments (Co)	Clones (C)	N	P	K	Ca	Mg	S	B	Cu	Mn	Zn
		(kg ha^{-1})									
Leaf	AAC 645	127.64aB	0.87aA	7.12aA	16.81aB	4.91aB	0.74aB	0.114aB	0.021aB	1.49aA	0.029aBC
	AAC 33	91.16aAB	0.20aB	3.30bAB	12.87aB	4.59aB	0.94aB	0.100aA	0.007aB	0.54bB	0.004bB
Bark	AAC 645	71.61aB	0.54aA	1.26aB	14.83aB	4.94aB	0.39aB	0.051aB	0.016aB	0.50aB	0.008aC
	AAC 33	41.83aB	0.34aB	1.49aB	9.30aB	3.94aB	0.19aC	0.039aA	0.016aB	0.32aB	0.009aB
Branch	AAC 645	243.75aA	0.85bA	9.01aA	63.12aA	21.52aA	0.85aB	0.414aA	0.071aA	1.15bAB	0.037bAB
	AAC 33	165.46aA	2.12aA	6.75aA	85.03aA	19.34aA	0.95aB	0.130bA	0.076aA	2.16aA	0.069aA
Miscellaneous	AAC 645	153.81aB	0.37aA	2.30aB	24.46aB	6.38aB	2.16aA	0.089aB	0.04aAB	0.81aAB	0.055aA
	AAC 33	138.37aAB	0.22aB	1.90aB	15.08aB	5.42aB	2.42aA	0.121aA	0.018aB	0.16aB	0.014bB
Total	AAC 645	596.81a	2.63a	19.69a	119.22a	37.75a	4.13a	0.67a	0.15a	3.95a	0.13a
	AAC 33	436.82a	2.87a	13.44a	122.29a	33.29a	4.51a	0.39a	0.12a	3.19a	0.10a
Prob (>F)											
C		0.012*	0.572^{ns}	0.009*	0.871^{ns}	0.407^{ns}	0.299^{ns}	0.001*	0.096^{ns}	0.127^{ns}	0.032 *
Co		<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*
C x Co		0.486^{ns}	<.0001*	0.061^{ns}	0.103^{ns}	0.966^{ns}	0.277^{ns}	<.0001*	0.143^{ns}	<.0001*	<.0001*

Notes: Values followed by ns are not significant with p-value greater than 0.05, and followed by * are significant with p-value less than 0.05. Different lowercase letters indicate difference between clones within each compartment and uppercase letters indicate difference between compartments of the same clone by Tukey's test (p ≥ 0.05). The total only compares the clones to each other.

compartments. However, litter plays an important role in carbon storage (Viera and Rodríguez-Soalleiro, 2019). The amount of carbon found in the AAC 645 clone litter was close to the carbon accumulation in the total tree biomass of a 1.6-year-old monoculture of *Eucalyptus* sp., and to that found in the leaf, branch, and bark compartments of *Eucalyptus urophylla* x *Eucalyptus grandis* of 5.5 years old with 8200 kg ha^{-1} and 8.51 kg ha^{-1}, respectively (Wink *et al.*, 2013; Ribeiro *et al.,* 2015), reiterating the importance that the carbon reservoir stored in the litter of forest ecosystems has in the global carbon cycle.

Concering litter biomass, the clones had an average of 14,839 kg ha^{-1} of production. Schumacher *et al.* (2019) found 12,300 kg ha^{-1} of litter in a *Eucalyptus* spp. stand at 8 years of age, while Barbosa *et al.* (2017) found 13,070 kg ha^{-1} in evaluating *Eucalyptus urophylla* at 5 years of age. Carbon stock is directly related to biomass accumulation (Barbosa *et al.*, 2017). Thus, the biomass variable, which followed the same behavior as the carbon stock, presented a 36% higher biomass contribution in the AAC 645 clone than in the AAC 33 clone, which is primarily due to the accumulation of branches, which represents an average of 53% of the total. Litter biomass accumulation is related to the material deposition falling from trees on the soil surface over an extended time. Litter deposition throughout the development of *Eucalyptus* sp. varies, being greater around 4 years of age and decreasing after this period (Abreu *et al.*, 2020). In addition to deposition, accumulation is also affected by mass loss through decomposition. It is known that the mass loss of *E. urophylla* is approximately 33% in one year, which makes it a good indication to accelerate the balanced cycle of nutrients (Vargas *et al.*, 2019; Oliveira *et al.*, 2020).

Therefore, the AAC 33 clone having a lower litter production may be related to a higher potential for decomposition, with a faster rate regarding the other clone, indicating a fundamental role in the system's dynamics and providing a faster release of nutrients for the plants. The decomposition rate can also be related to soil quality and climatic conditions. For example, Eucalyptus species in monoculture in China produced an average litter of 6.86 t ha^{-1}, constituting a lower value than that found in the present work with approximately the same age as the forest (Skorupa *et al.*, 2015). However, considering that the clones were planted side by side, the material characteristics concerning nutritional quality and carbon quality relative to the types of bonds could be what affected the litter accumulation.

The decomposition rate is linked to higher N and lower polyphenols, cellulose, and lignin levels. Another meaningufl relationship to be considered is the C/N ratio, as the smaller it is, the less resistant the material is, which favors the activity of decomposers (Oliveira *et al.,* 2020). N and P are essential in the litter decomposition process as they are resources for the growth of microorganisms, making the process faster where their concentration is higher (Cavalcante *et al.,* 2021). In analyzing these alone, the AAC 33 clone showed higher N and P levels for the branch compartment, which also had a lower C/N ratio (15.9) compared to the AAC 645 clone (17.7), resulting in branch biomass accumulation of 3,870.72 kg ha^{-1} less regarding AAC 645. Similarly, the miscellaneous compartment of AAC 645 also presented higher N and P contents and, consequently, lower litter content, which proves the relationship with the fastest decomposition rate.

The nutritional content varied as a function of compartments and clones. The branch and miscellaneous components had the highest average nutritional contents evaluated. Usually, the leaves have the highest concentration of nutrients, as they are the metabolite center of the plant. However, the quantity and quality of nutrients supplied to the soil by litter deposition can vary, mainly with the forest stand species, and of the plant structures present in the litter (Vargas *et al.,* 2019; Carvalho *et al.*, 2019).

The content gradient was similarly observed by Vargas *et al.,* (2019) (N>Ca>Mg>K>P) in the litter of eucalyptus clones in monoculture in Itatinga-SP at 6 years of age. The same authors found higher N levels in the leaves, which corroborates the data of the present work, in which N had a higher concentration in the leaf and miscellaneous compartments, with this compartment formed by fragments not identified due to size but mostly from leaf fragments. The sum of the N and Ca content corresponds to almost 92% of the total macronutrients found in the accumulated litter, and almost 95% of the total micronutrients corresponds to Mn and B.

Ca and Mg are essential for some *Eucalyptus* species to reach high productivity levels (Rocha *et al.*, 2019). The AAC 33 clone was statistically superior to AAC 645 in nutritional contents of the branch compartment for Ca, Mg, and miscellaneous for S. More mature plantations tend to have higher Mg contents and N, while higher Ca and P contents occur in younger areas, so the age of the material influences the litter quality (Camara *et al.*, 2018).

The nutrients with less accumulation in the fractions were K, P, and S. Very mobile nutrients, such as P, have their internal redistribution facilitated from older to younger tissues, therefore having minimal concentrations in all compartments (Abreu *et al.*, 2020). K has one of the highest release rates from decomposing leaf litter, more than 90% in the short term, as it is not a structural part of the plant tissue, so it can be released more efficiently, making it essential in its prompt ground re-availability (Momolli *et al.*, 2018).

In contrast, N, Ca, and Mg are part of the plant's structural tissue; consequently, their release is slower, depending on the biological decomposition of the litter. Therefore, these nutrients have a longer residence time in the litter and a lower return coefficient and are found in higher concentrations in the tissues (Cavalcante *et al.*, 2021).

The concentration gradient found for micronutrients was similar to that described by Viera *et al.* (2013) for a *Eucalyptus urophylla* × *Eucalyptus globulus* hybrid between 6 and 9 years of age in the South region of Brazil (Fe>Mn>B>Zn>Cu), only differing from the nutrient Fe with the highest content, which was not considered in this work, and also from the inversion between Zn and Cu in last placement. Studies indicate that micronutrients such as Cu, Zn, and Mn increase their concentrations during the decomposition period, which means the source of their accumulation in the organic material (Momolli *et al.*, 2018).

Nutrient stock, different from content, is affected by the biomass distribution in the compartments. Thus, the branch component, with the highest biomass fraction was also the component with the highest nutrient stock. The nutrients with the highest accumulation in the litter were N, Ca, and Mn, which was also found in a 5-year-old stand of hybrid *Eucalyptus urophylla* x *E. grandis* (Carvalho *et al.*, 2019).

The AAC 645 clone has a vaster nutritional accumulation in its soil surface biomass and a more considerable overall accumulation of litter-dry biomass and carbon contained therein. This data is interesting when choosing the genetic material to be planted, as it stands out in the re-availability of nutrients to the soil, and is interesting (for example) in soils that do not have adequate natural fertility.

The branch compartment of the AAC 645 clone has the most extensive N, K, Mg, and B stocks, while the branch compartment in the AAC 33 clone has the largest P, Ca, Mn, Cu, and Zn stocks. The data show that all nutrients are related to each other, so the higher an element, the higher the others, corroborating the data from Abreu *et al.* (2020), who evaluated the hybrid *Eucalyptus urophylla* x *E. grandis* with different ages in an integrated Crop-Livestock-Forestry system. Thus, litter is proven to be extremely necessary to replenish nutrients in significant amounts to the system, establishing its sustainability in the cycle under consideration and the following ones (Schumacher *et al*., 2019). The branch fraction has great weight as a nutritional source, as it contains high levels of nutrients in addition to composing the most significant biomass percentage. The branches show great relevance in nutrient cycling and maintenance of the soil-plant system. This vital issue leads us to further understand the relevance of natural pruning and trimming as a form of management, considering wood quality and the maintenance of the organic matter layer in the soil to make nutrients available during the whole cycle.

The accumulation and availability of nutrients from litter decomposition highlight the importance of biogeochemical cycling in the forest as a potentially important source of nutrients to the soil for plant supply and absorption. The integrated system model has many benefits that still need to be explored in studies, especially with different hybrids from conventional ones. Thus, future long-term studies to monitor cycles over 10 years are recommended for the integrated production system.

Conclusions

Litter production in an integrated system supplies high nutrient demands to the soil. The litter biomass, carbon, concentration, and nutrient stock were influenced by the clones and compartments evaluated. The most extensive litter biomass stock, and carbon content was found in the AAC 645 clone. The nutritional contents are different from each other in the different compartments of the litter. The AAC 645 clone had higher total nutrient content, except for Ca, Mg, and S. The litter branch fraction presented higher biomass, carbon content, and nutritional intake averages in both clones, standing out as an important part of nutrient cycling.

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