SCIENTIA FORESTALIS

ISSN 2318-1222 (online)

ORIGINAL ARTICLE

Litter decomposition in *Eucalyptus saligna* Smith plantation in Pampa biome in southern of Brazil

Decomposição da serapilheira em plantação de *Eucalyptus saligna* Smith no bioma Pampa no sul do Brasil

Matheus Severo de Souza Kulmann[1], Grasiele Dick[1], Mauro Valdir Schumacher[1]

[1]Universidade Federal de Santa Maria – UFSM, Santa Maria, RS, Brasil

How to cite: Kulmann, M. S. S., Dick, G., & Schumacher, M. V. (2024). Litter decomposition in *Eucalyptus saligna* Smith plantation in Pampa biome in southern of Brazil. *Scientia Forestalis*, *52*, e4008. https://doi.org/10.18671/scifor.v52.01

Abstract

The litter decomposition is an important source of nutrient return to forest plantations. This study the aimed to characterize the seasonal dynamics of nutrient cycling via litter decomposition, in a plantation of *Eucalyptus saligna*, cultivated in the Pampa biome in southern Brazil. We evaluated litter produced and accumulated, as well as accumulated nutrients. Seasonal rates of decomposition were indirectly estimated. The season with the highest values of litter decomposition was summer. On the other hand, winter was the season with the lowest values of litter decomposition. The low values of decomposition coefficient (k = 0.605) found in our study show that the remaining 95% ($t_{0.95}$) of the litter on the soil will be there for five years. The greatest stocks of nutrients in the litter produced and accumulated were Ca and N. Thus, the litter constitutes a long-term reservoir of larger amounts of Ca and N and, through decomposition, makes K available more immediately.

Keywords: Nutrient cycling; Forestry nutrition; Forest ecology.

Resumo

A decomposição da serapilheira constitui uma importante fonte de retorno de nutrientes às plantações florestais. Assim, este estudo objetivou caracterizar a dinâmica estacional da ciclagem de nutrientes, via decomposição da serapilheira, em plantação de *Eucalyptus saligna,* cultivada no bioma Pampa, no Sul do Brasil. Dessa forma, avaliamos a serapilheira produzida e acumulada, bem como nutrientes acumulados. As taxas estacionais de decomposição foram estimadas, de forma indireta. A estação com maiores valores de decomposição da serapilheira foi o verão. Por outro lado, o inverno foi a estação com menores valores de decomposição da serapilheira. Os valores baixos coeficiente de decomposição (k = 0,605) encontrados em nosso estudo mostram que a residência de 95% ($t_{0,95}$) da serapilheira sobre o solo será durante cinco anos. Os nutrientes em maiores estoques na serapilheira produzida e acumulada foram Ca e N. Dessa forma, a serapilheira constitui reservatório, em longo prazo, de maiores quantidades de Ca e N e, pela decomposição, disponibiliza K de forma mais imediata.

Palavras-chave: Ciclagem de nutrientes; Nutrição florestal; Ecologia florestal.

INTRODUCTION

The growing global demand for wood products has led to the establishment of forest stands, reaching 131 million hectares of planted forests for commercial purposes worldwide (Food and Agriculture Organization, 2020). The crops used in these stands are fast growth and short rotation species. However, critical socio-environmental questions are currently arising, such as reduced productivity and soil degradation (Zhou et al., 2015). For example, studies conducted in China and

Financial support: None.
Conflict of interest: Nothing to declare.
Corresponding author: matheuskulmann@hotmail.com
Received: 12 April 2023.
Accepted: 11 December 2023.
Editor: Mauro Valdir Schumacher.

Brazil on harvesting *Eucalyptus* plantations on short rotations of 2 to 6 years, resulted in large nutrient exports and possible declines in plantation productivity (Xu et al., 2004; Eufrade-Junior et al., 2016). The genus *Eucalyptus* is the most important and representative one, due to its fast growth, adequate wood properties and high adaptability to different soil and climate conditions (Flores et al., 2016), occupying around 20 million hectares worldwide, distributed in more than 100 countries (Booth, 2013; Myburg et al., 2014; Elli et al., 2019).

In Brazil, *Eucalyptus* constitutes the largest forest base, with approximately 7.6 million hectares planted (Indústria Brasileira de Árvores, 2023), and a productivity of 32.7 m^3 ha^{-1} $year^{-1}$; it is recognized as one of the largest in the world (Binkley et al., 2017; Indústria Brasileira de Árvores, 2023). Despite its rapid growth rates, significant concerns have arisen regarding the continuous decline in productivity of *Eucalyptus* spp. plantations. This decline is associated with successive nutrient exports, requiring special attention on the sustainability of the site nutrient balance (Kulmann et al., 2022; Guo & Sims, 1999). However, ensuring productivity in subsequent rotations is a central concern for long-term sustainability in commercial plantations (Subedi et al., 2019). A key strategy for maintaining stand productivity in the subsequent rotation, is soil nutrient management, which can contribute to silvicultural practice decisions, such as fertilization of *Eucalyptus* spp. plantations.

One of the main factors in the nutrient balance is the cycling of nutrients through the forest litter. Nutrient cycling in native forests and commercial plantations involves several pathways of nutrient inputs and outputs; however, throughfall is considered the most important (An et al., 2019; Michopoulos et al., 2019). The litter acts in maintaining soil fertility of forest ecosystems, as it is the main former of soil organic material, which is composed of organic fragments, coming from the shoots of plants, leaves, flowers, fruits, twigs, branches, bark, and other plant materials, as well as animal remains and fecal material (Dick & Schumacher, 2020; Michopoulos et al., 2019). In addition to litter participating in nutrient cycling, it plays an important role against erosion, it is a source of organic carbon, substrate for microorganisms and soil respiration (Michopoulos et al., 2019). Information about the rate and time of decomposition of litter, which is an important source of organic matter to plantations, are indirect predictions about the future stock and flow of nutrients in the plant-soil-plant system (Kulmann et al., 2022; Zaia & Gama-Rodrigues, 2004). Until the complete release of the nutrients contained in the organic material, the litter undergoes processes of decomposition, which is initiated by fragmentation by the macro- and mesofauna, followed by the deterioration induced by edaphic microfauna (Correia & Oliveira, 2000).

The organic/mineral diversity of the litter and composition of the decomposer community are the main factors that influence the decomposition rate and remaining time of the litter on the soil (Schilling et al., 2016). However, climate is the factor that mostly affects litterfall on a global scale (González-Rodríguez et al., 2017; Michopoulos et al., 2019). Seasonal variations directly influence the amount produced and accumulated litter (Skorupa et al., 2015), affecting the decomposition process and the proportion of senescent material accumulated on the soil (Viera et al., 2013). The fall of litter is directly related to the return of nutrients to the soil and consequently plays an important role in forest biogeochemical cycling (Zhou et al., 2015). The quantity and quality of litter production directly influence the productivity of natural or planted forest stands (Zhou et al., 2015). The dynamics of litter decomposition varies depending on the species and forest typology; in natural forests the decomposition rate tends to be more accelerated (Ferreira et al., 2014; Pires et al., 2006) when compared to areas with *Eucalyptus* plantations, where there is organic/nutritional homogeneity of the litter (Guo & Sims, 1999). Thus, the nutrients contained in the litter, which are made available after decomposition, are crucial to maintaining the fertility of forest soils and the productive capacity of the site (Alvarez et al., 2008).

Many studies on litter production and accumulation have focused on fluctuations in climatic factors, especially temperature and precipitation, showing significant effects on litter production (Zhou et al., 2015; González-Rodríguez et al., 2017; An et al., 2019; Dick & Schumacher, 2020; Michopoulos et al., 2019). However, studies comparing the decomposition of litter from commercial forest plantations, such as *Eucalyptus* spp. and, their relationships regarding litter production, chemical composition of litter fractions, decomposition rate of nutrients from litter to soil, are scarce in the literature. Thus, the aim of this study was to evaluate litter decomposition in a *Eucalyptus saligna* plantation in the Pampa biome in southern Brazil.

MATERIAL AND METHODS

Study area

The study was conducted from January 2011 to December 2012, in São Gabriel, central region of Rio Grande do Sul State, southern Brazil (-30° 30' 12" S and 54° 10' 0.8" W). The relief of the area is characterized as flat to slightly undulating. The climate of the region is of type Cfa humid subtropical, according to the Köppen classification, characterized by well distributed rainfall throughout the year and well-defined seasons with a lower temperature in winter. The average annual precipitation is 1,424 mm and average annual temperature is 19.5°C (Alvares et al., 2013) (Figure 1). The soil of the experimental area was classified as a typical

Dystrofic Haplic Cambissol (Santos, 2013). At the end of the experiment, the 0-20 cm soil layer revealed the following characteristics: 12.6% clay; 17 g kg^{-1} of organic matter (Walkley-Black method), 4.1 pH in water (1:1 ratio); 13.2 and 51.6 mg dm^{-3} of available P and K, respectively (both extracted by Mehlich-1); 2.0, 0.6 and 0.4 $cmol_c$ dm^{-3} of exchangeable Al, Ca and Mg, respectively (extracted by KCl 1 mol L^{-1}) (Tedesco et al., 1995).

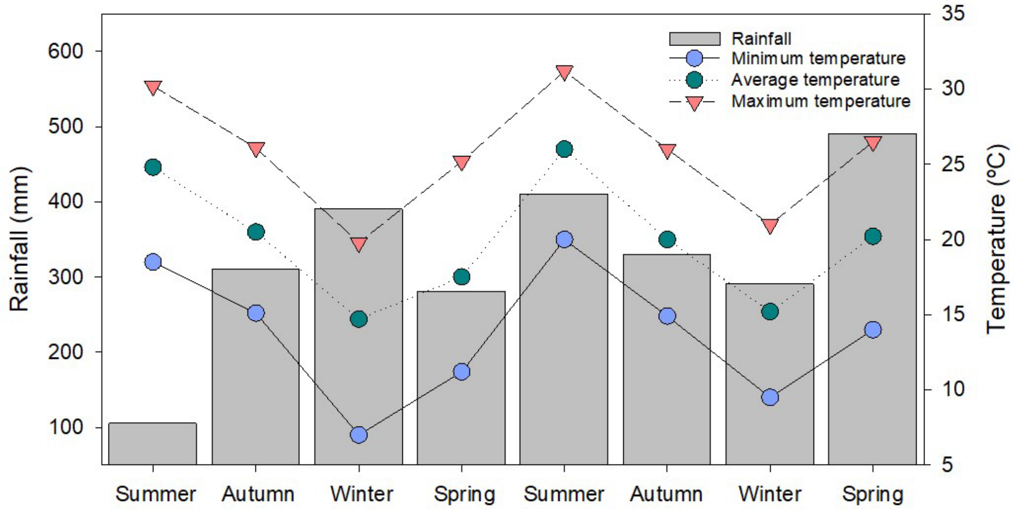

Figure 1. Climatic characterization of *Eucalyptus saligna* plantation in Pampa biome, Southern Brazil

The silvicultural practices for the implementation of the experimental area were soil preparation, with subsoiling to a depth of 50 cm. *Eucalyptus saligna* clones were transplanted in January 2007. Plant spacing was 3.5 m between plants and 2.75 m between rows. Fertilizer was applied in two moments: starter and top–dressing. Starter fertilization consisted of 2.0 Mg ha^{-1} of dolomitic limestone, 500 kg ha^{-1} of reactive phosphate, and 100 g $plant^{-1}$ of NPK fertilizer (06:30:06 N–P_2O_5–K_2O), applied in furrows. Top–dressing fertilization was applied 200 g $plant^{-1}$ of NPK+B fertilizer (12:00:12 N–P_2O_5–K_2O and 0.5% B) at 120 days and 200 g $plant^{-1}$ of NPK fertilizer (12:00:20 N–P_2O_5–K_2O) at 365 days.

Nutrients produced and accumulated in the litter

Four random plots of 23 m × 26 m were marked to quantify the litter deposition. The plots were marked at distances greater than 30 m from each other and 20 m from the edge of the forest ecosystem, distributed randomly. Within each plot litter–collectors were installed in the positions: line and between the planting line, diagonally between trees and near the tree trunk. Wooden collectors (0.5 m^2 - 1.0 m long × 0.5 cm wide) with a nylon mesh at the bottom (1.0 mm mesh) were installed 0.7 m from ground level. The contents of the litter–collectors were collected at biweekly intervals between January 2011 and December 2012.

The accumulated litter was collected at seasonal intervals, at the end of the season, using a 0.25 m × 0.25 m metal template. In each collection, 16 random samples were taken from all organic materials accumulated on the soil surface, according to the methodology reported by Santos et al. (2014). The produced and accumulated litter samples were dried in a forced air circulation oven at 65°C for 72 h. Then, the samples were weighed on a precision digital scale (Bel Engineering, Precision balance L, Brazil), for dry matter determination. Immediately after weighing, the samples were ground in a Wiley type mill, passed through a 2 mm mesh sieve and set aside for chemical analysis.

Chemical analysis of the litter

The samples of litter produced and accumulated were submitted to chemical analysis. Part of the fraction samples were submitted to sulfuric digestion for determination of N by micro-Kjeldahl distiller (TE 0363, Tecnal, Brazil). Another part of the samples was submitted to nitro-perchloric digestion for determination of P, K, Ca, Mg, and S concentrations, following the methodology of Tedesco et al. (1995). The extrapolation of the dry weight (g) of the litter to the unit Mg ha^{-1} and estimates of the amounts of nutrients in the biomass were performed according to Schumacher & Viera (2015).

Decomposition and nutrient return rates

The decomposition coefficient (k) of the litter was calculated according to Equation 1.

$$k = PL/AL, \quad (1)$$

where: *PL* refers to the litter produced and *AL* corresponds to the amount of litter accumulated on the ground, according to the methodology proposed by Olson (1963). This model considers the exponential decomposition of the litter and the estimated mean remaining time (MRT), in years. MRT was obtained by the relationship MRT = 1/k, with the half-life (50%), calculated by $t_{0.5}$= ln 2/k, and the 95% decomposition by $t_{0.95}$ = 3/k (Olson, 1963).

The return coefficient (RC) of nutrients (kg ha^{-1}) by litter decomposition was calculated according to Equation 2.

$$RC = S/(S + NA), \quad (2)$$

where: *S* corresponds to the seasonal amount of nutrients contributed by the litter produced, and *NA* refers to nutrients amount in the accumulated litter, both in kg ha^{-1}, according to the methodology reported by Chaturvedi and Singh (1987). The mean return time (MRT) of each nutrient, in years, was obtained by the ratio between the amount of the nutrient in the accumulated litter and amount in the litter produced annually, in kg ha^{-1} (Adams & Attiwill, 1986).

The amount of nutrients available (kg ha^{-1}) was estimated according to Equation 3.

$$ANA = (TAPL + NAL_0) - NAL_f, \quad (3)$$

where: *TAPL* refers to the total amount of produced litter in the period (2 years); NAL_0 corresponds to the amount of the nutrient in the accumulated litter at the beginning of the evaluation; and NAL_f is the amount of the nutrient in the litter accumulated at the end of the evaluation (year 2012), according to the methodology proposed by Viera et al. (2013).

Statistical analysis

All results obtained were submitted to analysis of variance using the R Studio program (R Core Team, 2021), and when the significance of the effects indicated by the analysis of variance, the comparison of means was performed by the Tukey test ($p < 0.05$). The effects of seasonal variation factors of the amount of accumulated and produced litter and decomposition rates were evaluated through descriptive data analysis, based on the standard error of the mean.

RESULTS

Litter decomposition

The decomposition coefficient (k) of litter in *Eucalyptus saligna* stands cultivated in southern Brazil is significantly higher in the summer season (0.186), indicating that decomposition is faster in this period of the year, when compared to winter (0.102). On the other hand, the amount of litter accumulated on the ground is lower in the season with the highest temperatures, while in periods of low temperatures and higher volumes of rainfall the production of litter is reduced (Table 1).

Table 1. Produced, accumulated and decomposition coefficient (k) of litter in in *Eucalyptus saligna* plantation in Pampa biome, Southern Brazil.

Season	AL	PL	k
	-----------------Mg ha^{-1}---------------		-
Summer	11.26 b[1]	2.30 a	0.186 a
Autumn	11.76 ab	1.79 b	0.145 b
Winter	12.32 ab	1.26 c	0.102 c
Spring	14.15 a	2.12 bc	0.172 ab
Annual	51.02	7.48	0.605

Al = accumulated litter; PL = produced litter; k = decomposition coefficient. [1]Equal lowercase letters, in the column, do not differ by the Tukey test at 5% probability of error.

The average remaining time of the litter in this *Eucalyptus saligna* plantation is 1.6 years, with the time required for 50% and 95% decomposition being 1.1 and 5.0 years, respectively.

About the nutritional quality of the litter evaluated in this study, there is less stock of P and S and greater amounts of Ca and N, which together correspond to 79.3% of all nutrients contained in the accumulated fraction and 63.2% in the produced fraction (Table 2). The accumulated litter in this *Eucalyptus saligna* plantation contains the greatest amounts of nutrients (Ca > N > Mg > K > S > P), especially Ca and N in the litter.

Table 2. Nutrient amount litter and litterfall in in *Eucalyptus saligna* plantation in Pampa biome, Southern Brazil.

Season	N	P	K	Ca	Mg	S
	AL (kg ha^{-1})					
Summer	78.36 ± 3.22	4.22 ± 0.05	23.16 ± 2.10	112.95 ± 11.83	21.95 ± 0.83	8.17 ± 1.70
Autumn	81.26 ± 9.35	4.26 ± 0.96	25.85 ± 6.48	130.46 ± 42.88	23.31 ± 2.89	7.27 ± 2.75
Winter	98.55 ± 1.46	5.41 ± 0.56	18.85 ± 4.41	156.944 ± 1.87	25.37 ± 4.05	8.35 ± 2.39
Spring	119.50 ± 18.47	5.55 ± 1.44	19.23 ± 2.79	153.98 ± 27.55	31.53 ± 6.58	11.38 ± 0.03
Mean	94.42	4.86	21.77	138.58	25.54	8.79
Total	377.67 ± 1.1	19.44 ± 0.04	87.09 ± 11.38	554.34 ± 5.37	102.16 ± 5.95	35.17 ± 6.81
	PL (kg ha^{-1})					
Summer	10.73 ± 1.59	0.80 ± 0.13	7.49 ± 0.02	13.61 ± 0.33	4.45 ± 0.12	1.11 ± 0.01
Autumn	7.66 ± 1.00	0.59 ± 0.07	6.52 ± 0.45	11.99 ± 0.32	3.46 ± 0.57	1.20 ± 0.09
Winter	5.37 ± 0.30	0.38 ± 0.04	4.78 ± 0.02	8.18 ± 2.51	2.32 ± 0.31	0.62 ± 0.05
Spring	9.43 ± 2.02	0.75 ± 0.30	7.64 ± 1.49	13.66 ± 1.28	3.67 ± 0.45	1.18 ± 0.01
Mean	8.30	0.63	6.61	11.86	3.47	1.03
Total	33.19 ± 4.30	2.52 ± 0.55	26.44 ± 1.03	47.45 ± 4.44	13.89 ± 0.55	4.11 ± 0.04

AL = accumulated litter; PL = produced litter; Values represent the average ± standard deviation.

Return of nutrients through the decomposition of litter

Seasonality influenced the amount of nutrients in the litter produced and accumulated (Table 2), whose seasonal fluctuation is directly related to the difference in the amount of biomass produced in each season (Table 1). Regarding the dynamics of nutrient release via decomposition of the *Eucalyptus saligna* litter, there is long-term storage mean return time and larger quantities of Ca and N, however, the fastest availability is of K. Despite the larger amounts of Ca and N that will be made available after decomposition, the higher TMR characterizes the slower cycling of these nutrients when compared to K, S and Mg (Table 3). Considering the temporal scale and nutrient return, the decreasing order is observed: K > S > Mg > P > N > Ca, distinct from the trend of the amount of nutrients available: Ca > N > K > Mg > S > P.

Table 3. Seasonal dynamics of litter decomposition in *Eucalyptus saligna* plantation in Pampa biome, Southern Brazil.

Season	N	P	K	Ca	Mg	S
Return coefficient (RC)						
Summer	0.34	0.38	0.61	0.32	0.39	0.40
Autumn	0.34	0.38	0.58	0.29	0.37	0.42
Winter	0.30	0.32	0.66	0.25	0.36	0.40
Spring	0.26	0.32	0.65	0.25	0.31	0.33
Mean	0.31	0.35	0.63	0.28	0.36	0.39
Average turnaround time (TMR; years)						
Summer	1.90	1.62	0.63	2.17	1.57	1.50
Autumn	1.97	1.63	0.71	2.47	1.67	1.36
Winter	2.39	2.09	0.52	3.01	1.81	1.52
Spring	2.91	2.15	0.53	2.97	2.25	2.08
Mean	2.29	1.87	0.60	2.65	1.83	1.61
Amount of nutrients available (ANA; kg ha^{-1})						
Summer	70.94	4.98	69.99	78.16	28.95	5.81
Autumn	79.60	6.41	62.04	155.53	31.87	4.32
Winter	68.45	5.84	46.64	97.54	22.04	4.83
Spring	40.25	3.02	48.92	55.94	36.65	8.26
Mean	64.81	5.06	56.90	96.79	29.88	5.81
Total	32.40	2.53	28.45	48.40	14.94	2.90

DISCUSSION

Litter decomposition

The annual litter decomposition coefficient of this plantation (k=0.605) is considered low when compared to natural forests in transition regions between tropical and subtropical climates, ecosystems in which k is greater than 1.0 (Pires et al., 2006). However, there is a trend for lower litter decomposition coefficients in monocultures, especially in *Eucalyptus* spp. plantations, where k values range from 0.54 (Viera et al., 2013) to 1.0 (Zaia & Gama-Rodrigues, 2004), as well as plantations of *Tectona grandis* (Rosa et al., 2017) and *Acacia* spp. plantations (Andrade et al., 2000).

As for the average remaining time of the litter in this *Eucalyptus saligna* plantation, the temporal pattern is already observed in *Eucalyptus saligna*, where Kolm & Poggiani (2003) estimated 1.2 and 5.3 years, to decompose 50 and 95% of the litter, respectively. However, the time required to decompose the material is not only an intrinsic characteristic of the species, but also of the monoculture system, as verified in plantations of *Eucalyptus urophylla x E. globulus* (Viera et al., 2013), *Eucalyptus saligna* (Poggiani, 1985) and *Tectona grandis* (Rosa et al., 2017). In contrast, in natural forests, where the decomposition rate is more accelerated, the half-life is reached in 248 days and the decomposition of 95% of the litter was obtained after 2.9 years (Ferreira et al., 2014). Despite the low decomposition coefficient, the longer remaining time of this litter provides soil cover for up to five years. This layer of senescent material promotes soil protection against erosive processes, which is intensified in seasons with higher rainfall volumes (Carvalho et al., 2017).

Temperature and rainfall oscillations regulate the dynamics of litter decomposition over the seasons (Carvalho et al., 2017), and influence the seasonal variation of the decomposing community (Scoriza & Piña-Rodrigues, 2014). The decomposition rate is regulated by seasonality, as the activity of functional groups that fragment senescent leaves and branches, such as ant communities (Hymenoptera) are reduced when temperatures are lower: in autumn and winter (Boscardin et al., 2012). On the other hand, the main orders of phytophagous organisms and primary fragments (Hemyptera and Coleoptera) are more abundant in *Eucalyptus* plantations in summer and spring (Garlet et al., 2016).

Based on the seasonal influence, the low decomposition coefficient, and the longer remaining time of the litter in monoculture are a result of the diversity of decomposers (Barbosa et al., 2017). The richness and abundance of these organisms are regulated by the diversity of organic material as well as their organic constituents (cellulose and lignin contents) in senescent plant tissues (Cizungu et al., 2014), C/N ratios (Barbosa et al., 2017), and the nutrients contained in the litter (Zaia & Gama-Rodrigues, 2004; Skorupa et al., 2015).

Return of nutrients through the decomposition of litter

The higher amounts of nutrients, especially Ca and N in the litter increase the decomposition rate (Cizungu et al., 2014). Among the macronutrients, N (Hobbie et al., 2012), P, and S (Berg & McClaugherty, 2008) are responsible for accelerating the initial process of transforming leaves, twigs, and miscellany into organic matter, as evidenced by Berg et al. (2022).

In *Eucalyptus* plantations the litter produced and accumulated is mostly composed of leaves, a fraction that contains the highest concentrations of nutrients and fastest decomposition (Barbosa et al., 2017). However, in addition to minerals, *Eucalyptus saligna* leaves contain high concentrations of lignin (>200 g kg^{-1}) and polyphenols (>60 g kg^{-1}) in the cell wall (Guo & Sims, 2002; Gama-Rodrigues & Barros, 2002). The high concentrations of lignin and phenolic compounds in the chemical constitution of the leaf litter and thin branches of the species eventually reduce the rate of decomposition of the litter; in monoculture the homogeneity in nutritional and organic quality of the litter causes slow degradability (Giesselmann et al., 2011), limiting the degree of complexity of decomposer groups, since dietary diversity (Barbosa et al., 2017), in addition to environmental conditions (Silva et al., 2018; Ferreira et al., 2014) are the main regulators of the activities of these organisms.

The influence of seasonality on the amount of nutrients in the litter produced and accumulated is explained by the mobility of nutrients as a function of the maturity of plant tissues (Malavolta, 2006), in addition to physiological reactions of leaf loss and transport of minerals, which are triggered by changes in air temperature and water availability (Taiz et al., 2017), as demonstrated by Ma et al. (2023).

In the dynamics of litter decomposition in *Eucalyptus* plantations, whether evaluated through direct (Carvalho et al., 2017) or indirect (Viera et al., 2013) estimation, K is the nutrient with the highest availability, by the highest return coefficient and lowest temporal of nutrient return, i.e., it is intensely leached from senescent plant tissues and more rapidly made available to the soil. Besides the high mobility (Malavolta, 2006), the rapid cycling of K is related to the non-structural function of this element in the composition of plant tissues, so it does not depend on biological activity for its availability (Alvarez et al., 2008).

The litter produced and accumulated in the plantation evaluated is a source of large amounts of nutrients and the seasonal influence is more pronounced on the rates of amount of nutrients available, which is directly related to the amount of litter produced, accumulated and nutrient stock as observed in Table 2. The trend of nutrient availability manifests itself in different ways over time, influenced according to the mobility, concentration, and biotic function of nutrients, as well as the activity of organisms and environmental conditions (Goya et al., 2008).

Considering the temporal scale and nutrient return, variability in nutrient cycling is indicative of future nutrient sustainability of this site. Despite the higher amounts of Ca, N, and P, there is a need to pay attention to fertilization with replacement of these nutrients, aiming to guarantee the productive capacity and conduct a new rotation in the area. This also applies to K fertilization, because despite the faster cycling of K in the litter-soil system, this nutrient has a high vertical mobility when incorporated into the soil and is the second element required in larger quantities by *Eucalyptus* trees (Ernani et al., 2007).

CONCLUSION

Litter decomposition in *Eucalyptus saligna* plantations in the Pampa biome is greater in summer and reduced in winter. The low decomposition coefficient conditions implies that 95% of this litter remains in the soil for up to five years. Seasonality influences the amount of nutrients in the produced and accumulated litter, which contains higher stocks of Ca and N and lower levels of S and P. Litter constitutes a long-term reservoir of larger amounts of Ca and N, while it provides K more rapidly through decomposition.

ACKNOWLEDGEMENTS

We are grateful to the National Council for Scientific and Technological Development (CNPq) for granting scholarship and Mauro Valdir Schumacher (UFSM) for coordinating and to support this research.

REFERENCES

Adams, M. A., & Attiwill, P. M. (1986). Nutrient cycling and nitrogen mineralization in eucalypt forests of south-eastern Australia: II. Indices of nitrogen mineralization. *Plant and Soil*, *92*(3), 341-362. http://dx.doi.org/10.1007/BF02372483.

Alvares, C. A., Stape, J. L., Sentelhas, P. C., Gonçalves, J. D. M., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, *22*(6), 711-728. http://dx.doi.org/10.1127/0941-2948/2013/0507.

Alvarez, E., Fernández Marcos, M. L., Torrado, V., & Fernández Sanjurjo, M. J. (2008). Dynamics of macronutrients during the first stages of litter decomposition from forest species in a temperate area (Galicia, NW Spain). *Nutrient Cycling in Agroecosystems*, *80*(3), 243-256. http://dx.doi.org/10.1007/s10705-007-9140-4.

An, J. Y., Han, S. H., Youn, W. B., Lee, S. I., Rahman, A., Dao, H. T. T., Seo, J. M., Aung, A., Choi, H.-S., Hyun, H. J., & Park, B. B. (2019). Comparison of litterfall production in three forest types in Jeju Island, South Korea. *Journal of Forestry Research*, *31*(3), 945-952. http://dx.doi.org/10.1007/s11676-019-00929-6.

Andrade, A. G., Costa, G. S., & Faria, S. M. (2000). Deposição e decomposição da serapilheira em povoamentos de Mimosa caesalpiniifolia, *Acacia mangium* e *Acacia holosericea* com quatro anos de idade em Planossolo. *Revista Brasileira de Ciência do Solo*, *24*(4), 777-785. http://dx.doi.org/10.1590/S0100-06832000000400010.

Barbosa, V., Barreto-Garcia, P., Gama-Rodrigues, E., & Paula, A. D. (2017). Biomassa, carbono e nitrogênio na serapilheira acumulada de florestas plantadas e nativa. *Floresta e Ambiente*, *24*, e20150243. http://dx.doi.org/10.1590/2179-8087.024315.

Berg, B., & McClaugherty, C. (2008). *Plant litter: decomposition, humus formation, carbon sequestration* (No. 04, QH541. 5. S6, B4 2008). Berlin: Springer.

Berg, B., Lönn, M., Ni, X., Sun, T., Dong, L., Gaitnieks, T., Virzo De Santo, A., & Johansson, M. B. (2022). Decomposition rates in late stages of Scots pine and Norway spruce needle litter: influence of nutrients and substrate properties over a climate gradient. *Forest Ecology and Management*, *522*, 120452. http://dx.doi.org/10.1016/j.foreco.2022.120452.

Binkley, D., Campoe, O. C., Alvares, C., Carneiro, R. L., Cegatta, Í., & Stape, J. L. (2017). The interactions of climate, spacing and genetics on clonal *Eucalyptus* plantations across Brazil and Uruguay. *Forest Ecology and Management*, *405*, 271-283. http://dx.doi.org/10.1016/j.foreco.2017.09.050.

Booth, T. H. (2013). Eucalypt plantations and climate change. *Forest Ecology and Management*, *301*, 28-34. http://dx.doi.org/10.1016/j.foreco.2012.04.004.

Boscardin, J., Garlet, J., & Costa, E. C. (2012). Mirmecofauna epigéica (Hymenoptera: Formicidae) em plantios de *Eucalyptus* spp. (Myrtales: Myrtaceae) na região oeste do estado do Rio Grande do Sul, Brasil. *Entomotrópica*, *27*(3), 119-128.

Carvalho, D. C., Pereira, M. G. G., Toledo, L. O., Simon, C. A., Rodrigues, J. S., Fernandes, J. C. F., & Silva Neto, E. C. (2017). Ciclagem de nutrientes de um plantio de eucalipto em regeneração de espécies nativas no sub-bosque. *Floresta*, *47*(1), 17-28. http://dx.doi.org/10.5380/rf.v47i1.43652.

Chaturvedi, O. P., & Singh, J. S. (1987). The structure and function of pine forest in Central Himalaya. I. Dry matter dynamics. *Annals of Botany*, *60*(3), 237-252. http://dx.doi.org/10.1093/oxfordjournals.aob.a087442.

Cizungu, L., Staelens, J., Huygens, D., Walangululu, J., Muhindo, D., Van Cleemput, O., & Boeckx, P. (2014). Litterfall and leaf litter decomposition in a central African tropical mountain forest and Eucalyptus plantation. *Forest Ecology and Management*, *326*, 109-116. http://dx.doi.org/10.1016/j.foreco.2014.04.015.

Correia, M. E., & Oliveira, L. C. M. (2000). *Fauna de solo: aspectos gerais e metodológicos.* Seropédica: Embrapa Agrobiologia.

Dick, G., & Schumacher, M. V. (2020). Litterfall in the semideciduous seasonal forest in southern Brazil. *Floresta e Ambiente*, *27*(2), 1-7. http://dx.doi.org/10.1590/2179-8087.029818.

Elli, E. F., Sentelhas, P. C., Freitas, C. H., Carneiro, R. L., & Alvares, C. A. (2019). Intercomparison of structural features and performance of *Eucalyptus* simulation models and their ensemble for yield estimations. *Forest Ecology and Management*, *450*, 117493. http://dx.doi.org/10.1016/j.foreco.2019.117493.

Ernani, P. R., Almeida, J. D., & Santos, F. D. (2007). Potássio. In R. F. Novais, V. H. Alvarez, N. F. Barros, R. L. F. Fontes, R. B. Cantarutti & J. C. L. Neves (Eds.), *Fertilidade do solo* (1ª ed.). Viçosa: Sociedade Brasileira de Ciência do Solo.

Eufrade Junior, H. J., Melo, R. X., Sartori, M. M. P., Guerra, S. P. S., & Ballarin, A. W. (2016). Sustainable use of eucalypt biomass grown on short rotation coppice for bioenergy. *Biomass and Bioenergy*, *90*, 15-21. http://dx.doi.org/10.1016/j.biombioe.2016.03.037.

Ferreira, M. L., Silva, J. L., Pereira, E. E., & Lamano-Ferreira, A. P. D. N. (2014). Litter fall production and decomposition in a fragment of secondary Atlantic Forest of São Paulo, SP, southeastern Brazil. *Revista Árvore*, *38*(4), 591-600. http://dx.doi.org/10.1590/S0100-67622014000400002.

Flores, T. B., Alvares, C. A., Souza, V. C., & Stape, J. L. (2016). *Eucalyptus no Brasil: zoneamento climático e guia para identificação* (447 p.). Piracicaba: IPEF.

Food and Agriculture Organization – FAO. (2020). *Global forest resources assessment, global forest resources assessment*. Rome: FAO. http://dx.doi.org/10.4060/ca8753en.

Gama-Rodrigues, A. C., & Barros, N. F. (2002). Ciclagem de nutrientes em floresta natural e em plantios de eucalipto e de dandá no sudeste da Bahia, Brasil. *Revista Árvore*, *26*(2), 193-207.

Garlet, J., Costa, E. C., & Boscardin, J. (2016). Levantamento da entomofauna em plantios de *Eucalyptus* spp. por meio de armadilha luminosa em São Francisco de Assis-RS. *Ciência Florestal*, *26*(2), 365-374. http://dx.doi.org/10.5902/1980509822737.

Giesselmann, U. C., Martins, K. G., Brändle, M., Schädler, M., Marques, R., & Brandl, R. (2011). Lack of home-field advantage in the decomposition of leaf litter in the Atlantic Rainforest of Brazil. *Applied Soil Ecology*, *49*, 5-10. http://dx.doi.org/10.1016/j.apsoil.2011.07.010.

González-Rodríguez, H., Ramírez-Lozano, R. G., Cantú-Silva, I., Gómez-Meza, M. V., Estrada-Castillón, E., & Arévalo, J. R. (2017). Deposition of litter and nutrients in leaves and twigs in different plant communities of northeastern Mexico. *Journal of Forestry Research*, *29*(5), 1307-1314. http://dx.doi.org/10.1007/s11676-017-0553-x.

Goya, J. F., Frangi, J. L., Pérez, C., & Dalla Tea, F. (2008). Decomposition and nutrient release from leaf litter in Eucalyptus grandis plantations on three different soils in Entre Ríos, Argentina. *Bosque*, *29*(3), 217-226. http://dx.doi.org/10.4067/S0717-92002008000300005.

Guo, L. B., & Sims, R. E. H. (1999). Litter decomposition and nutrient release via litter decomposition in New Zealand eucalypt short rotation forests. *Agriculture, Ecosystems & Environment*, *75*(1-2), 133-140. http://dx.doi.org/10.1016/S0167-8809(99)00069-9.

Guo, L. B., & Sims, R. E. H. (2002). Eucalypt litter decomposition and nutrient release under a short rotation forest regime and effluent irrigation treatments in New Zealand: II. Internal effects. *Soil Biology & Biochemistry*, *34*(7), 913-922. http://dx.doi.org/10.1016/S0038-0717(02)00023-8.

Hobbie, S. E., Eddy, W. C., Buyarski, C. R., Adair, E. C., Ogdahl, M. L., & Weisenhorn, P. (2012). Response of decomposing litter and its microbial community to multiple forms of nitrogen enrichment. *Ecological Monographs*, *82*(3), 389-405. http://dx.doi.org/10.1890/11-1600.1.

Indústria Brasileira de Árvores – IBÁ. (2023). *Relatório anual 2023.* Brasília.

Kolm, L., & Poggiani, F. (2003). Ciclagem de nutrientes em povoamentos de Eucalyptus grandis submetidos à prática de desbastes progressivos. *Scientia Forestalis*, (63), 79-93.

Kulmann, M. S. S., Eufrade-Junior, H. J., Dick, G., Schumacher, M. V., de Azevedo, G. B., Azevedo, G. T. D. O. S., & Guerra, S. P. S. (2022). Belowground biomass harvest influences biomass production, stock, export and nutrient use efficiency of second rotation *Eucalyptus* plantations. *Biomass and Bioenergy*, *161*, 106476. http://dx.doi.org/10.1016/j.biombioe.2022.106476.

Ma, N., Ji, Y., Yue, K., Peng, Y., Li, C., Zhang, H., Ma, Y., Wu, Q., & Li, Y. (2023). Effect of the seasonal precipitation regime on shrub litter decomposition in a subtropical forest. *Forest Ecology and Management*, *548*, 121423. http://dx.doi.org/10.1016/j.foreco.2023.121423.

Malavolta, E. (2006). *Manual de nutrição mineral de plantas* (Vol. 1). São Paulo: Agronômica Ceres.

Michopoulos, P., Kaoukis, K., Karetsos, G., Grigoratos, T., & Samara, C. (2019). Nutrients in litterfall, forest floor and mineral soils in two adjacent forest ecosystems in Greece. *Journal of Forestry Research*, *31*(1), 291-301. http://dx.doi.org/10.1007/s11676-019-00952-7.

Myburg, A. A., Grattapaglia, D., Tuskan, G. A., Hellsten, U., Hayes, R. D., Grimwood, J., Jenkins, J., Lindquist, E., Tice, H., Bauer, D., Goodstein, D. M., Dubchak, I., Poliakov, A., Mizrachi, E., Kullan, A. R., Hussey, S. G., Pinard, D., van der Merwe, K., Singh, P., van Jaarsveld, I., Silva-Junior, O. B., Togawa, R. C., Pappas, M. R., Faria, D. A., Sansaloni, C. P., Petroli, C. D., Yang, X., Ranjan, P., Tschaplinski, T. J., Ye, C. Y., Li, T., Sterck, L., Vanneste, K., Murat, F., Soler, M., Clemente, H. S., Saidi, N., Cassan-Wang, H., Dunand, C., Hefer, C. A., Bornberg-Bauer, E., Kersting, A. R., Vining, K., Amarasinghe, V., Ranik, M., Naithani, S., Elser, J., Boyd, A. E., Liston, A., Spatafora, J. W., Dharmwardhana, P., Raja, R., Sullivan, C., Romanel, E., Alves-Ferreira, M., Külheim, C., Foley, W., Carocha, V., Paiva, J., Kudrna, D., Brommonschenkel, S. H., Pasquali, G., Byrne, M., Rigault, P., Tibbits, J., Spokevicius, A., Jones, R. C., Steane, D. A., Vaillancourt, R. E., Potts, B. M., Joubert, F., Barry, K., Pappas, G. J., Strauss, S. H., Jaiswal, P., Grima-Pettenati, J., Salse, J., Van de Peer, Y., Rokhsar, D. S., & Schmutz, J. (2014). The genome of *Eucalyptus grandis. Nature*, *510*(7505), 356-362. PMid:24919147. http://dx.doi.org/10.1038/nature13308.

Olson, J. S. (1963). Energy storage and the balance of producers and decomposers in ecological systems. *Ecology*, *44*(2), 322-331. http://dx.doi.org/10.2307/1932179.

Pires, L. A., Britez, R. M. D., Martel, G., & Pagano, S. N. (2006). Produção, acúmulo e decomposição da serapilheira em uma restinga da Ilha do Mel, Paranaguá, PR, Brasil. *Acta Botanica Brasílica*, *20*(1), 173-184. http://dx.doi.org/10.1590/S0102-33062006000100016.

Poggiani, F. (1985). Ciclagem de nutrientes em ecossistemas de plantações florestais de *Eucalyptus* e *Pinus*: implicações silviculturais. *IPEF*, (31), 33-40.

R Core Team. (2021). *R: a language and environment for statistical computing.* Vienna: R Foundation for Statistical Computing.

Rosa, T. F. D., Scaramuzza, W. L. M. P., Feitosa, I. P., & Abreu, F. F. M. (2017). Produção e decomposição de serapilheira em povoamentos de teca no estado de Mato Grosso, Brasil. *Ciência Florestal*, *27*(4), 1117-1127. http://dx.doi.org/10.5902/1980509830288.

Santos, H. G. (2013). *Sistema Brasileiro de Classificação de Solos* (3ª ed., 353 p.). Brasília: Embrapa.

Santos, J. C., Schumacher, M. V., Witschoreck, R., Araújo, E. F., & Lopes, V. G. (2014). Nutrientes na serapilheira acumulada em um povoamento de *Eucalyptus saligna* Smith em São Grabriel, RS. *Revista Ecologia e Nutrição Florestal-ENFLO*, *2*(1), 1-8. http://dx.doi.org/10.5902/2316980X15045.

Schilling, E. M., Waring, B. G., Schilling, J. S., & Powers, J. S. (2016). Forest composition modifies litter dynamics and decomposition in regenerating tropical dry forest. *Oecologia*, *182*(1), 287-297. http://dx.doi.org/10.1007/s00442-016-3662-x.

Schumacher, M. V., & Viera, M. (2015). Ciclagem de nutrientes em plantações de eucalipto. In M. V. Schumacher & M. Viera (Eds.), *Silvicultura do eucalipto no Brasil* (pp. 273-307). Santa Maria: UFSM.

Scoriza, R. N., & Piña-Rodrigues, F. C. M. (2014). Influência da precipitação e temperatura do ar na produção de serapilheira em trecho de Floresta Estacional em Sorocaba, SP. *Floresta*, *44*(4), 687-696. http://dx.doi.org/10.5380/rf.v44i4.34274.

Silva, W. B., Périco, E., Dalzochio, M. S., Santos, M., & Cajaiba, R. L. (2018). Are litterfall and litter decomposition processes indicators of forest regeneration in the neotropics? Insights from a case study in the Brazilian Amazon. *Forest Ecology and Management*, *429*, 189-197. http://dx.doi.org/10.1016/j.foreco.2018.07.020.

Skorupa, A. L. A., Barros, N. F. D., & Neves, J. C. L. (2015). Forest litter decomposition as affected by eucalyptus stand age and topography in south-eastern Brazil. *Revista Árvore*, *39*(6), 1055-1064. http://dx.doi.org/10.1590/0100-67622015000600008.

Subedi, P., Jokela, E. J., Vogel, J. G., & Martin, T. A. (2019). Sustained productivity of intensively managed loblolly pine plantations: persistence of fertilization and weed control effects across rotations. *Forest Ecology and Management*, *446*, 38-53. http://dx.doi.org/10.1016/j.foreco.2019.05.025.

Taiz, L., Zeiger, E., Møller, I. M., & Murphy, A. (2017). *Fisiologia e desenvolvimento vegetal.* Porto Alegre: Artmed.

Tedesco, M. J., Gianello, C., Bissani, C. A., Bohnen, H., & Volkweiss, S. J. (1995). *Análises de solo, plantas e outros materiais* (Vol. 5, 174 p.). Porto Alegre: UFRGS.

Viera, M., Schumacher, M. V., & Caldeira, M. V. W. (2013). Dinâmica de decomposição e nutrientes em plantio de *Eucalyptus urophylla* × *Eucalyptus globulus* no sul do Brasil. *Floresta e Ambiente*, *20*, 351-360. http://dx.doi.org/10.4322/floram.2013.021.

Xu, D., Yang, Z., & Zhang, N. 2004. *Effects of site management on tree growth and soil properties of a second-rotation plantation of Eucalyptus urophylla in Guangdong province, China.* Bogor: CIFOR. Retrieved in 2021, October 19, from http://www.cifor.org/publications/pdf_files/Books/BKallio0801.pdf

Zaia, F. C., & Gama-Rodrigues, A. C. (2004). Ciclagem e balanço de nutrientes em povoamentos de eucalipto na região norte fluminense. *Revista Brasileira de Ciência do Solo*, *28*(5), 843-852. http://dx.doi.org/10.1590/S0100-06832004000500007.

Zhou, L., Shalom, A.-D. D., Wu, P., Li, S., Jia, Y., & Ma, X. (2015). Litterfall production and nutrient return in different-aged Chinese fir (*Cunninghamia lanceolata*) plantations in South China. *Journal of Forestry Research*, *26*(1), 79-89. http://dx.doi.org/10.1007/s11676-014-0011-y.

Author contributions: MSSK: conceptualization, writing; GD: conceptualization, data curation, formal analysis, methodology; MVS: conceptualization, funding acquisition, supervision, writing.