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Clonal teak litter in tropical soil: decomposition, nutrient cycling, and biochemical composition

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ABSTRACT: Litter decomposition dynamics and nutrient release are also dependent on their biochemical composition, and such information is important for adequate nutritional management but is still incipient for plants like teak. This study aimed to evaluate the decomposition dynamics, nutrient release, and biochemical composition of clonal teak litter. The study was conducted in areas of clonal teak stands, in São José do Rio Claro, Mato Grosso, Brazil. Litter collectors were arranged in the area to collect material along the entire dry period. Subsequently, this litter was placed in litter bags, which were distributed in the area. The litter bags were collected every month, for 0.91 years, to determine the dry matter and mineral nutrient contents, in order to estimate the decomposition and nutrient release. Litter biochemical composition was determined at the times of 0, 0.25, 0.58, 0.75, and 0.91 years. Teak litter, essentially leaves, had a half-life time ($t_{1/2}$) of dry matter and C of 0.74 years, due to the high content of insoluble lignin, which corresponds to 2.28 Mg ha^{-1} of dry matter and 1.2 Mg ha^{-1} of C. The $t_{1/2}$ values of N and P release (1.20 and 1.01 years) were higher than those of K, Ca, and Mg (0.08, 0.47, and 0.66 years, respectively). Hence, the nutrient release rate of the litter followed the descending order: K > Ca > Mg > P > N. The litter biochemical composition at the end of the experimental period showed reductions of 18.7 % in polysaccharides and holocellulose, 56 % in polyphenols, 56.3 % in tannins, 22.2 % in extractives, and 28.5 % in soluble lignin; and increases of 25.6 % in insoluble lignin and 22.6 % in total lignin. These data are useful for the balance of carbon and mineral nutrients and to support fertilization management in teak plantations in low-fertility soils.

Keywords: *Tectona grandis*, litter quality, decomposition rate, mineralization of nutrients, immobilization of nutrients.

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INTRODUCTION

In forest ecosystems, litter plays a fundamental role in nutrient availability in soil. Litter biochemical composition, the physical-chemical environment, and the composition of the microorganism community are the three main characteristics that regulate litter decomposition. The nutrients released during this process can account for 67 to 87 % of the annual demand of forest species (Krishna and Mohan, 2017).

Deciduous forest species with broad and deciduous leaves have better strategies of adaptation to drought stress than perennial trees. In addition, the litter of deciduous species usually has higher contents of nutrients (Liu et al., 2014). Among these species that have been cultivated in tropical and subtropical regions, teak (*Tectona grandis*) occupies an important space in the market among those which produce wood (Kollert and Cherubini, 2012).

Teak belongs to the botanical family Lamiaceae and is classified as deciduous heliophyte, losing all leaves in the period of low precipitation (Schnell and Paludzyszyn Filho, 2010). It originated in the south and southeast regions of the Asian continent, with distribution in India, Myanmar, Thailand, and Laos (Pelissari et al., 2014). In the teak tree, the largest amount of nutrients is concentrated in the reproductive parts and leaves, whereas the lowest contents of some nutrients such as N, P, K, Ca, Mg, S, and Cl are found in the wood. This contributes to high rates of return of nutrients to the soil in its superficial layers, via litter deposition, which are again available for absorption by the plant (Kumar et al., 2009).

Evaluating the production and decomposition of teak litter in Nigeria, Egunjobi (1974) observed that six to eight months were necessary for the fallen leaves to decompose completely during the dry months. It was also verified that all the litter produced in one year completely decomposes within one year. The author also related the decomposition pattern to the edaphoclimatic conditions of other sites and observed divergence in the results, with a specific time of litter decomposition for each region.

The decomposition of litter from forest species is mainly influenced by its biochemical composition, with more labile compounds, such as polysaccharides, as well as more recalcitrant compounds, such as lignin, total polyphenols, tannins, among others. However, despite being considered recalcitrant, polyphenols and tannins can be leached from the litter to the soil depending on the forest species (Acero et al., 2010; Berg, 2014; Min et al., 2015).

In the literature, there are few studies with regular monitoring of decomposition and nutrient release in teak plantations, with only two in Brazil, Rosa et al. (2015) and Rosa et al. (2017), who conducted experiments in areas with seminal teak and found higher contents of nutrients deposited in the litter from seven-year-old plants, followed by five- and six-year-old plants. The order of nutrient contribution in the litter was Ca > N > K > Mg > P > S for all tree ages. In the international literature, there is the study of Das and Mondal (2016), who found nutrient release pattern of K > P > N in teak litter in India. In addition, these authors also determined organic compounds in the litter and found low lignin content and high N content, hence inferring that the material had less resistance to decomposition. However, due to the economic importance and expansion of the areas cultivated with teak, more information on litter decomposition, nutrient release, and organic compounds in tropical soils become necessary.

It is worth pointing out that information about the decomposition and nutrient release is important for the nutritional balance in the soil-plant system, particularly in plantations of clonal teak, which has gained space in recent years due to its higher productivity compared to seminal teak. We hypothesized that litter decomposition is slow in clonal

teak plantations, due to the higher contents of recalcitrant organic compounds, which delay the release of macronutrients. This study aimed to evaluate the decomposition dynamics, nutrient release, and biochemical composition of clonal teak litter.

MATERIALS AND METHODS

Study area

The experiment was carried out in a clonal teak stand, with the clones A1 and A3 randomly distributed in 126.83 ha, in 2010, at a density of 625 trees per hectare, with 4 × 4 m spacing between plants. The plantation is located in São José do Rio Claro, Mato Grosso, Brazil (13° 26' 49" S; 56° 43' 15" W; average altitude of 350 m) and belongs to the *Guavirá Industrial e Agroflorestal* company. The climate of the region is tropical hot and sub-humid, with five dry months, from May to September (Figure 1). The study area has a flat topography and the predominant soil order is *Latossolo Vermelho-Amarelo* (Oxisol) of sandy texture.

The original vegetation of the area was composed of a transition forest between the Amazon rainforest and Cerrado. The pasture was introduced in the area in 1960, with a transition to *capoeira* (Tupi-guarani term for the underbrush growing on an area of recently cleared scrubland), and clonal teaks were planted in 2010 (Figure 2).

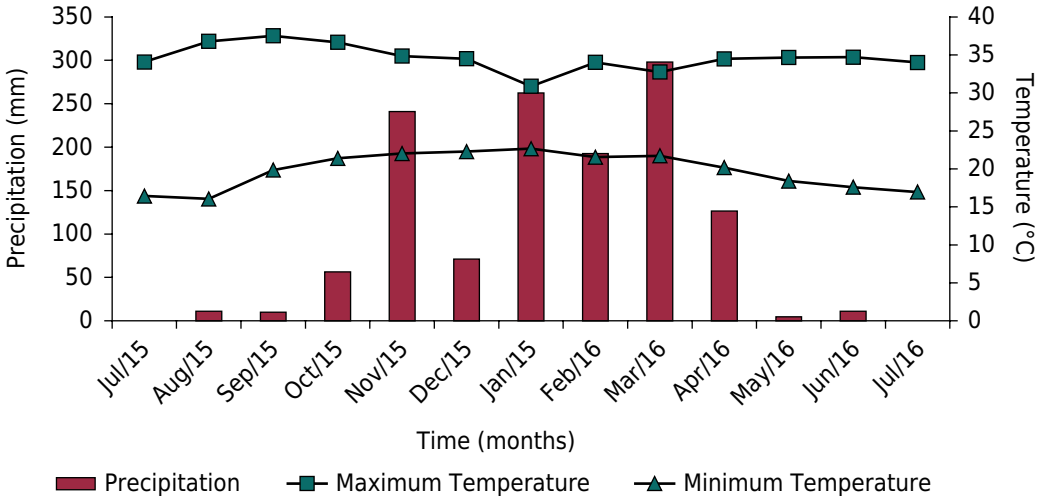

Figure 1. Climate data in the 2015-2016 period in the city of Diamantino, Mato Grosso, Brazil. Source: Inmet (2016).

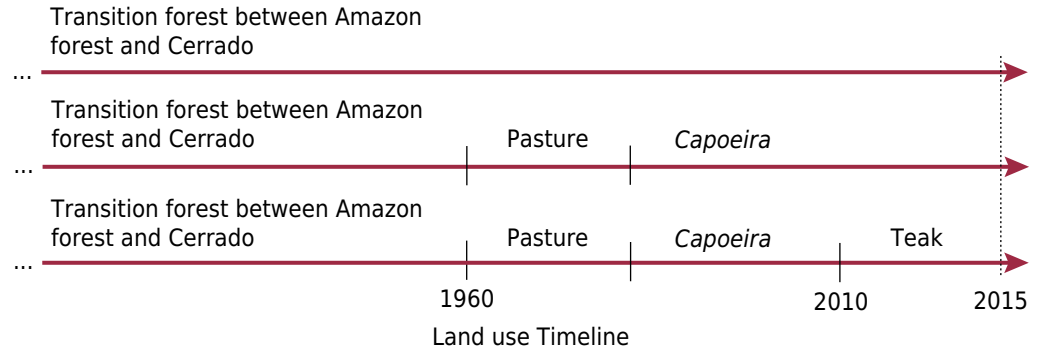

Figure 2. Chronosequence of the study area occupation until the teak experiment was set up in 2015.

Experimental design

The experiment was carried out in the period from August 2015 to July 2016, and the plots were distributed according to a systematic experimental design. Twelve litter collectors (1.0 m^2 each), constructed with 1.0 × 1.0 mm-mesh nylon screen, were randomly distributed in each plot, suspended at 0.80 m from the soil.

The stand was in the first rotation with teak planting. At teak planting, the area received fertilization and correction, which consisted of 6 Mg ha^{-1} of limestone, 270 kg ha^{-1} of 00-25-00 NPK, 30 kg ha^{-1} of FTE BR12 (Fritted Trace Elements, with 0.1 % Mo, 1.8 % B, 0.8 % Cu, 3 % Fe, 2 % Mn, and 9 % Zn), 200 kg ha^{-1} of 05-30-15 NPK, 30 kg of FTE CO (Fritted Trace Elements West Center, with 2 % B, 2 % Cu, 10 % Mn, and 15 % Zn), 40 kg ha^{-1} of ammonium sulfate, 5 kg ha^{-1} of Borogran 10 % B and 3 kg ha^{-1} of boric acid. Limestone was applied broadcast, 00-25-00 NPK was applied in 2 furrows beside the plant at approximately 0.30 m distance, and the other fertilizers were divided and applied in two holes beside the plant at 0.15 m distance, 30 days after planting. After one year, the following amounts and products were applied in two holes at 0.30 m distance from the plant: 200 kg ha^{-1} of 05-30-15 NPK, 60 kg ha^{-1} of KCl, 3 kg ha^{-1} of Borogran 10 % B, and 3 kg of boric acid. Two years after planting, 100 kg ha^{-1} of KCl were applied broadcast in the entire area.

In April 2015, soil samples were collected from the layers defined by the layers of 0.00-0.20, 0.20-0.40, and 0.40-0.60 m to evaluate fertility and texture (Table 1), according to the methods described by Defelipo and Ribeiro (1981) and Claessen (1997).

Experimental trial

Litter collectors were set up in April 2015 and, after approximately 90 days, in the dry period, all teak leaves had fallen. The material was composed of approximately 1-year-old leaves deposited in 12 collectors, which were used to obtain a composite sample in each plot. This sample was divided into portions of approximately 100 g and placed in 2-mm-mesh (nylon) litter bags, with dimensions of 0.20 × 0.20 m.

Seventy two litter bags were placed in direct contact with the soil randomly in each plot, and six litter bags were collected in each plot every month, for a period of 12 months, at the times: 0.00, 0.08, 0.16, 0.25, 0.33, 0.41, 0.50, 0.58, 0.66, 0.75, 0.83, and 0.91 years. The samples from the litter bags were cleaned to remove the adhered soil.

Table 1. Chemical and granulometric properties of the soil from the experimental area before the experiment

Layer	pH(H_2O)	C total	N total	P	K	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al^{3+}	SB
m		dag kg^{-1}		mg dm^{-3}		$cmol_c$ dm^{-3}				
0.00-0.20	5.58	0.89	0.06	1.00	6.75	0.58	0.38	0.18	3.25	0.95
0.20-0.40	5.05	0.57	0.04	0.50	6.25	0.13	0.13	0.45	3.05	0.25
0.40-0.60	4.85	0.44	0.02	0.30	5.25	0.03	0.08	0.48	2.80	0.10
Layer	**t**	**T**	**V**	**m**	**Prem**	**Clay**		**Silt**	**Sand**	
m	$cmol_c dm^{-3}$		%		mg L^{-1}	g kg^{-1}				
0.00-0.20	1.13	4.20	22.50	17.00	31.05	115.0		72.5	812.5	
0.20-0.40	0.70	3.30	8.50	61.75	29.18	150.0		75.0	775.0	
0.40-0.60	0.58	2.90	3.50	79.75	27.78	142.5		100.0	757.5	

pH(H_2O) at a soil:water ratio of 1:2.5; C total: oxidizing C with dichromate ($Cr_2O_7^{2-}$) in an acidic medium (Yeomans and Bremner, 1988); N: determined by the Kjeldahl method (Bremner and Mulvaney, 1982) and Tedesco et al. (1995); P and K extracted by Mehlich-1; Ca^{2+}, Mg^{2+}, and Al^{3+} extracted by KCl 1 mol L^{-1}; H+Al: calcium acetate extractant 0.5 mol L^{-1} (pH 7.0); SB: sum of bases (Ca^{2+}+Mg^{2+}+K^{+}); t: effective cation exchange capacity; T: cation exchange capacity at pH 7.0; V: base saturation; m: aluminum saturation; Prem: remaining phosphorus, equilibrium solution P method; clay and silt: sedimentation technique; and sand: Pipette Method with slow stirring.

Average teak trees (with DBH around the average) had a total height (Ht) of 13.72 m and a diameter of 19.48 cm at 1.30 m height from the soil (DBH). Before the decomposition of the plant material deposited in the collectors during the dry season, a sample was collected to characterize the litter with respect to the contents of nutrients and organic compounds (Table 2).

Nutritional analysis

The samples present in the monthly collected litter bags were dried at 65 °C until reaching constant weight, to determine the dry matter. Subsequently, these samples were crushed, homogenized, and subjected to nitric-perchloric digestion, in a 4:1 proportion of nitric acid:perchloric acid. Phosphorus was determined by colorimetry at 725 nm (Braga and Defelipo, 1974); S by turbidimetry of sulfates (Alvarez et al., 2001); Ca and Mg by atomic absorption spectrophotometry, and K by flame emission photometry. The N content was determined in sulfuric digestion extracts by the Kjeldahl method.

Determination of organic compounds and nutrients available in the soil

In five periods, corresponding to the times 0, 0.25, 0.58, 0.75, and 0.91 years, the total organic C was determined by oxidizing C with dichromate ($Cr_2O_7^{2-}$) in an acidic medium (Yeomans and Bremner, 1988), and then the C/N, C/P and C/S ratios were obtained. To determine the total carbon content, the amount of litter in the area was initially estimated using a rectangular frame (1 m^2). Ten samples were taken randomly, and the material was weighed to obtain dry matter. Then, the amount of material on the soil (kg ha^{-1}) was obtained. Afterward, the relationship between the carbon content in the litter bag and the amount of litter in the area over time was obtained, and carbon accumulation (kg ha^{-1}) was calculated.

Also, polysaccharides (POLS) were determined using the method based on the release of saccharide monomers through hydrolysis with sulfuric acid, estimated by colorimetry (Lowe, 1993); total polyphenols (POLP) and tannins (TAN) were determined by the Folin-Ciocalteu's procedure (Grubešić et al., 2005); extractives (EX) were obtained by acetone extraction using the Soxhlet apparatus (Abtcp, 1974); Klason lignin (Gomide and Demuner, 1986) separated into the content of insoluble lignin (ILIG), which is not solubilized during hydrolysis; and content of soluble lignin (SLIG), which remains in the filtered extract obtained in the lignin determination procedure, was determined

Table 2. Contents of macronutrients and organic compounds present in the clonal teak litter after decay of all leaves, in Oxisol

Macronutrients ans dry matter		Organic compounds	
Dry Matter (Mg ha^{-1})	5.16	POLS (g kg^{-1})	217.08
C (g kg^{-1})	400.50	POLP (g kg^{-1})	110.85
N (g kg^{-1})	7.30	TAN (g kg^{-1})	26.16
P (g kg^{-1})	0.50	EX (g kg^{-1})	8.14
K (g kg^{-1})	3.40	SLIG (g kg^{-1})	3.50
Ca (g kg^{-1})	17.70	ILIG (g kg^{-1})	35.71
Mg (g kg^{-1})	6.80	TLIG (g kg^{-1})	39.21
S (g kg^{-1})	0.60	HOLO (g kg^{-1})	56.13

C: oxidizing C with dichromate ($Cr_2O_7^{2-}$) in an acidic medium (Yeomans and Bremner, 1988); N: determined by the Kjeldahl; P: determined by colorimetry at 725 nm; K determined by flame emission photometry; Ca and Mg determined by atomic absorption spectrophotometry; S determined by turbidimetry of sulfates; POLS (polysaccharides): method of release of saccharide monomers through hydrolysis with H_2SO_4; POLP (polyphenols) and TAN (tannin) were determined by the Folin-Ciocalteu's procedure; EX (extractives) were obtained by acetone extraction using the Soxhlet apparatus; SLIG (soluble lignin) and ILIG (insoluble lignin): Klason lignin; TLIG (total lignin): summation between the contents of SLIG and ILIG; and HOLO (holocellulose): difference between the contents of EX and ILIG.

by spectroscopy in the ultraviolet region, as described by Goldschimid (1971); and holocellulose content (HOLO) was determined by the difference between the contents of extractives and insoluble lignin. These determinations were used to obtain the ratios C/N, C/P, C/S, LIG/N, LIG/P, LIG/POLP, and LIG+POLP/N.

Data analysis and model fitting

Data on contents of nutrients and organic compounds were presented by descriptive statistics (mean and standard deviation), whereas the relationships between nutrients were subjected to the Scott-Knott grouping test ($p<0.05$) (Ferreira, 2008). Pearson's correlations were calculated between the dry matter and the contents of organic compounds in the litter, C/N, C/N, C/P, C/S, LIG/N, LIG/P, LIG/POLP, and LIG+POLP/N ratios, as well as between the relative contents of nutrients and organic compounds in the litter.

The dry matter decomposed over time, the contents of nutrients, and the contents of organic compounds released by the litter were transformed into relative values from the originals (at time zero) and those determined in each period of evaluation, obtaining the remaining values. Mathematical models were fitted to the values of nutrient release, dry matter decomposition, total organic carbon content, and relative content of organic compounds (Table 3), which allowed obtaining the half-life times ($t_{1/2}$). The program CurveExpert 1.4 was used to fit the models.

RESULTS

Litter decomposition and release of macronutrients

The dry matter of clonal teak litter deposited inside the collectors was 5.16 Mg ha^{-1}, consisting mainly of leaves that fell during the dry period. The amount of other materials

Table 3. Nonlinear regression models fitted to values of litter decomposition, carbon content, and release of nutrients and organic compounds

Models	Form[(1)]	Description	Parameter definition
Exponential decay	$Y = Yo\ e^{-kx}$ $Y = Yo + ae^{-kx}$	The first model is known in soil science as Olson's (1963) and is used to describe the decomposition of straw residues. It is a simple equation with one major unknown, the rate constant (k). The second model is an adaptation of the first but is based on the same principle (Archontoulis and Miguez, 2015)	Y is the response variable (e.g., remaining dry matter), x is the explanatory variable (e.g., time), Yo is the initial or the maximum Y value, k is a rate constant that determines the steepness of the curve (e.g., decomposition constant). In the second model, a is the ordinate of the point at which the line intersects the y-axis when x is zero
Harris	$Y = 1/(a + bx^c)$	This is a yield-spacing model, used to evaluate both the decomposition of the litter and the organic compounds present in it (Vitale et al., 2019)	Y is the response variable (e.g., relative contents of N), x is the explanatory variable (e.g., time), a is the ordinate of the point at which the line intersects the y-axis when x is zero, b is the initial or the maximum Y value, and c is a rate constant that determines the steepness of the curve (e.g., the relative content of N)

[(1)] Adjustment factor has been multiplied for some models, it does not disturb the shape of the curve and does not interfere with the value of the parameters.

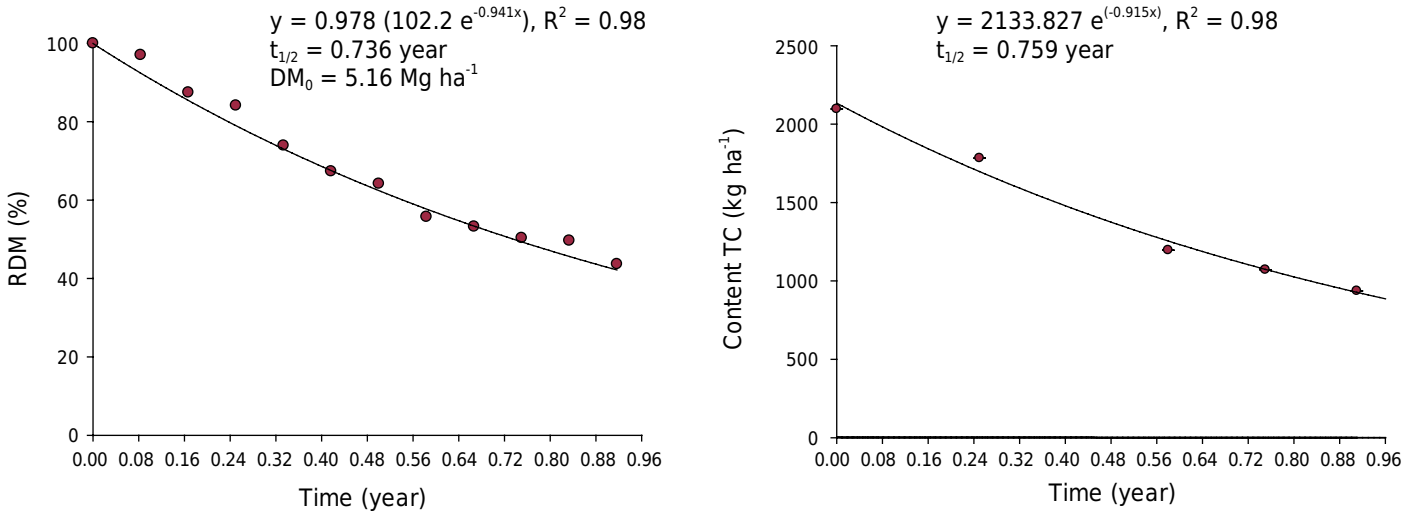

Figure 3. Remaining dry matter (RDM, %) (a) and total carbon content (TC, kg ha^{-1}) (b) in the litter of clonal teak plantation as a function of time. DM0: dry matter at time zero.

Table 4. Contents of macronutrients and C/N, C/P, C/S, N/P ratios in the clonal teak litter vs. time

Time	C	N	P	K	Ca	Mg	S	C/N[(1)]	C/P[(1)]	C/S[(1)]
year				g kg^{-1}						
0.000	400.5±1.1	7.3±0.2	0.5±0.0	3.4±0.6	17.7±1.9	6.8±0.7	0.6±0.0	54.9b±1.9	681.5a±29.2	641.9b±31.9
0.083		6.6±0.4	0.5±0.0	1.5±0.2	16.3±1.0	5.3±0.1	1.0±0.0			
0.166		6.9±0.2	0.5±0.0	1.4±0.2	16.7±1.2	5.4±0.2	1.0±0.0			
0.250	400.8±0.5	6.6±0.2	0.6±0.0	1.8±0.5	11.7±0.3	8.3±0.9	0.4±0.0	61.8a±1.9	678.5a±31.4	964.3a±70.5
0.333		6.9±0.2	0.5±0.0	1.2±0.2	12.8±0.6	8.5±0.3	0.3±0.0			
0.416		7.9±0.2	0.5±0.0	0.9±0.1	13.5±0.6	8.1±0.3	0.3±0.0			
0.500		7.8±0.4	0.6±0.0	0.6±0.1	12.9±0.3	7.7±0.2	0.3±0.0			
0.583	413.0±0.9	8. 5±0.4	0.6±0.0	0.6±0.0	14.3±1.0	4.1±0.4	0.8±0.0	48.5c±1.7	640.6a±41.3	487.2c±17.9
0.666		8.6±0.4	0.6±0.0	0.5±0.0	15.0±0.8	4.5±0.4	0.8±0.0			
0.750	412.0±0.7	8.5±0.3	0.6±0.0	0.5±0.0	15.0±0.5	4.4±0.2	0.7±0.0	48.3c±2.1	628.3a±42.4	531.1c±23.3
0.833		8.6±0.9	0.6±0.1	0.5±0.1	14.8±1.4	4.6±0.8	0.7±0.0			
0.916	413.0±0.7	8.8±1.2	0.6±0.1	0.5±0.1	14.9±1.2	4.5±0.7	0.7±0.1	47.3c±2.9	649.5a±43.3	519.5c±13.84

[(1)] Significant at 1 % probability level by F test. Means followed by the same letter in the column do not differ by Scott-Knott test at 5 % probability level. Means ± standard error, n = 4.

such as branches, twigs, and fruits was negligible. This material had decomposition of 50 % of the initial residue ($t_{1/2}$) in 0.74 year, corresponding to 2.28 Mg ha^{-1} of DM (Figure 3a), with an exponential response in litter decomposition dynamics. The carbon content in the clonal teak litter also showed the same behavior, with a reduction of 55 % during the evaluation time (Figure 3b) and $t_{1/2}$ similar to that of RDM.

The contents of carbon and other nutrients in the litter varied according to the time of decomposition of the plant residue (Table 4). Over time, the contents of C, N, P, K, Ca, Mg, and S varied respectively from 400.5 to 413 g kg^{-1}, 7.3 to 8.8 g kg^{-1}, 0.5 to 0.6 g kg^{-1}, 3.4 to 0.5 g kg^{-1}, 17.7 to 14.9 g kg^{-1}, 6.8 to 4.5 g kg^{-1} and 0.6 to 0.7 g kg^{-1}. Thus, the contents of C, N, P, and S increased and stabilized from 0.58 years, while the contents of K, Ca, and Mg decreased during the evaluation. The C/N, C/P, and C/S ratios decreased at the end of the evaluation period compared to the initial values, with a similar behavior between C/N and C/S ratios, in which three groups were formed and the group with the lowest carbon:nutrient ratio occurred between the times of 0.583 and 0.916 years.

Compared to the initial values, the relative contents of N, P, K, Ca, and Mg in teak litter decreased by 51.5, 46.7, 7.7, 37.7, and 29.3 %, respectively, as a function of time (Figure 4). For S, although the C/S ratio indicated immobilization (Table 4), it was not possible to fit a model to its relative content as a function of time. The relative content of K indicates that there was faster release, with $t_{1/2}$ of 0.087 years, in comparison to the other nutrients. Similarly, Ca and Mg had $t_{1/2}$ of 0.474 years and 0.662 years, respectively, i.e., they were released faster than N, with $t_{1/2}$ of 1.2 years, and P, with $t_{1/2}$ of 1.01 years.

Dynamics of organic compounds in the litter

The organic compounds of teak litter influenced its decomposition over time. During the evaluation period, the following reductions were observed: polyphenols from 110.8 to 48.7 g kg^{-1}, tannins from 26.1 to 11.4 g kg^{-1}, polysaccharides from 217.0 to 176.4 g kg^{-1}, extractives from 8.1 to 6.3 g kg^{-1}, soluble lignin from 3.5 to 2.5 g kg^{-1} and holocellulose from 56.1 to 45.6 g kg^{-1} (Table 5). It is worth pointing out that, among all the organic compounds evaluated, the concentrations of insoluble and total lignins increased over time from 35.7 to 48.0 g kg^{-1} and from 39.2 to 50.7 g kg^{-1}, respectively, and the relative contents of these compounds in the litter were higher at the end of the evaluation, compared to the others (Figure 5).

Most organic compounds had a close and positive correlation with DM (Table 6), except for soluble lignin, which was not significantly correlated, and the insoluble and total lignin's, which were negatively correlated. The C/N and C/S ratios were positively correlated with DM, whereas the LIG/P and LIG/POLP ratios were negatively correlated with DM, probably because of the negative correlation between TLIG and DM.

The content of polyphenols decreased by 19.6 % compared to the initial value (Figure 5). Polyphenols were positively correlated with other organic compounds such as tannins, extractives, holocellulose, and the LIG+POLP/N ratio, and were negatively correlated with insoluble lignin and the LIG/POLP ratio (Table 6). In addition, polyphenols had a close positive correlation with all macronutrients, especially with N (Table 7). The tannin content decreased by 13 % at end of the experiment (Figure 5). This organic compound showed a close positive correlation only with polyphenols, extractives, and LIG+POLP/N ratio, and a negative correlation with LIG/POLP (Table 6). Table 7 also shows the close correlation of tannins with the macronutrients, except for Mg.

Despite the drastic reduction of polyphenols and tannins in the first months of decomposition, the relative content of polysaccharides stabilized up to 0.25 years and decreased at 0.91 years, reaching 36 % of the initial value (Figure 5). Polysaccharides showed a close positive correlation with the contents of extractives, holocellulose, C/N and C/S ratios, and with all macronutrients apart from Ca, and a negative correlation with the insoluble lignin content and with the LIG/P and LIG/POLP ratios (Tables 6 and 7).

The relative contents of extractives and holocellulose decreased slowly up to 0.25 years and then decreased considerably until reaching 34 and 35 %, respectively (Figure 5). Similarly, the soluble lignin content decreased over time. In addition, there was also a close negative correlation between insoluble lignin and extractives, holocellulose, C/N, and C/S (Table 6). These compounds also influence the nutrient release (Table 7), due to the close positive correlation between N, P, K, Ca, and Mg and the extractives and holocellulose, and the close negative correlation between these nutrients and the insoluble lignin.

DISCUSSION

The decomposition of the litter deposited annually in clonal teak stand (Figure 3a) indicates that the time to decompose all the material is possibly longer than 1.25 years,

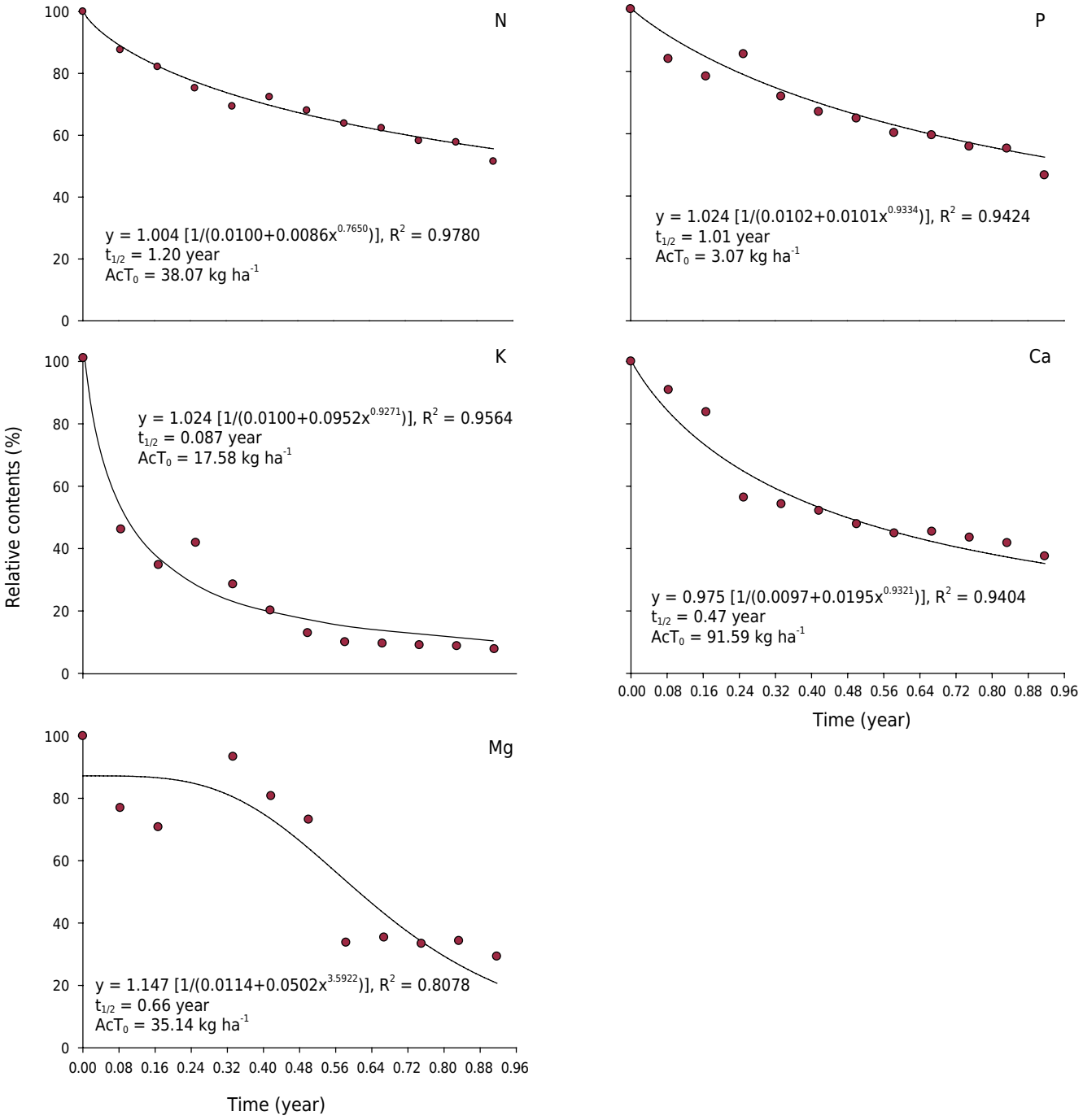

Figure 4. Relative contents of N, P, K, Ca, and Mg in clonal teak litter vs. time. AcT0: nutrient accumulation at time zero.

Table 5. Contents of polyphenols (POLP), tannins (TAN), polysaccharides (POLS), extractives (EX), soluble lignin (SLIG), insoluble lignin (ILIG), total lignin (TLIG), and holocellulose (HOLO) in clonal teak litter vs. time (T)

T	POLP	TAN	POLS	EX	SLIG	ILIG	TLIG	HOLO
year	g kg^{-1}							
0.00	110.8±5.3	26.1±4.5	217.0±17.1	8.1±0.3	3.5±0.2	35.7±1.0	39.2±0.6	56.1±0.7
0.25	53.6±5.1	7.6±4.0	245.1±1.7	7.8±0.2	2.6±0.2	34.6±2.6	37.3±2.1	57.5±2.4
0.58	42.7±6.3	14.5±2.7	212.2±4.1	6.1±0.1	2.3±0.2	45.3±0.4	49.2±0.6	48.4±0.5
0.75	49.2±14.5	9.4±2.5	193.4±6.7	5.5±0.4	2.4±0.1	46.4±0.8	49.3±0.5	48.0±0.9
0.91	48.7±3.1	11.4±3.8	176.4±10.2	6.3±0.1	2.5±0.1	48.0±0.1	50.7±1.3	45.6±0.1

Means ± standard error, n = 4. POLP and TAN were determined by the Folin Ciocalteu's procedure; POLS: method of release of saccharide monomers through hydrolysis with H_2SO_4; EX were obtained by acetone extraction using the Soxhlet apparatus; SLIG and ILIG: Klason lignin; TLIG: summation between the contents of SLIG and ILIG; and HOLO: difference between the contents of EX and ILIG.

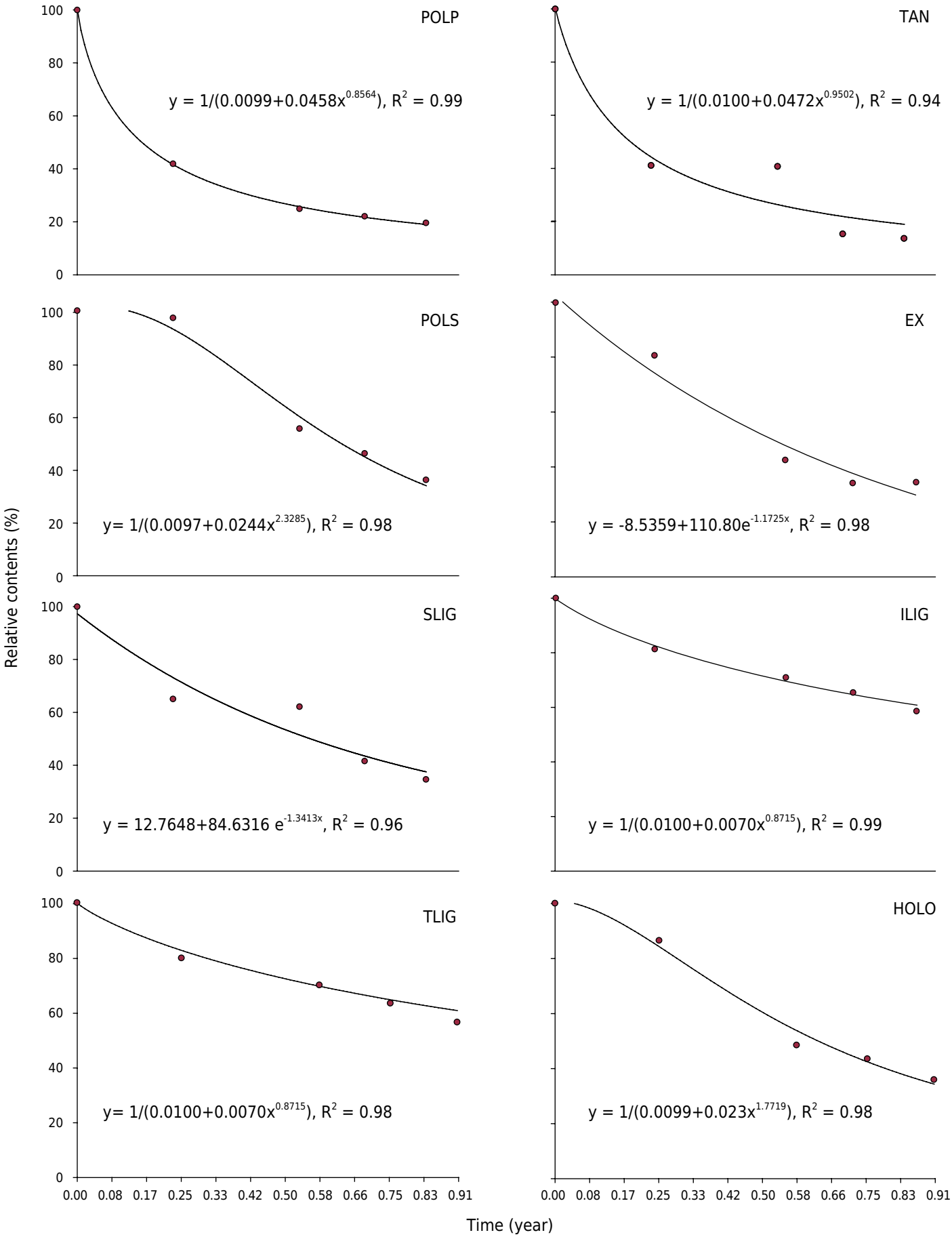

Figure 5. Relative contents of polyphenols (POLP), tannins (TAN), polysaccharides (POLS), extractives (EX), soluble lignin (SLIG), insoluble lignin (ILIG), total lignin (TLIG), and holocellulose (HOLO) in clonal teak litter vs. time.

Table 6. Coefficients of Pearson correlation between dry matter (DM, g), polysaccharides (POLS, g kg^{-1}), polyphenols (POLP, g kg^{-1}), tannin (TAN, g kg^{-1}), extractives (EX, dag kg^{-1}), soluble lignin (SLIG, dag kg^{-1}), insoluble lignin (ILIG, dag kg^{-1}), total lignin (TLIG, dag kg^{-1}), holocellulose (HOLO, dag kg^{-1}), and C/N, C/P, C/S, LIG/N, LIG/P, LIG/POLP and LIG+POLP/N ratios of clonal teak vs. time

Variables	POLS	POLP	TAN	EX	SLIG	ILIG	TLIG	HOLO	C/N	C/P	C/S	LIG/N	LIG/P	LIG/ POLP	LIG+ POLP/N
DM	0.60**	0.70**	0.44º	0.85**	0.09^{ns}	-0.90**	-0.41º	0.87**	0.72**	0.37^{ns}	0.58**	-0.34^{ns}	-0.55*	-0.75**	0.31^{ns}
POLS	-	0.23^{ns}	0.08^{ns}	0.50*	0.09^{ns}	-0.61**	-0.23^{ns}	0.61**	0.53*	0.04^{ns}	0.58**	-0.08^{ns}	-0.47*	-0.45*	0.18^{ns}
POLP	-	-	0.75**	0.62**	0.17^{ns}	-0.51*	-0.18^{ns}	0.47*	0.25^{ns}	0.13^{ns}	0.06^{ns}	-0.35^{ns}	-0.34^{ns}	-0.86**	0.41º
TAN	-	-	-	0.40º	0.31^{ns}	-0.30^{ns}	0.14^{ns}	0.26^{ns}	0.21^{ns}	0.14^{ns}	-0.22^{ns}	-0.15^{ns}	-0.19^{ns}	-0.62**	0.44*
EX	-	-	-	-	-0.02^{ns}	-0.85**	-0.39º	0.78**	0.68**	0.46*	0.66**	-0.39º	-0.47*	-0.79**	0.18^{ns}
SLIG	-	-	-	-	-	0.04^{ns}	0.74**	-0.05^{ns}	-0.13^{ns}	-0.33^{ns}	-0.27^{ns}	0.16^{ns}	-0.06^{ns}	-0.22^{ns}	0.33^{ns}
ILIG	-	-	-	-	-	-	0.47*	-0.99**	-0.77**	-0.25^{ns}	-0.73**	0.53*	0.77**	0.67**	-0.00^{ns}
TLIG	-	-	-	-	-	-	-	-0.48*	-0.36^{ns}	-0.30^{ns}	-0.44*	0.39º	0.30^{ns}	0.21^{ns}	0.22^{ns}
HOLO	-	-	-	-	-	-	-	-	0.76**	0.19^{ns}	0.72**	-0.54*	-0.81**	-0.62**	-0.04^{ns}
C/N	-	-	-	-	-	-	-	-	-	0.55*	0.77**	0.05^{ns}	-0.40º	-0.47*	0.37^{ns}
C/P	-	-	-	-	-	-	-	-	-	-	0.42º	0.22^{ns}	0.37^{ns}	-0.24^{ns}	0.35^{ns}
C/S	-	-	-	-	-	-	-	-	-	-	-	-0.15^{ns}	-0.43 º	-0.34^{ns}	0.01^{ns}
LIG/N	-	-	-	-	-	-	-	-	-	-	-	-	0.70**	0.34^{ns}	0.69**
LIG/P	-	-	-	-	-	-	-	-	-	-	-	-	-	0.42º	0.33^{ns}
LIG/POLP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.36^{ns}

^{ns} not significant; ** significant at 1 %; * significant at 5 %; º significant at 10 %.

Table 7. Coefficients of Pearson correlation between macronutrients (N, P, K, Ca, Mg, and S, %), polysaccharides (POLS, g kg^{-1}), polyphenols (POLP, g kg^{-1}), tannin (TAN, g kg^{-1}), extractives (EX, dag kg^{-1}), soluble lignin (SLIG, dag kg^{-1}), insoluble lignin (ILIG, dag kg^{-1}), total lignin (TLIG, dag kg^{-1}), and holocellulose (HOLO, dag kg^{-1}) during the one year of decomposition of clonal teak litter

Variables	N	P	K	Ca	Mg	S
POLS	0.48*	0.60**	0.39º	0.35^{ns}	0.63**	0.18^{ns}
POLP	0.80**	0.71**	0.84**	0.82**	0.59**	0.78**
TAN	0.52*	0.47*	0.59**	0.69**	0.33^{ns}	0.75**
EX	0.75**	0.77**	0.77**	0.66**	0.80**	0.41 º
SLIG	0.20^{ns}	0.20^{ns}	0.11^{ns}	0.12^{ns}	0.02^{ns}	0.44*
ILIG	-0.79**	-0.90**	-0.74**	-0.69**	-0.92**	-0.41º
TLIG	-0.33^{ns}	-0.34^{ns}	-0.39º	-0.36^{ns}	-0.44*	-0.00^{ns}
HOLO	0.77**	0.89**	0.71**	0.67**	0.91**	0.40^{ns}

^{ns} not significant; ** significant at 1 %; * significant at 5 %; º significant at 10 %.

which was observed in India for the litter of teak leaves by Kumar et al. (2010). Other deciduous species also have longer decomposition times, as evidenced by Ramírez et al. (2014) for oak (0.844 years) compared to conifers such as pine (0.304 years) and cypress (0.479 years), and by Liu et al. (2016) for the deciduous species *C. pubescens*, *P. longipes*, and *Q. aliena* compared to perennial trees. Thus, deciduous species have a slower decomposition than perennial species, varying the decomposition time between species and the edaphoclimatic conditions. The carbon content in the teak litter also decomposed slowly (Figure 3b) since it is closely related to RDM decomposition (Figure 3a). This is consistent with Polyakova and Billor (2007), who observed in deciduous forests the loss of litter mass following the release of carbon, especially in the early stages of decomposition.

Nutrient dynamics can be controlled by different biological and physical factors, and the ratios (carbon:nutrients) indicate whether mineralization or immobilization of nutrients

is occurring in the residue (Table 4). The C/N and C/S ratios increased between the time zero (0) and 0.25 years due to the reductions in N and S contents in the litter in this period. However, as there was loss of mass (carbon-rich organic compounds), although the C/N, C/P, and C/S ratios were high and would indicate immobilization, it is likely that a microbiota adapted to decompose litter that is poor in N, P, and S. The immobilization of nutrients up to 0.25 years occurred due to the dry period and high temperatures (Figure 1); this process is commonly verified under these climatic conditions (Dolschak and Berger, 2020). Precipitation was intensified in the period from 0.32 to 0.75 years, which favors the higher activity of decomposers (Naik et al., 2017). Decomposers sequester carbon and nutrients from organic substrates and exchange inorganic nutrients with the environment to maintain their stoichiometric balance (Manzoni et al., 2010). In addition, physical losses of organic compounds by leaching and other processes may alter the nutrient content of the litter (Manzoni et al., 2012).

The critical ratios between carbon and mineral nutrients observed with their initial increment indicate that decomposers adapt to low nutrient conditions, exhibiting a reduction in carbon use efficiency (Manzoni et al., 2012). For eucalyptus litter, Ferreira et al. (2016) found high decomposition rates despite an initial C/N ratio of 120, so there was N immobilization. These authors attributed this result to the effect of specific microorganisms on litter decomposition. Nitrogen mineralization usually occurs when the C/N ratio is between 20:1 and 30:1 (Edmonds and Mikkelsen, 2010). In the present study during the entire evaluation period, it was possible to observe C/N ratio greater than the critical value for mineralization, evidencing the immobilization of N. The C/N ratio from 0.58 years was similar to that found in other deciduous species such as oak (Ramírez et al., 2014), yellow poplar, and elm (Polyakova and Billor, 2007).

The C/P ratio in teak litter was also limiting for the decomposition of the plant residue and release of P since it did not vary during the evaluation period and did not differ statistically between the evaluation times. During the entire evaluation period, the C/P ratio was higher than the value of 450 found by Costa et al. (2005), considered high by these authors for the mineralization of the nutrient in eucalyptus litter to occur at the end of the decomposition period. Likewise, the C/S ratio indicates that there was S immobilization, as similarly observed by Berger et al. (2015) when studying beech litter. In addition, the soil microbiota is responsible for mineralizing the organic bond S to inorganic sulfate, since this is the main pathway through which plants absorb sulfur. On the other hand, microorganisms can also immobilize inorganic sulfate, first for relatively labile ester sulfates and later for more stable C-linked S species. The variation of the change and temperature can contribute to the fluctuation of the C/S ratio and consequently to the immobilization of the nutrient (Dolschak and Berger, 2020), as also observed at 0.58 years in the present study.

Concerning the low N and P release from the litter (Figure 4), that is, slower than decomposition, a similar result was found by Liu et al. (2016), who observed transient N immobilization and low P release in the litter of deciduous species compared to evergreen species. In the present study, there was also a slow release of N and P, which led to an average N/P ratio in the litter of 13.9 during the evaluation period. The limitations of N and P in the litter decomposition are correlated, and the higher the N/P ratio the higher the concentration of soluble organic compounds (amino acids, sugars, or starch) due to P deficiency. In addition, the N/P ratio influences the decomposer microorganisms because, with a low ratio, the bacteria are predominant, while a high ratio leads to greater adaptation of fungi (Güsewell and Gessner, 2009). Phosphorous is not usually considered in nutrient release studies due to its large fluctuations (Ferreira et al., 2016).

With respect to K, Ca, and Mg, there was a fast release by the litter. For K, it was expected because this nutrient neither participates in organic compounds nor is it structural, so it can be easily leached from the tissue, a process that was stimulated with the beginning

of the rains from 0.25 years. Berger et al. (2015), studying the litter of beech (*Fagus sylvatica*), a deciduous species, and Berg et al. (2017), working with a litter of temperate forest species, observed faster mineralization of Ca compared to N and P; the release of N and P occurred after two years due to the immobilization of these nutrients. Jacob et al. (2009) observed in six deciduous forest species (*Fagus sylvatica*, *Tilia* spp., *Fraxinus excelsior*, *Carpinus betulus*, *Acer pseudoplatanus,* and *Acer platanoides*) higher rates of release of K, Ca, and Mg, compared to N and P, as also found in the present study.

The fast release of Ca by the litter observed in this study may be a consequence, at least in part, of possible storage of Ca in the vacuoles of teak leaf cells. The importance of the vacuole for Ca storage in plant cells, and for its remobilization to the cytosol, is reported by Peiter (2011). In the present study, the leaf content of Ca in the litter at the beginning of the decomposition period was 17.71 ± 1.9 g kg^{-1} (Table 4), a value that does not differ from the content of this nutrient before leaf fall in the studied plantations (18.72 ± 0.80 g kg^{-1}) (results not published), suggesting that Ca was still present in the vacuole at leaf fall, and is compatible with the rapid release of Ca by the litter.

The higher concentration in the litter of the most recalcitrant organic compounds, such as insoluble lignin and total lignin, at the end of the evaluation period (Table 5), justifies the slow decomposition of the litter (Figure 3), as well as the longer time of N release (Figure 5), since the lignin concentration in the litter controls the overall rate of N release (Pei et al., 2019). The recalcitrant fraction of lignin in the litter increases with the later decomposition stages, due to the material becoming enriched with lignin and N. The degradation of lignin does not regulate decomposition in the initial stages, but in the later ones. In the first stage of litter decomposition, it is characterized by large losses of water-soluble organic compounds. In the second stage of decomposition, the degradation of lignin in the litter increases the production of organic matter adsorbed from the decomposing litter and increases the contribution of compounds derived from lignin (Rahman et al., 2013; Berg, 2014).

It is worth pointing out that all organic compounds evaluated were correlated with the dry matter (Table 6). Each organic compound in the litter requires a certain time to be released by the microorganisms and has its dynamics in soil. Polysaccharides, polyphenols, tannins, extracts, soluble lignin, and holocellulose showed a reduction after 0.58 years; additionally, this period was among those with the highest precipitation and high temperatures during the experiment. Naik et al. (2017) studying litchi litter observed positive correlations of fungi and bacteria count with precipitation, which indicates that there was a greater activity of these microorganisms with the increase in precipitation. Conversely, significant negative correlations were found between the initial chemistry and the monthly weight loss rate, which indicates the slow decomposition and release of nutrients and organic compounds, similar to the results found in the present study.

In the soil solution, polyphenols can be found dissolved, either physically or chemically protected, and when these substances are dissolved they become more easily found by the microorganisms and are consequently processed and assimilated (Min et al., 2015). This organic compound has a close positive correlation with N, P, K, Ca, Mg, and S (Table 7). Among these nutrients, the correlation with N stands out because polyphenols can form a complex with N, making it difficult to release the nutrient (Costa et al., 2005). According to Naik et al (2017), the reduction of polyphenols in the litter was largely due to their strong oxidizing capacity and water solubility. Probably, with the constant contents of polyphenols after the greater transfer from the litter to the soil, it influenced the longer $t_{1/2}$ of N compared to the other nutrients (Figure 4). Therefore, the correlations between the organic compounds resulted from their lower recalcitrance.

Tannins showed similar behavior to that of polyphenols (Tables 5, 6, and 7; Figure 5). This result occurred because tannins are normally defined as water-soluble polyphenols and up to 80 % can be released by the litter of deciduous and conifer forests during a one-year

period of decomposition. This organic compound commonly reduces N decomposition and release and can be considered a nutrient conservation mechanism (Kraus et al., 2003). In the litter, tannins hamper decomposition due to their characteristic of defense against the fauna, so at the end of the decomposition process, the remaining dry matter has a higher content of tannin (Coq et al., 2010). However, there are low-molecular-weight tannins that are quickly lost by the litter to the soil through leaching, as also occurs with polyphenols, but this varies among forest species (Acero et al., 2010).

Polysaccharides are soluble carbohydrates considered labile and energy-rich compounds whose increasing concentration is not normally measured in plant litter, but despite that, together with phenolic compounds, they are well correlated with the loss of litter dry matter (Hättenschwiler and Jørgensen, 2010). In the present study, this fact was not observed for the content of this organic compound in the litter since its reduction over time was slow. However, a reduction was observed in the relative content, but it was still greater than the contents of polyphenols and tannins.

The extractives obtained with an organic reagent such as ethanol or acetone are a set of compounds such as resin acids, fats, fatty acids, terpenes, oils, and tannins. These in turn promote the resistance of teak wood to the attack of fungi (Brocco et al., 2017). The extractives in the litter in the present study were obtained by the same method, indicating that their reduction over time reflects the greater susceptibility of the material to decomposition by specific microorganisms.

Extractive organic compounds and holocellulose were released from the litter faster than the evaluated forms of lignin (Figure 4). This result and the close positive correlation of these substances with N, P, K, Ca, and Mg contents indicates that extractives and holocellulose were also correlated with the release of nutrients. In addition, Berg (2014) reported that lignin has a negative close correlation with the dry matter of the litter from leaves of forest species and that the higher the N concentration, the greater the delay in the decomposition of this organic compound, due to the suppression of ligninolytic enzymes and the combination of N compounds with reactive groups.

CONCLUSIONS

Our results suggest that clonal teak litter decomposition is slow in tropical soils, with a half-life time ($t_{1/2}$) of dry matter and C of 0.74 years, which is also related to the higher content of insoluble lignin. The $t_{1/2}$ values of N and P release are higher than those of K, Ca, and Mg, so the rate of nutrient release by the litter followed the descending order: K > Ca > Mg > P > N. The biochemical composition of clonal teak litter influences the decomposition and nutrient release in low-fertility soils characteristic of the region where the teak stands are cultivated.

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