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Decomposition, biochemical composition and nutrient cycling of macauba palm in a Cerrado Entisol

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ABSTRACT: Leaf litter decomposition and the release of nutrients from macauba palm leaves play a major role in nutrient return to the soil in a conservation environment. This study evaluated macauba palm leaf decomposition, macronutrient contents and biochemical composition under contrasting water conditions in the Brazilian Cerrado. Macauba leaves were collected from plants in two different environments (low and high water table conditions), placed in litter bags and evaluated according to their decomposition, macronutrients, lignin, cellulose and hemicellulose for 420 days. In addition, green and dry leaves were collected for macronutrient analyses. Litter decomposition ranged between 49 % and 59 % up to 180 days. The half-life of litter ranged from 141 to 198 days. The leaf litter decomposition of macauba was practically stable during the dry season, whereas at the beginning of the rainy season, decomposition resumed. Nitrogen, P and S were higher in the green leaves, whereas the Ca levels were higher in the dry leaves. In addition, the K levels were twofold higher in the green leaves than in the dry leaves. Lignin release from macauba residues was slower than cellulose and hemicellulose. The decomposition rates of hemicellulose were higher initially due to its high solubility, although it gradually decreased with the decomposition process. Lignin decomposition was also higher at the beginning of the process but stabilized during the drought period. The study indicates that the decomposition process and nutrient cycling of macauba are influenced by its biochemical composition.

Keywords: *Acrocomia aculeata*, macronutrients, lignin, cellulose, hemicellulose

Introduction

Macauba (*Acrocomia aculeata)* is a Brazilian palm with significant potential to be a sustainable source of energy and a source of conservation of native areas. It is found both in areas subject to water restrictions as well as those closer to water-courses (Teles et al., 2011). This palm grows in tropical forests and is widely dispersed in Brazil, with dense natural stands mainly in parts of the Cerrado biome. Macauba palm has the potential to supply between 4 and 6 t oil ha^{-1} for biodiesel production and to fix between 796 and 1137 Mg CO_2 eq ha^{-1} (César et al., 2015; Barbosa-Evaristo et al., 2018).

The maintenance of native plant life is essential to production and environmental conservation (Luz et al., 2020). Plant residue decomposition and nutrient cycling dynamics depend on the plant's biochemical composition and biotic and abiotic factors that may influence soil microbial activity (Carvalho et al., 2012; Zhang et al., 2018).

For perennial species, the decomposition process begins in the tree itself. It continues with its senescence and death (Sadaka, 2003) when the leaves detach and fall, forming the litterfall, which will result in organic matter and carbon (C) storage in the soil (Bargali et al., 2015; Ramos et al., 2020).

The change in water table levels affects water availability and biotic processes, which can influence the dynamics of decomposition and the cycling of nutrients (Barbosa-Evaristo et al., 2018; Nwaishi et al., 2016). During the long dry period in the Cerrado region, the microorganisms are inactive (Borges et al., 2014; Souza et al., 2016), but when the first rains begin (the soil rewets) the "birch effect'' occurs (Birch, 1964; Jarvis et al., 2007; Nijs et al., 2018) which leads to an increase in microbial activity that accelerates the decomposition process, regardless of the water table.

Studies that relate the rates of litter decomposition to the biochemical composition of native tropical palms are essential to an understanding of nutrient cycling. However, these studies are limited (Luz et al., 2020) without information on the native macauba population found in parts of the Brazilian Cerrado. We hypothesize that the decomposition process and nutrient cycling in macauba are influenced by its biochemical composition under both low and high water levels. This study evaluated macauba palm leaf decomposition, macronutrient contents and biochemical composition under contrasting water conditions in the Brazilian Cerrado.

Material and methods

The study was conducted at the Santa Fé farm in the municipality of São Gabriel, Goiás State, Brazil, located at the coordinates: 15°25′12″ S, 48°23′28″ W, altitude 578 m (Figure 1). According to the Köppen-Geiger

Figure 1 – Location of the area of Fazenda Santa Fé and area of the natural occurrence of macauba, São Gabriel-GO, 2011. Litter bags are shown at the right side of the figure. The yellow dots represent the places where litter bags were placed (identify high and low water table). Source: Google Earth/2011; GPS: Datum-WES 84.

classification, the regional climate is Aw, with an average annual rainfall of 1,345 mm. The rainiest quarter is concentrated in November, December and January, with average cumulative precipitation values close to 635 mm and average yearly temperatures between 18 and 28.5° C (Alvares et al., 2013). The mean temperatures and the cumulative rainfalls during the time of the experiment are shown in Figure 2.

The soil is classified as an Entisol (Soil Survey Staff, 2014), medium texture, non-floodable gallery phase in smooth undulating relief. There is no difference in altitude between the two water table height levels due to the smooth undulating relief. At the beginning of the experiment, the soil chemical and physical properties in the 0-5 cm soil layer were as follows: pH (in water) = 5.10; pH (in KCl) = 3.96; organic matter = 29.9 g dm^{-3}; P (Mehlich−1) = 2.32 mg dm^{-3}; K = 72 mg dm^{-3}; Al = 1.31 cmol$_c$ dm^{-3}; Ca = 2.27 cmol$_c$ dm^{-3}; Mg = 1.41 cmol$_c$ dm^{-3}; H+Al= 7.9 cmol$_c$ dm^{-3} Cu = 0.93 mg dm^{-3}; Fe = 257 mg dm^{-3}; Mn = 44 mg dm^{-3}; Zn = 0.4 mg dm^{-3}. In the 5-10 cm layer, chemical analysis of this experiment showed the following results: pH (in water) = 5.25; pH (in KCl) = 4.15; organic matter = 33.5 g dm^{-3}; P (Mehlich−1) = 2.93 mg dm^{-3}; K = 142.5 mg dm^{-3}; Al = 0.96 cmol$_c$ dm^{-3}; Ca = 2.62 cmol$_c$ dm^{-3}; Mg = 1.13 cmol$_c$ dm^{-3}, H+Al= 6.8 cmol$_c$ dm^{-3}, Cu = 0.60 mg dm^{-3}; Fe = 182 mg dm^{-3}; Mn = 48 mg dm^{-3}; Zn = 0.6 mg dm^{-3}. According to Diniz et al. (2014) the soil used in the experiment, in the layer of 0 to 20 cm presented 327 g kg^{-1} of clay, 250 g^{-1} of silt and 423 g kg^{-1} of sand.

Data were collected from a massif of native macauba trees in the Brazilian Cerrado biome, with Palmeiral vegetation and subtype macaubal, next to a non-floodable forest gallery associated with the pasture of *Brachiaria* sp.

The water table heights were measured before sampling the macauba leaves and placing the litter bags in the field. Measurements were taken by digging holes up to 3 meters at different points of the experimental site to determine the groundwater's height (Figure 3). The depth to groundwater was measured using a graduated ruler with a sensor attached to the end that signals when contact is made with water. The highest water table (1.25 m) found during the dry period was identified as the high water table condition. In contrast, the lowest water table (3.0 m) was found farther away from the groundwater, and was considered the low water table.

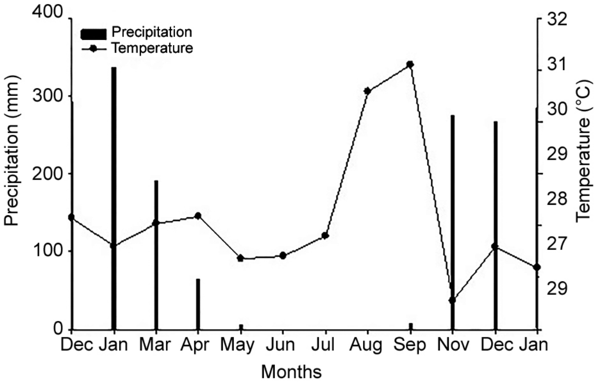

Figure 2 – Monthly averages of temperature (°C) and cumulative monthly precipitation (mm) from December 2010 to January 2012, São Gabriel, GO. Information obtained from the São Gabriel-GO meteorological station, 2011.

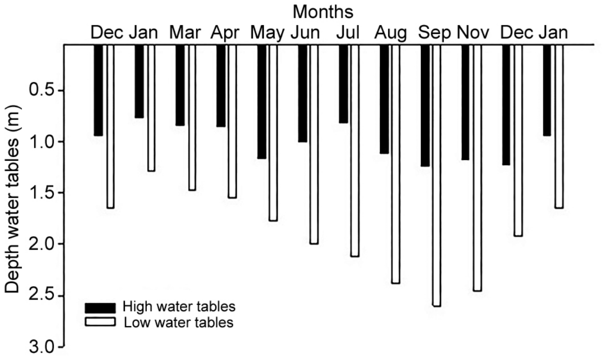

Figure 3 – Depth of water table (m) in the area of a natural population of macauba, Fazenda Santa Fé municipality of São Gabriel-GO, 2011.

The study area was approximately 5 ha with three meters of plant spacing. We selected two hectares to evaluate litter decomposition. Twenty-two trees approximately 10 meters in height were selected and isolated within a radius of three meters from possible interference from the roots of other trees and shrubs. A horizontal line was drawn from the base of macauba stem, and litter bags were installed. The experimental design was arranged in a completely randomized design with four replicates and repeated measurements in time. Around the trees, litter bags were left on the soil surface, and at each evaluation date, three litter bags were collected per replicate, totaling 12 litter bags per evaluation. In addition, green and dry leaves were removed from the macauba tree to analyze nutrient content in high and low water tables. The litter bags were made with bags of nylon mesh of 2 mm, 20 × 20 cm, containing 20 grams of plant material (green leaves recently detached from the palm trees) that were chopped and dried in an oven at 65°C for 72 hours. These bags were removed from the field at 30, 60, 120, 150, 180, 210, 240, 270, 300, 360, 390 and 420 days after being placed on the field in December 2010 (Figure 1). Three litter bags were removed from each block in each evaluation under low and high water table conditions. For each sampling period, the remaining material inside the bags was weighed and then placed in an oven at 65 °C for 72 hours to obtain the remaining dry material weight. After drying, the dry material was burned at 600 °C for a minimum of 8 hours to obtain the final inorganic content of the plant species. The methodology of Carvalho et al. (2012) was used to determine the decomposition rate of macauba residues.

Litter decomposition per area was calculated as proposed by Santos and Whitford (1981), based on the litter decay rate (percentage). The remaining litter rate was determined as the difference between the initial total litter mass amount (100 %) and each rate per assessment period.

Lignin, cellulose and hemicellulose levels were determined in the plant material (green leaves), and the plant residues of each litter bag were removed from the field by the sequential method (Robertson and Van Soest, 1981). In addition, the analysis of the dry matter at 105 °C, the fiber in acid detergent (FAD), the fiber in neutral detergent (FND), and lignin were also performed by this sequential method.

Analyses of neutral detergent fiber (NDF) and acid detergent fiber (FAD) were performed on macauba leaves according to Robertson and Van Soest. (1981) and modified (Komarek, 1993) for use in an Ankom fiber apparatus (Ankom Technology Corp). Lignin analysis was performed by digestion of the FAD residue with 72 % sulfuric acid, which extracts cellulose and hemicellulose, generating lignin and inorganic matter as a residue. The differences between FND and FAD residues and between FAD and lignin residues were determined by hemicellulose and cellulose levels. The difference between the acid digestion residue and the ash after burning at 600 °C for four hours resulted in the lignin content.

The total N content (TN) of the residues was analyzed by colorimetry with a Lachat 228 Quikchem flow injection analyzer (Lachat Instruments). The other nutrients were extracted by digestion with perchloric acid and hydrogen peroxide, heated to 350 °C in a digester block for one hour, and analyzed by plasma emission spectrophotometry.

The decomposition data were adjusted to the exponential model, with the residue rate remaining as a function of time ($TR = 100 * Ek*(t)$). Based on the constant (k) of the exponential equation ($TR = 100 * Ek*(t)$), the half-life ($h = \ln2/k$) and the recycling time ($\tau = 1/k$) of the macauba plant material were calculated. The data were subjected to regression analysis using the Sigma Plot 10.0 software program (Systat Software, Inc).

The analysis of lignin, cellulose and hemicelluloses from the litter bags were adjusted to the quadratic polynomial model. One-way ANOVA analyzed the data after the normality test with the Shapiro-Wilk 5 % significance test, which proved that the residuals could be considered normal. The averages of all variables of the treatments of the low and high water table levels and green and dry leaves were compared by the Tukey test ($p < 0.05$) using the statistical software SAS program (Statistical Analysis System) version 9.1.2.

Results

The exponential model was adjusted to the remaining mass data for both water table heights, and their respective angular coefficients were similar in both equations (Figure 4). The leaf litter decomposition of macauba was practically stable during the dry season, whereas at the beginning of the rainy season, decomposition resumed (Figure 4).

Based on the constant (k) of the adjusted equation, the half-life time of the residues ($h = \ln^2 k^{-1}$) was calculated, which corresponded to the period needed to decompose 50 % of the initial mass. The estimated half-

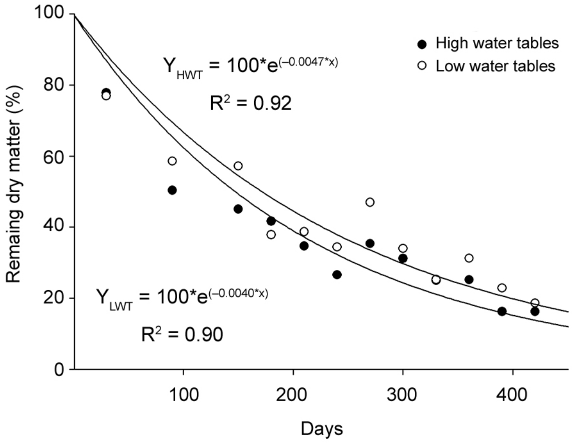

Figure 4 – Decomposition of plant residues of a natural macauba population in areas with high and low water table.

life time values were 147 and 173 days. In comparison, the data obtained from calculating the recycling time for macauba material were 250 and 213 days for the low and high water table levels, respectively.

After 420 days from when the litter bags were placed in the field, the remaining residues was 19 % and 15 % compared to the initial mass under low and high water table conditions, respectively (Figure 4).

The N, P, K, and S levels were higher in the green leaves ($p < 0.05$). Moreover, the K levels were twofold higher in the green leaves than in the dry leaves (Table 1). The Ca levels were higher in the dry leaves of macauba, diverging from the behavior of the other nutrients (N, P, K, S) that were higher in the green leaves. An adjustment to the exponential model of the evaluated macronutrients, both for low and high water tables (Figure 5). A gradual reduction in N of the remaining macauba residues was observed. Under both water table conditions (low and high), the exponential model was adjusted with R^2 greater than 90 %. The release of N

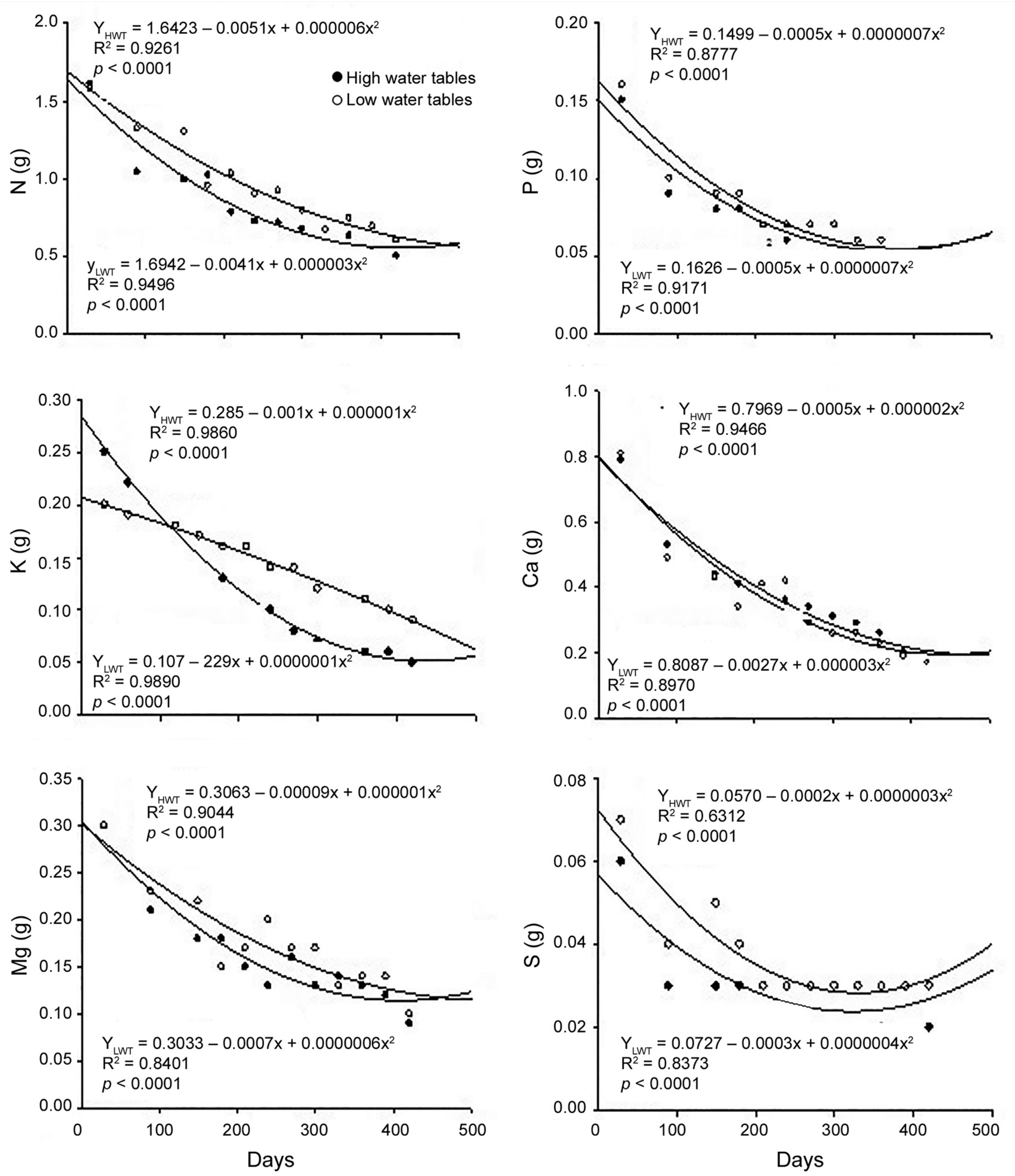

Figure 5 – Macronutrient content in macauba residues as a function of time.

Table 1 – Macronutrient content in green and dry leaves of macauba.

Leaves	Nutrient content					
	N	P	K	Ca	Mg	S
	------------------------------ g kg^{-1} ------------------------------					
Green	13.38 a	1.76 a	7.95 a	5.91 b	2.34 a	0.69 a
Dry	10.10 b	1.33 b	3.54 b	7.08 a	2.84 a	0.50 b

Means followed by the same letter in each column do not differ statistically by the Tukey test ($p < 0.05$).

from the remaining residues was more intense at the beginning of the process. It remained stable throughout the drought period, from May to September, following the same decomposition rate model of macauba leaves.

The P release kinetics of macauba residues accelerated more at the beginning of the decomposition process. It stabilized in the period of full drought under both conditions. Considering that this initial period of greater decomposition corresponds to the first 60 days after the litter bags were placed in the field the accumulated precipitation reached about 330 mm (Figures 2 and 5).

The availability of calcium in the soil was gradual over time under both water table conditions. Mg showed similar behavior during the decomposition process for both water table conditions, and sulfur was the nutrient that remained most stable during the decomposition of plant residues at the two water table heights.

The lignin release kinetics in macauba residues was more intense at the beginning of the decomposition process. It stabilized during 153 days of full drought (from May to September) for both water table conditions and accompanied the decomposition process (Figure 6a).

There was a gradual reduction in the amount of cellulose in the remaining residues of macauba and, under the two conditions of the water table (low and high), the exponential model was adjusted with R^2 higher than 90 %, and the cellulose contents were higher than those of lignin and hemicellulose (Figure 6b).

Under both water table conditions the hemicellulose decomposition process was adjusted to the quadratic polynomial model (Figure 6c). Under the high water table condition, there was a sharp drop in hemicellulose levels only at 60 days after the litter bags were placed in the field. After this period, and up to 210 days (May 2011), hemicellulose release was stabilized and gradually decreased. Under the low water table condition and at 60 days, the hemicellulose decomposition rate was less pronounced than the high water table. During the decomposition evaluation process, the hemicellulose was more resistant to decomposition than cellulose.

The macronutrient contents of green and dry macauba leaves, and under both low and high water table levels, are presented in Table 1 and 2, respectively. There were no differences between the levels of macronutrients under the two groundwater conditions ($p < 0.05$).

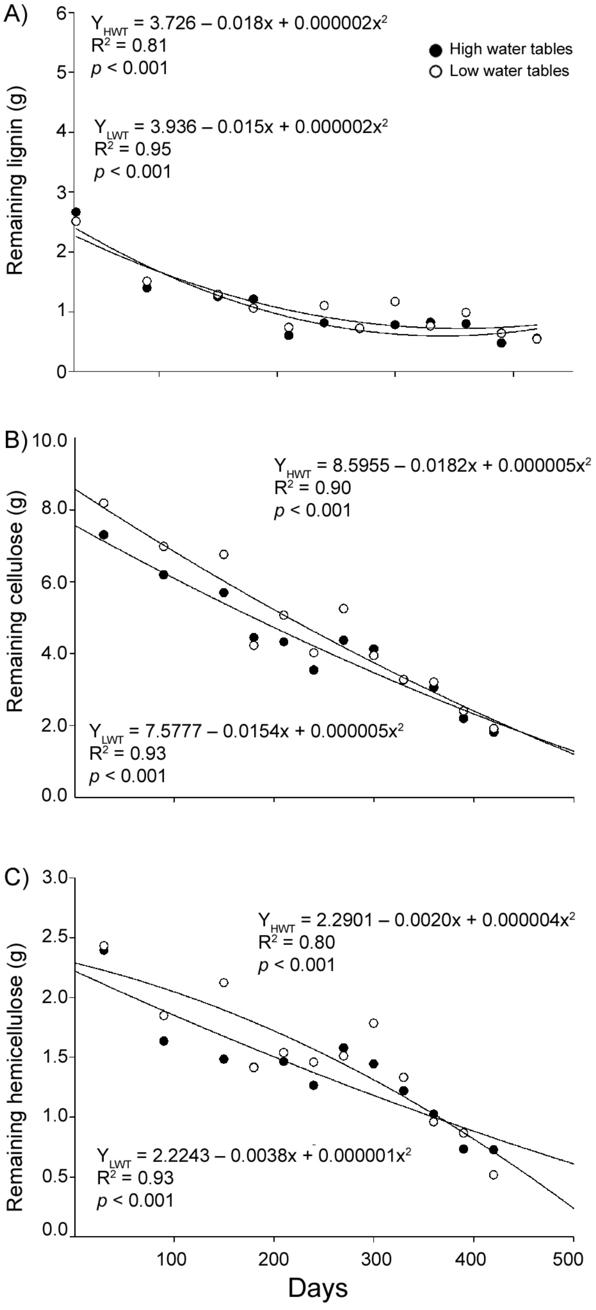

Figure 6 – (A) Lignin, (B) cellulose and (C) hemicellulose contents in the remaining plant residues of macauba.

Table 2 – Macronutrient content in leaves of macauba in areas with high and low water table.

Water table	Nutrient content					
	N	P	K	Ca	Mg	S
	------------------------------ g kg^{-1} ------------------------------					
High	11.71 a	1.52 a	6.29 a	6.27 a	2.61 a	0.58 a
Low	11.87 a	1.57 a	5.19 a	6.72 a	2.57 a	0.60 a

Means followed by the same letter in each column do not differ statistically by the Tukey test ($p < 0.05$).

Discussion

Our results showed that both water table heights presented an exponential model. Natural populations of macauba are found in landscapes both closer and further away from water sources which could suggest that this palm adapts to different areas and soil moisture conditions. According to Cardoso et al. (2017), field surveys indicated that natural populations of macauba are found under different environmental conditions.

During the dry season in the Cerrado biome, the decomposition of plant residues is stable (Figure 4) because of the low soil moisture and, consequently lower soil microbial activity (Borges et al., 2014; Souza et al., 2016). However, when the first rains begin, they lead to the "Birch Effect'' (Jarvis et al., 2007; Nijs et al., 2018). This effect results from soil drying/rewetting events that occur right after a long drought period (Birch, 1964) and when the rainy season in the Cerrado region begins, the soil microbial activity is increased.

A prolongated dry season is a climatic characteristic of the Cerrado biome (Alvares et al., 2013), with a very severe dry season, between May and September, the microorganism activity is limited due to water stress, which strongly influences the decomposition process (Souza et al., 2016), in both the low and the high water table. Climatic factors, especially the amount and distribution of rainfall that reflects on soil moisture, are factors that influence soil microbial biomass and activity (Borges et al., 2014; Oliveira et al., 2016) and, therefore, affect the dynamics of leaf litter decomposition of macauba during both the dry and rainy seasons.

At the end of the evaluations, once the litter bags had already been in the field for 420 days, only 19 % and 15 % of the residues remained in the soil for the low and high water tables, respectively. These results are lower than those found for eucalyptus residues and litterfall in the Cerrado after 720 days, when the remaining mass of eucalyptus ranged from 35 to 37 %, whereas the remaining mass from the Cerrado litterfall was 22 % (Ribeiro et al., 2018). Similar results show that the highest rates of litterfall decomposition under the Cerrado are found after the first rains (Penã-Penã and Irmler, 2016; Souza et al., 2016), reflecting the "Birch Effect" (Jarvis et al., 2007; Nijs et al., 2018).

The results of macronutrient levels in green and dry macauba leaves show the process of nutrient transfer in the plant (when comparing nutrient contents from green and dried leaves) before the leaves fall and begin the nutrient release process during the decomposition process of plant residues in the soil. The N, P, K, and S levels were higher in the green leaves ($p < 0.05$), showing that in this vegetative stage, these nutrients have not yet been redistributed in the plant (Teklay, 2004). In addition, the K levels were twofold higher in the green leaves compared to the dry leaves, indicating its high mobility in the plant (Ranjbar and Jalali, 2012). Furthermore, it is known that the plant needs higher K uptake to adapt to both biotic and abiotic stresses (Wang et al., 2013).

Higher Ca content found in dry leaves is related to the low mobility of this nutrient in the plant, which was not redistributed to the younger parts of macauba before leaf abscission (Vitti et al., 2006).

The macronutrient contents in the leaves of macauba seedlings (six months old) obtained by Hernández et al. (2018) were higher than those presented in this study. However, it should be considered that younger plants tend to have higher nutrient levels when compared to adult plants due to the effect of mass concentration (Marschner, 2012). The N, P and S levels found in this study were very close to those observed by Teles et al. (2011) in leaves of adult macauba plants in Brazil. Pimentel et al. (2015) analyzed leaf contents in macauba palm for N, P, K, Ca, Mg, S, and Cl, and found 30.70, 1.67, 13.64, 4.94, 1.48, 2.26, and 3.67 g kg^{-1}, respectively. For the micronutrients B, Cu, Zn, Fe, and Mn, the authors obtained 39.28, 4.00, 11.33, 126.89 and 30.22 mg kg^{-1}, respectively.

The P was rapidly released at the initial stage of the decomposition process, which may be associated with the loss of fractions from these water-soluble nutrients (Jalali and Ranjbar, 2009). Most of the P in plants is inside the vacuole, in mineral form, which has a high capacity for solubilizing in water (Marschner, 2012).

As cited before, the potassium release rate was higher under the high water table condition compared to the other nutrients. This may be related to higher soil moisture increasing decomposition.

The rapid initial release of K results from this element is not associated with any structural component of plant tissue (Marschner, 2012). As the aerial part of the plants starts the decomposition process, after rupture of the plasma membranes, the concentration of this nutrient in the tissue decreases drastically (Marschner, 2012; Ranjbar and Jalali, 2012), especially under rainfall. This result may be due to the macauba plants being located farther away from the watercourses, which slows down the decomposition process of the macauba leaves due to lower soil moisture.

The calcium release from macauba residues over both water tables was similar, indicating a gradual release of this nutrient over 420 days. The release of Ca in plant residues depends on the plant species and the C:N ratio (Ranjbar and Jalali, 2012). These authors indicate that crop residues with a higher C:N ratio release Ca more slowly than residues with a low C:N ratio.

Release of Mg from macauba residues showed similar behavior in both water tables. However, the release of this nutrient was slower when compared to calcium, as obtained by Vitti et al. (2006). The release of N, P, Ca and Mg in a study with cover crops was positively associated with the decomposition rate of plant residues (Xavier et al., 2017). The decomposition of plant residues depends on the plant species and the C:N ratio (Ranjbar and Jalali, 2012).

Of all the evaluated nutrients, sulfur was the most stable in both water tables. These results are similar to those obtained by Xavier et al. (2017) for various cover crops, indicating that the half-life time of S from the cover crops studied varied from 25 to 30 days. The same authors also observed that K was the fastest-release nutrient from the cover crop residues and that P and S were released faster than N, Ca and Mg.

Lignin release from macauba residues was slower than cellulose and hemicellulose (Figure 6) due to recalcitrant compounds that are difficult to be decomposed by microorganisms. In this study, higher lignin release from macauba residues occurred at the beginning of the decomposition. It corresponded to the first 60 days after placing the litter bags in the field and to the higher precipitation period that accumulated 330 mm (Figures 2 and 6a).

The gradual reduction of the cellulose levels in macauba residues in both water tables indicates that plant materials with higher cellulose content, an organic compound that is difficult to decompose, are more resistant to microbial degradation (Cui et al., 2019). Cellulose allows for the permanence of plant residues in the soil, reducing the action of microorganisms and slowing down the decomposition process. There is interaction between lignin, cellulose and N content controlling litter decomposition; lignin protects cell wall compounds from decomposition, and cellulose is a co-substrate for lignin degradation (Talbot et al., 2012).

As we did not find other studies with litter decomposition in macauba leaves, a number of authors obtained similar results as the present study, showing that the decomposition of eucalyptus litterfall was also positively correlated with the reduction in cellulose content, the least recalcitrant of the C compounds analyzed. Although hemicellulose is the most labile structural component (Wagner and Wolf, 1999), cellulose was decomposed more quickly in eucalyptus litterfall (Ribeiro et al., 2018). According to Cotrufo et al. (2013), cover crops with a high content of more labile constituents, such as hemicelluloses, can be quickly converted into microbial products.

Cellulose and lignin are the main constituents of plant residues (Cui et al., 2019; Chen et al., 2018), and are cell wall structural constituents (lignin and cellulose) that control the decomposition process of plant residues (Talbot et al., 2012). In addition, cellulose and lignin degradation is related to climatic conditions: evapotranspiration for lignin, precipitation for cellulose and temperature for hemicellulose. Nevertheless, these compounds are not degraded separately and depend on the percentage of each compound and climatic conditions (Fioretto et al., 2005).

The half-life of litter ranged from 141 to 198 days. The results of macronutrient levels in green and dry macauba leaves showed the process of nutrient transfer in the plant (when comparing nutrient contents from green and dried leaves) before the leaves fall and begin the nutrient release process during the decomposition process of plant residues in the soil. Green leaves showed the highest macronutrient content, while Ca content was predominant in dry leaves. The study suggests that, due to the decomposition, nutrient content, and structural components, the natural population of macauba is therefore important in nutrient cycling and soil protection for the conservation and maintenance of soil fertility. Furthermore, the study indicated that the macauba decomposition process and nutrient cycling are influenced by its biochemical composition, which is essential to the sustainability of macauba in the natural population of the Brazilian Cerrado.

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Authors' Contributions

Conceptualization: Carvalho AM, Souza AM. **Investigation**: Quintana LG, Carvalho AM, Souza AM. **Formal analysis**: Quintana LG, Carvalho AM, Souza AM, Oliveira AD, Ramos MLG, Sousa TR. **Methodology**: Quintana LG, Carvalho AM, Souza AM, Coser TR, Oliveira A. **Writing original draft**: Ramos MLG, Carvalho AM, Souza AM, Sousa TR, Coser TR.

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