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Seasonal dynamics of carbon and nutrients in litter in *Khaya* stands in Southeastern Brazil

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SILVICULTURE

ABSTRACT

Background: Scarce information is available on soil-plant interactions to guide management practices for the *Khaya* genus. This study aims to evaluate the influence of seasonality on the accumulation of litter during two different rainfall periods, as well as to determine its nutrient and carbon content and stock in stands of *Khaya* at 10.6 years of age. The samples were collected using a template measuring 0.25 m × 0.25 m (0.0625 m^2) in a zigzag pattern with a minimum distance of 4 m between points.

Results: Nutrient contents were quantified, including macronutrients (N, P, K, Ca, Mg, and S) and micronutrients (Fe, Zn, Cu, Mn, and B), as well as organic carbon in the plant tissue of three species of *Khaya* (*K. grandifoliola*, *K. ivorensis*, and *K. senegalensis*). In terms of C content, no statistical differences were found between the species during the rainy season. However, for the same period, higher stocks of macronutrients were observed in the following order: Ca > N > Mg > K > S > P. Among micronutrients, Fe showed the highest and Cu showed the lowest stocks.

Conclusion: *K. ivorensis* species exhibited the highest biomass production and the best nutritional quality.

Keywords: Mahogany; nutrition; biogeochemical cycling; forest productivity; soils.

HIGHLIGHTS

The *K. ivorensis* species produced more litter and showed better nutritional quality.
The highest carbon and nutrient stocks were observed in the rainy season.
Higher stocks of macronutrients were observed in the order: Ca > N > Mg > K > S > P.
During the rainy season, no statistical differences were observed in the C content.

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INTRODUCTION

The genus *Khaya*, popularly known as African mahogany, originated on the African continent and comprises four important wood-producing species belonging to the Meliaceae family (Pinheiro et al., 2011; Opuni-frinpong et al., 2016). They show a high commercial value and excellent physical and mechanical qualities, being used to build furniture, civil and naval constructions, laminates, and musical instruments (Reis et al., 2019). These species are planted in 12 Brazilian states and more than 47 municipalities, occupying approximately 50,000 hectares, most of them in the state of Minas Gerais (Ferraz Filho et al., 2021).

Although this genus is adapted to diverse environmental conditions, such as long periods of drought due to its deep root system, scarce information is available on soil-plant interactions to outline actions aimed at management practices, as well as the best use of nutrients by different species (Wulder et al., 2020; Dick and Schumacher, 2020). Thus, studying nutrient cycling via litter becomes crucial to understanding the flow of nutrients in the environment and between species (Viera et al., 2022).

The litter can be considered the main source of organic material in forest ecosystems, as it is composed of all plant and animal materials deposited on the ground, such as branches, leaves, bark, fruit, and fecal remains (Valadão et al., 2019; Cheng et al., 2023). In addition, litter protects the soil from erosion and leaching and helps regulate soil temperature and humidity (Martinelli et al., 2017).

The release of nutrients via litter decomposition can be influenced by biological, edaphic, and climatic factors (Santos et al., 2017). In tropical regions, variations in temperature associated with high levels of rainfall dictate the annual behavior of decomposition, which directly impacts the structure, quantity, and quality of the matter deposited under the soil (Pang and Bao, 2020; Pereira et al., 2022). By knowing the dynamics of nutrients at different times, it is possible to devise management strategies and silvicultural practices that aid maintain nutrients, promoting greater sustainability of the forest site (Schumacher et al., 2019).

This study aims to quantify the litter biomass during two different periods, with different rainfall rates, as well as to determine its nutrient and organic carbon content and stock in stands of *Khaya* at 10.6 years of age. The following hypotheses were considered: (i) Is there a difference in litter biomass between *Khaya* when there are variations in rainfall rates? (ii) Does the rainy season promote greater accumulations of nutrients to be recycled? and (iii) Which species shows the greatest return of nutrients via litter?

MATERIAL AND METHODS

Study area

The study was conducted in the *Reserva Natural Vale* (Vale Nature Reserve), which is located in the municipality of Sooretama, in the state of Espírito Santo, Brazil. According to the Köppen classification, the region's climate is Aw, marked by the occurrence of rainy summers and dry winters, with rainfall poorly distributed throughout the year (Figure 1). The average air temperature is 23.5 °C and the average annual rainfall is 1,294 mm (Alvares et al. 2013). It presents a flat topography, with slope ranging from 0 % to 3 %. The soil is identified as of the Acrisol type, featuring a moderate A horizon (FAO, 2015) (Table 1).

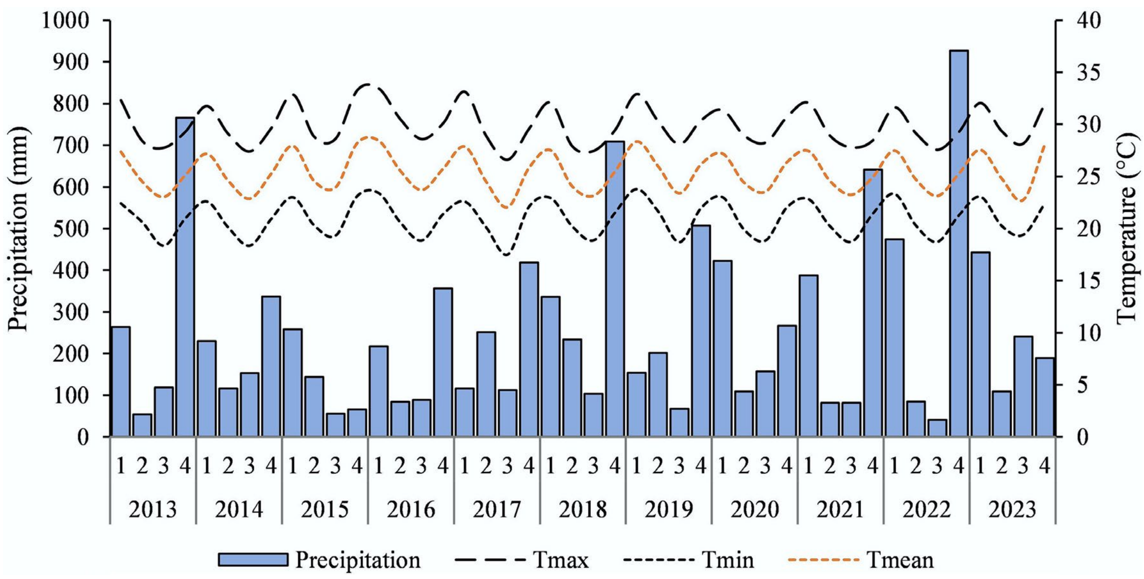

Figure 1: Meteorological diagram of rainfall and temperature corresponding to the productive period of the three species of *Khaya* in Sooretama, ES.

Table 1: Soil chemical attributes at various depths within the experimental area in Sooretama, ES.

Species	Depth	pH	P	K	Ca	Mg	Al	H+Al	SB	CEC	BS	OM
	Cm	H_2O	---mg dcm^{-3}---		-----cmolc dm^{-3}-----						%	g kg^{-1}
K. grandifoliola	0–20	6.13	2.33	26.33	1.89	0.50	0.00	1.66	2.48	4.13	59.69	2.79
	20–40	5.93	1.00	13.89	1.07	0.32	0.00	1.63	1.44	3.07	46.80	1.49
K. ivorensis	0–20	5.92	2.11	28.11	1.52	0.52	0.00	1.98	2.14	4.12	51.70	2.60
	20–40	5.77	1.00	16.22	0.84	0.28	0.02	1.86	1.18	3.03	38.46	1.50
K. senegalensis	0–20	6.27	2.56	26.89	2.11	0.53	0.00	1.61	2.74	4.35	62.96	2.93
	20–40	5.94	1.00	15.00	0.88	0.29	0.00	1.78	1.22	3.00	40.33	1.64

pH in water, contents of phosphorus (P), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), aluminum (Al^{3+}), potential acidity (H + Al), sum of bases (SB), cation exchange capacity (CEC), base saturation (BS), and organic matter (OM).

Stand characterization

Historically, in the 1980s, in the area where the experiment was conducted, a monoculture of leguminous species was established, followed by fallow (Caldeira et al. 2020). Subsequently, in 2013, seedlings of seminal origin corresponding to three species of African mahogany (*K. grandifoliola* C. DC. [KG]; *K. ivorensis* A. Chev. [KI]; and *K. senegelensis* A. Juss. [KS]) were planted using hand-dug holes measuring 30 cm × 30 cm × 30 cm. Fertilization consisted of 150 g of Yoriin® thermophosphate and 15 g of FTE BR 12 per seedling. The planting was a monoculture, installed at a spacing of 3 m × 3 m and distributed in rectangular plots measuring 1,260 m, with a useful area of 810 m (15 m × 54 m) and a simple border, totaling 90 useful trees per repetition.

Litter

The first litter sample was collected in November 2022, the period of highest rainfall, and the second in June 2023, the period of lowest rainfall. In total, 15 single samples were collected using a template measuring 0.25 m × 0.25 m (0.0625 m^2), which were homogenized and divided into three composite samples. The samples were collected in a zigzag pattern with a minimum distance of 4 m between points. The sampled material was placed in paper bags, identified and taken to an oven with air circulation and renewal at a temperature of 65 °C for 72 hours until it reached a constant mass.

The material was weighed to obtain its dry weight, grounded in a Willey mill, and passed through a 1.0 mm mesh sieve (20 mesh). Then, it was stored and sent to the Water Resources laboratory at Ufes/CCAE/DCFM, in Jerônimo Monteiro, Espírito Santo. The nutrient contents, which include macronutrients (N, P, K, Ca, Mg, and S) and micronutrients (Fe, Zn, Cu, Mn, and B), as well as the organic carbon of the plant tissue were determined following the method proposed by Tedesco et al. (1995) and Embrapa (2009). The nutrient stock was estimated using the content of each nutrient (g kg^{-1}) multiplied by the dry biomass of the plant material (kg ha^{-1}).

Statistics

The data was subjected to the normality (Shapiro-Wilk) and homogeneity of variances (Levene) tests. When they did not show homogeneity and normality, data transformation was applied. On the other hand, considering these assumptions, the F test was applied at a 5 % probability level to compare the production, content, and nutritional stocks of the accumulated litter during the two periods (higher and lower rainfall), whereas the Tukey test was applied to assess the effect of the African mahogany species within each period. A Principal Components Analysis (PCA) was applied to verify the correlations between the treatments and the response variables (soil fertility, meteorological parameters, dendrometric averages, as well as the mass, nutrient content, and carbon in the litter). Statistical analyses were conducted using the R software (R Core Team, 2024).

RESULTS

The litter biomass varied both between the African mahogany species and during the collection period (Figure 2a). We found the highest average values in the *K. ivorensis* area (18.5 Mg ha^{-1} in the rainy season and 15.7 Mg ha^{-1} in the dry season), which represents an average superiority of approximately 17 % for *K. senegalensis* and 31 % for *K. grandifoliola*, regardless of the sampling period. We also point that the period with the highest rainfall exhibited the highest accumulation of litter for all the areas with *Khaya*.

In terms of C content, we found no statistical differences between the species during the period with the highest rainfall, with average values of 374.4 g kg^{-1} ($p > 0.05$). However, the *K. grandifoliola* area stood out with the highest averages in the period of lowest rainfall (361.2 g kg^{-1}), followed by *K. ivorensis* (292.1 g kg^{-1}) and *K. senegalensis* (270.9 g kg^{-1}) (Figure 2b). An inverse pattern was observed for the carbon stock when evaluating the collection seasons, as we noted no statistical differences between the species during the period of lowest rainfall (4.0 Mg ha^{-1}). However, during the period of highest rainfall in the *K. ivorensis* area, the highest average values were observed (7.1 Mg ha^{-1}), which represents a superiority of 18.3 % and 33.8 % for the *K. senegalensis* and *K. grandifoliola* plantation areas, respectively (Figure 2c).

The C/N ratio was higher for *K. grandifoliola* compared to *K. ivorensis* during the period of highest rainfall, with average values of 42.3 and 38.0, respectively. This same pattern was observed in the period with the lowest rainfall, in which the highest average values were recorded in the *K. grandifoliola* area, with an average of 43.8, whereas the other species showed average values close to 32 (Figure 2d).

In general, the macronutrient levels did not differ between the periods of highest and lowest rainfall, with the nutrients being distributed in the following descending order: Ca > N > Mg > K or S > P. We found that the highest levels of N, P, K, and S were observed in the *K. ivorensis* areas during the period of highest rainfall when compared to the other species (Figure 3a-c, f). We observed no statistical differences in Ca concentration between the periods but we found that the *K. ivorensis* area showed higher values of this nutrient than those recorded in the *K. senegalensis* area during the period of greatest rainfall, with this increase being in the order of 20 % (Figure 3d). Regarding Mg, the *K. grandifoliola* area showed the highest average values among the species in both periods, with averages of 2.6 g kg^{-1} and 2.4 g kg^{-1}, respectively (Figure 3e).

The micronutrient levels followed the same decreasing order during both evaluation periods: Fe > B > Mn > Zn > Cu. Thus, Fe was the micronutrient with the highest concentrations and did not differ between the species during the collection periods, with average values of 610.8 mg kg^{-1} and 1,046.63 mg kg^{-1} during the periods with the highest and lowest rainfall, respectively. On the other hand, the highest Fe concentrations were observed in the areas of the *K. ivorensis* and *K. senegalensis* species during the period of lowest rainfall (Figure 4a).

Despite showing the highest Zn concentrations, the *K. grandifoliola* area recorded the lowest values for Cu during both periods and Mn during the period of highest rainfall (Figure 4b). In addition, all the African mahogany species showed higher Cu concentrations during the period of lowest rainfall, with averages of 7.07 mg kg^{-1}, and Mn levels during the period of highest rainfall, with values close to 42 mg kg^{-1} (Figure 4c-d). Regarding B content, we found no significant differences between the species but *K. grandifoliola* showed the highest averages during the period of lowest rainfall (Figure 4e).

As for nutrient stocks, the highest values were observed during the period of greatest rainfall for all the species evaluated. This same trend was seen in the *K. ivorensis* areas during both collection periods. The average macronutrient stock was 89.8 kg ha^{-1} and 69.25 kg ha^{-1} for the period with the highest and lowest rainfall, respectively, corresponding to a contribution of approximately 60 % Ca and 27 % N (Figure 5a-f). The order of the macronutrient stocks was the same as the contents: Ca > N > Mg > K > S > P.

Fe and Cu were the micronutrients with the highest and lowest stocks, respectively, and the values quantified in the *K. ivorensis* and *K. senegalensis* areas were mostly higher during the period of lowest rainfall (Figure 6a-c). On the other hand, the highest Mn stocks were observed in the areas of these species during the period of highest rainfall, with average values of 817.4 and 673.3 g kg^{-1} (Figure 6d). Zn stocks did not differ between species or between evaluation periods (Figure 6b). As for B, which accounts for approximately 6.3 % of the total stocks, higher values were found in the areas of *K. ivorensis* (1,032.2 g kg^{-1}) and *K. senegelensis* (875.1 g kg^{-1}) during the period of highest rainfall, whereas no significant differences were observed during the period of lowest rainfall (Figure 6e).

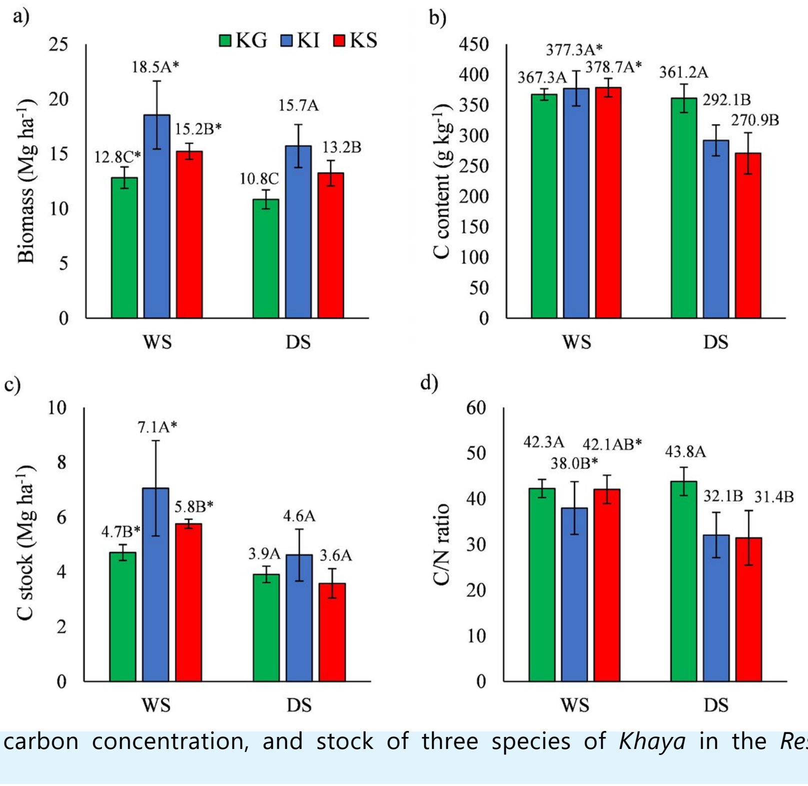

Figure 2: Biomass, carbon concentration, and stock of three species of *Khaya* in the *Reserva Natural Vale*, Sooretama, ES.

The multivariate principal component analysis with only eigenvalues greater than 1 (λ > 1) extracted two components, which together accounted for 68.5 % of the variability in the data (Figure 7). From a set of 22 input variables, principal component 1 alone was responsible for covering almost half, 48.8 %, of the variation in the data. PCA was efficient in sorting out the different soil fertility parameters, meteorological variables, which here portray the seasons, dendrometric averages, as well as the mass, nutrient content, and carbon in the litter.

The boxplot shows that the blue polygon representing the *K. ivorensis* species is associated with most of the input variables, especially mass, carbon, and macro- and micronutrients. In addition, the quality of the litter accumulated under the *K. ivorensis* stand stands out from the other species in the genus, despite sharing a small intersection band formed by the points in its polygon. Moreover, the species lies to the right of the vertical axis, with eigenvalues greater than one (λ > 0). The chemical attributes of the soil spatially showed a greater association with the areas indicated for *K. grandifoliola* and *K. senegalensis*. Both species converge due to their overlapping areas and because they are located to the left of the vertical axis (λ < 0).

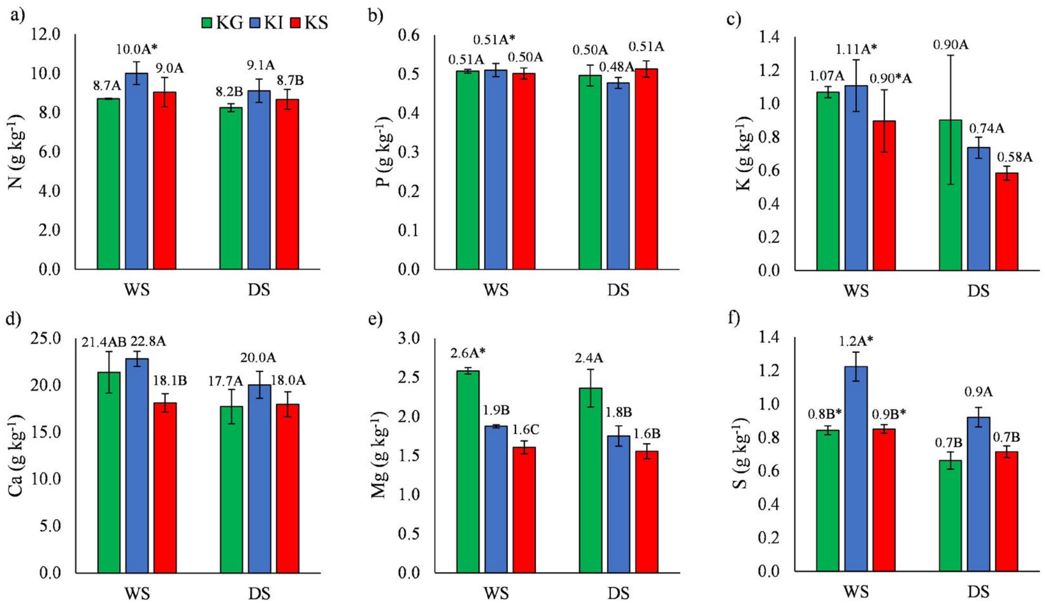

Figure 3: Macronutrient concentration in three species of *Khaya* in *Reserva Natural Vale*, Sooretama, ES.

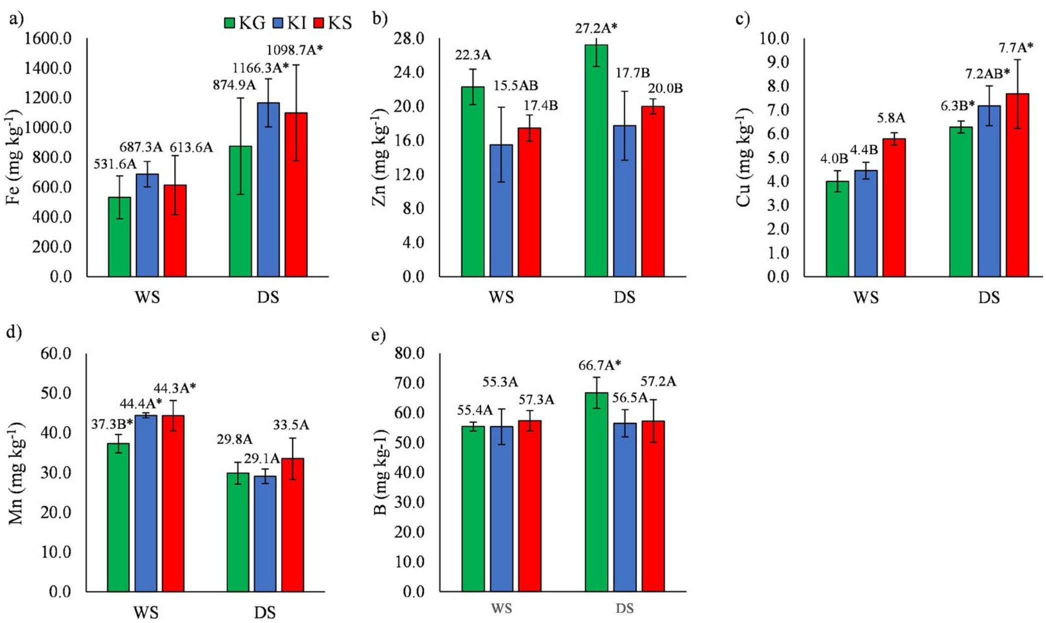

Figure 4: Micronutrient concentration in three species of *Khaya* in *Reserva Natural Vale*, Sooretama, ES.

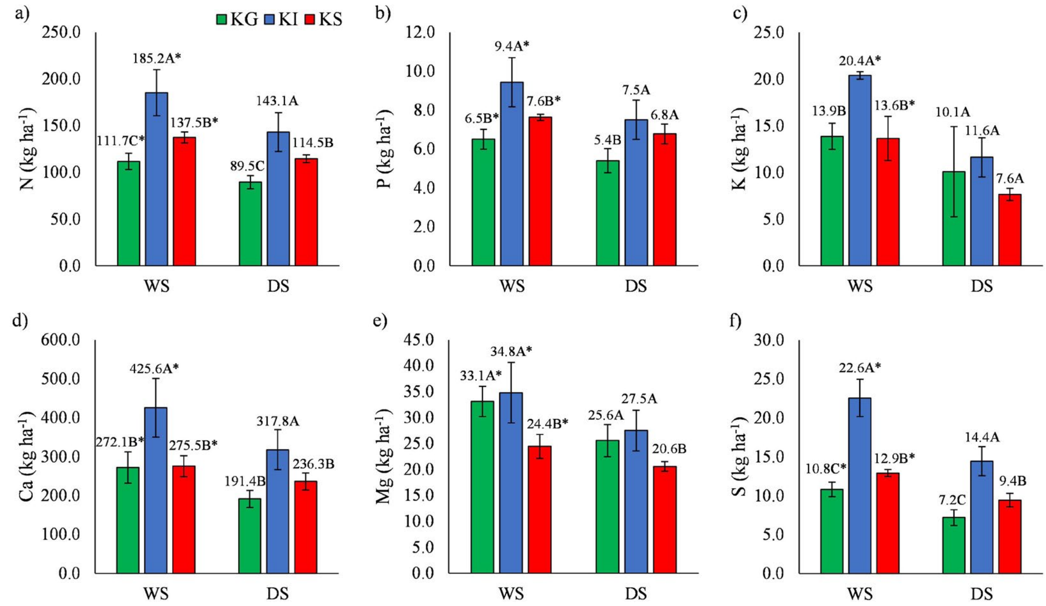

Figure 5: Macronutrient stocks in three species of *Khaya* in the *Reserva Natural Vale*, Sooretama, ES.

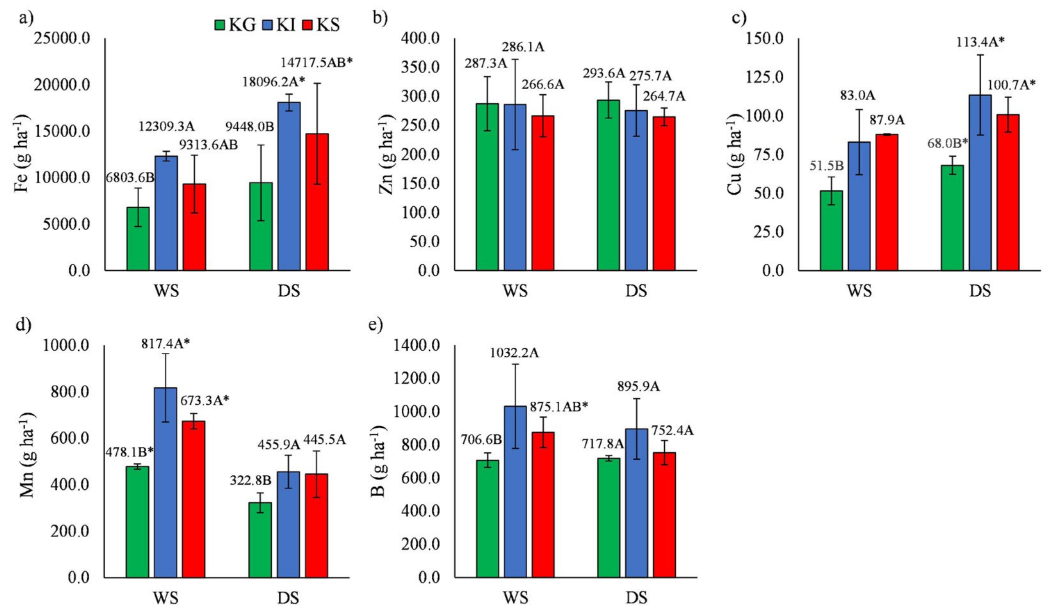

Figure 6: Micronutrient stocks in three species of *Khaya* in *Reserva Natural Vale,* Sooretama, ES.

DISCUSSION

Production and C/N ratio

The nutrients that accumulate in the litter play a crucial role in maintaining the sustainability of the forest ecosystem (Caldeira et al., 2008). The biogeochemical cycle begins with the temporary availability of nutrients contained in litter and their possible absorption by plants. Thus, both the quality and quantity of litter impact the productivity of species, as nutrients are made available by a series of factors, such as the physical and chemical properties of the soil, ecophysiology of the species, weather conditions, and time of collection (Cook et al., 2016; Viera and Rodriguez-Soalleiro, 2019).

The highest biomass values were observed during the rainy season, which is mainly related to the rate of decomposition, as well as the influence of temperature and rainfall (Oliveira et al., 2020). During the rainy season, raindrops and winds contribute to higher levels of deposition, whereas the accumulation of litter biomass depends on the deciduousness of the species during the dry season (Quesada et al., 2011; Maas et al., 2021). Regarding the African mahogany species, *K. ivorensis* showed high biomass values, justified by the intrinsic characteristics of the species itself, with the densest canopy of leaves and the best dendrometric characteristics, which include tree size and volume (Praciak et al., 2013).

The litter values for African mahogany are higher when compared to the deposition observed in areas with other forest species. When assessing the impact of spacing, species richness, and sampling time on the production of litter in forest restoration areas in Espírito Santo, Caldeira et al. (2019) observed an annual production of around 3.68 and 5.19 $Mg\ ha^{-1}$ for the periods of lowest and highest rainfall, respectively. This same trend was verified by Pinto et al. (2016), in which the authors quantified a total accumulation of litter for *E. urophylla* in the order of 12.7 $Mg\ ha^{-1}$ at seven years of age in southwest Bahia.

The higher C stocks in the rainy season can be explained by the high availability of water and temperature during this period, which interferes with the rate of decomposition and, in turn, enhances the quantity and accumulation of nutrients in the litter (Caldeira et al., 2019; Braga et al., 2022). This pattern was also observed in the studies conducted by Godinho et al. (2014), in which they state that the carbon content in the soil is affected by the contribution, decomposition rate, and nutritional quality of the litter deposited. Another important fact was observed in the *K. grandifoliola* area, which presented the highest C contents, especially during the period of lowest rainfall but, in turn, showed the lowest amounts of biomass. This is reflected in reduced C stock values when compared to the other mahogany species.

The C/N ratio results obtained for the African mahogany species are close to those observed by Barbosa et al. (2017), who obtained C/N ratios of 30.7 and 34.8 for native forest and *Pterogyne nitens* plantation areas, respectively. However, the authors found ratios of 66.7 in the *E. urophylla* area. These differences can be explained by the inverse relationship between C/N values and lignin contents, as plant materials with high C/N values (> 25) have been associated with low nutritional contents, and high lignin and polyphenol contents have been found to decompose more slowly (Adams and Atiwill, 1986; Freitas et al., 2016).

Nutritional content

The order of the nutrient contents in the litter of the African mahogany species is similar to those observed in studies conducted in areas composed of forest restoration and Atlantic Forest (Godinho et al., 2014; Klippel et al., 2016; Caldeira et al., 2020). This pattern shows that nutritional levels are related to soil and climate conditions, diversity of the species, degree of mobility of each nutrient within the plant tissue, and population density (Cunha Neto et al., 2013; Rebêlo et al., 2022).

P was the macronutrient with the lowest concentrations in the litter, regardless of the sampling period. This may be related to the low availability and adsorption of this element in the soil (Tomasi et al., 2012). The same pattern was also observed for K, which can be explained by its high mobility within plant tissues, leaching caused by rain, and participation of high rates of retranslocation before the senescence of leaves and other compartments (Godinho et al., 2014).

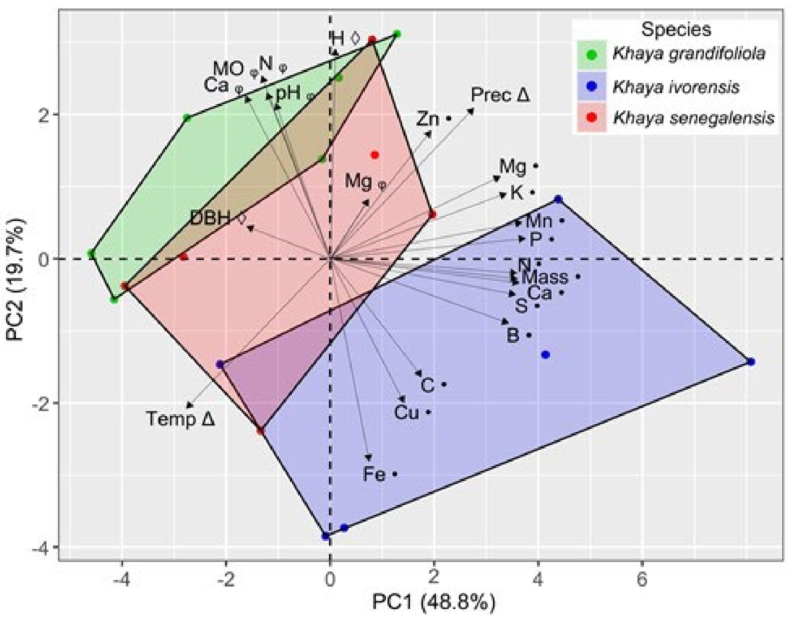

Figure 7: Multivariate analysis of principal component 1 (PC1), principal component 2 (PC2), and the input variables amount of mass, carbon, and macro- and micronutrients in the accumulated litter (●), soil fertility (φ), diameter at breast height (DBH ◊), and height (H ◊) of the trees, temperature (Temp Δ), and precipitation (Prec Δ) recorded in the experimental area.

On the other hand, Ca and N were the macronutrients with the highest concentrations in the litter in both seasons analyzed. This can be explained by the fact that one of the main constituents of the litter are the compound leaves, characteristic of the *Khaya* genus, which are formed by petioles and rachis (Nikiema and Patenak, 2008; Praciak et al., 2013). These latter play a structural and supporting role, which requires a high amount of Ca in the composition of the lignified structures (Reis et al., 2019). In addition, Ca shows low mobility in the plant, hindering it impossible to redistribute it internally to other compartments. As for N, it is an element highly required by leaves, as it is an integral part of plant components, including chlorophyll, although it is highly mobile (Taiz et al., 2016).

The intermediate concentrations of Mg may be related to the oxidation of chlorophyll in the leaves and the beginning of the decomposition process (Godinho et al., 2014). In general, although no difference was observed between the collection periods, it can be seen that the highest values were quantified in the rainy season in the *K. grandioliola* area. This pattern is confirmed by the fact that, in its natural occurrence, *K. grandioliola* is found in semi-deciduous forest, especially in the drier types and savannah (Opuni-Frimpong, 2008; Praciak et al., 2013). Regarding the difference in Mg content between the species, Albuquerque et al. (2013) mention that when *K. ivorensis* seedlings are subjected to water stress, they make strategic use of photoassimilates, investing part of the phosphate trioses in maintaining starch content and the other part in cellular respiration. *K. senegalensis*, on the other hand, shows high stomatal control, low leaf chlorophyll concentration, and reduced transpiration (Matos et al., 2016).

The highest S levels were found in the period of highest rainfall among the species, despite the fact that this nutrient occurs in low levels in the soil. These results are lower than those found by Caldeira et al. (2013) for a native forest in Alegre, ES, where the authors recorded average values of 1.82 g kg^{-1} and 1.55 g kg^{-1} for the rainy and dry seasons, respectively. Also, in a study aimed at quantifying the biomass, content and content of nutrients in the accumulated litter in the Granito rupestrian complex, Mimoso do Sul, ES, Freitas et al. (2015) state that S levels are strongly related to organic matter in the soil, which is the main source of this element for plants. Thus, high concentrations of S are found mainly in rainy periods when there is decomposition of leaf litter via microbial activity.

Information on nutrition for African mahogany species is scarce, especially regarding micronutrient levels (Smiderle et al., 2016). Different factors can interfere with the levels of these elements, as they are highly dependent on the soil solution, soil pH, oxidation-reduction reactions, concentration of other ions, humidity, temperature, and plant absorption rates (Caldeira et al., 2020).

The higher Fe concentrations in the dry season may be related to the high concentrations of this element in the soil or the presence of clay particles in the different compartments at the time of collection, with the Fe possibly coming from the destruction of this material. Even if the collection protocols are followed, contamination of the litter can be caused by the difficulty in separating the soil from the plant residues, as well as the advanced stage of decomposition (Viera et al., 2010). In a study aimed at assessing the development and mineral composition of plants subjected to omission of macro- and micronutrients in seedlings for planting *K. ivorensis*, Corcioli et al. (2016) observed a high nutritional requirement for Fe levels, with averages of 521.2 mg kg^{-1} in the leaves supplied with nutrient solution.

Zn showed significant differences between the species, justified by the fact that it is a mobile element in plant tissues and is required in high quantities for chlorophyll biosynthesis (Taiz et al., 2016). The *K grandifoliola* and *K. ivorensis* species show large and numerous leaves, respectively, explaining their nutritional requirements in terms of Zn (Reis et al., 2019). Moreover, lower values are observed in the rainy season due to the greater need for growth and cell expansion by the roots, given that 90 % of the element occurs in exchange sites or adsorbed on the walls of the cortical parenchyma cells (Faquin, 2005).

Cu plays an important role in oxidation-reduction reactions, especially in the transfer of electrons during the light-dependent reactions of photosynthesis (Broadley et al., 2012; Lunkes et al., 2022). Thus, higher Cu concentrations in the dry season for all species are required, as temperature and precipitation are factors that contribute to higher photosynthetic and respiration rates in this period. On the other hand, Mn shows the highest concentrations during the rainy season due to its relationship with the energy bonds between ATP and the enzyme complex required in photosynthesis, which aids increase the rate of growth (Corcioli et al., 2016).

Nutrient stocks

The stocks of nutrients in the litter and the possible soil-plant transfer are affected by different factors that include the functional characteristics of each element, nutritional requirements of the species, time of year, and soil and climate conditions (Mueller et al., 2015; Almeida et al., 2020). In addition, nutritional stocks correspond to the multiplication of nutrient concentrations and biomass, the latter being responsible for the greatest contribution to the amount of nutrients (Godinho et al., 2013). In this study, we found that the produced biomass directly influenced the stocks, contributing to high levels, mostly in the rainy season.

During the rainy season, a higher stock of K was found, which is justified by the fact that this element does not constitute organic compounds, given its soluble form or adsorption in cell juice. Allied to this factor, rainfall aids leach K, mainly by washing the leaves and subsequent accumulation on the forest floor (Godinho et al., 2014; Formaglio et al., 2023). Rainfall also contributes to greater deposition of N via atmospheric precipitation, as well as greater microbiological activity in the soil, leading to greater decomposition and availability of nutrients for plants, especially Ca (Langenhove et al., 2020; Tonello et al., 2021).

Among the species studied, *K. ivorensis* is the most nutritionally demanding, requiring a greater amount of photoassimilates for the growth and development of the vegetative parts (Pinheiro et al., 2011; Opuni-frinpong et al., 2016). Thus, the superiority of this species in relation to stocks may be associated with low efficiency in biochemical cycling before the leaves and rachis, the main components of the accumulated litter, abscond. Another influential factor is the high C/N ratio, above 30, which favors the immobilization of N, P, and S (Stevenson, 1982).

The stocks of micronutrients were influenced by the concentrations present in the litter, following the same order of contribution. The higher Fe stocks may be related both to the content of this element in the soil and the high absorption rates by the African mahogany species (Corcioli et al., 2016). On the other hand, the lower Cu stocks can be explained by the low mobility in plant tissues. These results corroborate those observed by Carvalho et al. (2019), who found that Cu is one of the micronutrients with the lowest stocks in the accumulated litter for different types of vegetation in the Cerrado.

The accumulation of Mn in the litter may be associated with the negative relationship with Fe, which is quite common in acidic soils such as those observed in the planting areas of this study, as well as the low availability of this element in the leaves (Caliman et al., 2020). Regarding the higher stocks during the rainy season, it is believed that the washing of the material combined with the decrease in the soil oxidation potential contributes to high levels of Mn in the litter, as it favors the solubilization of manganese oxides (Faquin, 2005; Brady and Weil, 2013). For B, this same trend can be seen in the rainy season for *K. senegelensis*, which is justified by the low mobility of this element, which results in higher levels of biogeochemical cycling given that its availability is highly impacted by the water content in the soil (Broadley et al., 2012; Tonello et al., 2023).

The seasons, represented by the meteorological variable's precipitation and temperature, are contrasting. These variables form an approximate 180° angle between them, and a diagonal axis to the boxplot. These results possibly reflect the contrasting characteristics of the two seasons. While the highest rainfall is in quadrant one and shows positive eigenvalues, the temperature is in the opposite quadrant and exhibits negative eigenvalues. We interpret that summer correlates directly with higher rainfall and higher temperature. The negative eigenvalues for temperature indicate an opposite ratio to precipitation, characterizing a winter with mild temperatures and lower rainfall.

Principal component analysis

Although there is no direct influence of rainfall and temperature on the amount of litter, it is clear that the main macronutrients are especially accumulated during the rainy season. The intensity of rainfall is possibly responsible for the renewal of the leaf canopy, as during the passage of rainwater through the structures of the canopy, branches, bark, and trunk, basic cations and monovalent ions are leached and carried to the surface of the litter covering the soil (Oliveira et al., 2020).

On the other hand, iron, copper, and carbon are associated with the season presenting lower temperatures and rainfall. The micronutrients Fe and Cu are characterized by low mobility in the phloem and thus remain in the cell structures for longer, especially during periods with lower rainfall (Lunkes et al., 2022). Moreover, these periods without precipitation favor the adhesion of soil particles with high iron concentrations to plant structures. The structure of carbon, among the other constituents, is more resilient to decomposition, which is why it was found to be more associated with the season in which precipitation and temperatures were lower (Corcioli et al., 2016).

As we observed in our analysis, and via the spatial ordering of this data set, we understand that the seasonal influence on stands of *Khaya* is mainly due to the precipitation regime, which not only acts physiologically and physically to renew the canopy, but also leaches the main cations from the cell structures. This understanding shows the importance of studying the interaction between soil and climate variables and their contributions to geo- and biogeochemical cycling.

CONCLUSION

The *K. ivorensis* species produced more litter and showed better nutritional quality, with high levels and stocks of nutrients in the accumulated litter. Lower values were found for the *K. grandifoliola* and *K. senegalensis* species. As for the influence of seasonality, the highest carbon and nutrient stocks were observed in the rainy season, indicating a relationship between the species and the highest levels of deposition and nutritional quality.

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