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# CONTRIBUTION OF TREE SPECIES IN THE DEPOSITION AND ACCUMULATION OF NUTRIENTS IN THE LITTER OF COFFEE CROP

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## ABSTRACT

One of the benefits of shade-grown coffee crops is litter deposition, which can improve nutrient cycling and increase organic matter in the soil. The objective of this study was to evaluate the contribution of tree species in the production and deposition of litter, as well as in the potential of nutrient cycling in a coffee crop. Litter samplings were carried out in the tree planting rows (TPR) and between tree planting rows (TPI). Four deposition points were sampled in the TPR and TPI, spaced apart at 1.5, 3.0, 4.5, and 6.0 m from the trunk of the trees (*Anadenanthera falcata*, *Peltophorum dubium* and *Cassia grandis*). Nine samplings were carried out between October 2016 and September 2017. Higher deposition occurred in May, August, and September, and it was higher in the TPR. The species that most contributed to the deposition were the coffee plants and *C. grandis*. The coffee crop showed the highest accumulation of nutrients owing to the higher deposition of litter and higher levels of N, K and Mg, while *C. grandis* was the forest species that concentrated most Ca and S. The influence of forest species on nutrient cycling is minimal, primarily due to the reduced contribution of litter compared to coffee trees.
**Additional keywords**: *Coffea arabica*, nutrient cycling, plant diversity, shading

## RESUMEN

**Contribución de las especies arbóreas en la deposición y acumulación de nutrientes en la hojarasca de los cultivos de café**
Uno de los beneficios de los cultivos de café bajo sombra es la deposición de hojarasca, que puede mejorar el ciclo de nutrientes y aumentar la materia orgánica en el suelo. El objetivo de este estudio fue evaluar la contribución de las especies arbóreas en la producción y deposición de hojarasca, así como en el potencial del ciclo de nutrientes en un cultivo de café. Se realizaron muestreos de hojarasca en las hileras de plantación de árboles (TPR) y entre las hileras de plantación de árboles (TPI). Se muestrearon cuatro puntos de deposición en las TPR y TPI, espaciados a 1,5 m, 3,0 m, 4,5 m y 6,0 m del tronco de los árboles (*Anadenanthera falcata*, *Peltophorum dubium* y *Cassia grandis*). Se realizaron nueve muestreos entre octubre de 2016 y septiembre de 2017. La mayor deposición se produjo en mayo, agosto y septiembre, y fue mayor en la TPR. Las especies que más contribuyeron a la deposición fueron el café y *C. grandis*. El cafeto mostró la mayor acumulación de nutrientes debido a la mayor deposición de hojarasca y a los mayores niveles de N, K y Mg, mientras que *Cassia grandis* fue la especie forestal que más concentró Ca y S. La influencia de las especies forestales en el ciclo de nutrientes es mínima, debido principalmente a la menor contribución de la hojarasca en comparación con el cafeto.
**Palabras clave adicionales:** Ciclo de nutrientes, *Coffea arabica*, diversidad vegetal, sombreado

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## INTRODUCTION

Coffee (*Coffea arabica* L.) is one of the most consumed drinks, with a growing international market. Brazil is the world's largest coffee producer and exporter, and most of the crops are grown under full sun (Gomes et al., 2020), a productivity-oriented strategy to increase short-term profits (Hernandez et al., 2019).

Although productivity is successful, the predominance of coffee plants under full sun makes production in Brazil vulnerable because there are several challenges posed by extreme weather events (Souza et al., 2012; Gomes et al., 2020), biodiversity decline and soil degradation, which may have strong implications for ecosystem functions, e.g., nutrient cycling. Consequently, the

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system may become less resilient and dependent on high fertilizer doses for maintain soil fertility (Nesper et al., 2018; Hernandez et al., 2019).

In contrast, coffee bushes intercropped with other trees is a sustainable production system that allows the conservation of biodiversity (Hernandez et al., 2019; Sousa et al., 2019). This system supports various ecosystem services, including soil protection against erosion, increased soil fertility and moisture, carbon sequestration, and nutrient cycling (Iverson et al., 2019; Bertrand et al., 2021).

The inclusion of trees in coffee crops can improve cation exchange capacity and reduce soil acidity (Cerda et al., 2017; Tully et al., 2013). Trees can absorb nutrients in the deeper layers, making them available in the upper layers of the soil, in addition to reducing nutrient leaching and nitrogen loss by volatilization and phosphorus by fixation (Getachew et al., 2023). Also, leguminous trees (Fabaceae) increase N in the soil because of their ability to fix the nutrient biologically (Waktola and Fekadu, 2021). Therefore, they are an alternative to reduce the use of synthetic inputs and restore soil balance (Sauvadet et al., 2019). Afforestation can also add value to coffee crops, which will be produced with fewer inputs, following regenerative practices, resulting in improved quality of the grains and the drink, and thereby helping coffee growers to enter the specialty coffee market (Silva et al., 2019; Bertrand et al., 2021).

One of the main ways to improve soil fertility in shade-grown coffee crops is nutrient recycling through the decomposition of tree biomass, especially litter (Petit et al., 2019). This compartment is a link between vegetation and soils, by which nutrients are returned to the soil; therefore, the amount and pattern of the material regulate the nutrient cycle (Asigbaase et al., 2021).

The improvement of soil quality with litter deposition in shaded coffee crops depends on several factors, e.g., tree species (Piato et al., 2020), spatial distribution of trees (Morinigo et al., 2017) and nutrient accumulation in the added biomass (Petit et al., 2019). Understanding how these factors affect the amount and quality of litter is necessary to ensure that shaded coffee crops are properly grown. Thus, more heterogeneous systems will be able to be produced, with lower production costs and greater ecological gains (Iverson et al., 2019).

In this context, the objective of this study was to evaluate the contribution of tree species for production and deposition of litter, as well as their potential for nutrient cycling in coffee crops.

## MATERIALS AND METHODS

The study was conducted between October 2016 and September 2017, on a farm (“Fazenda Retiro Santo Antonio”: 22º06'57" S and 46º40'48" W) in the municipality of Santo Antonio do Jardim, São Paulo. The climate of the region is characterized by the occurrence of cold winters and summers with mild temperatures (Köppen, 1948). Figure 1 shows the temperature and precipitation values during the study period.

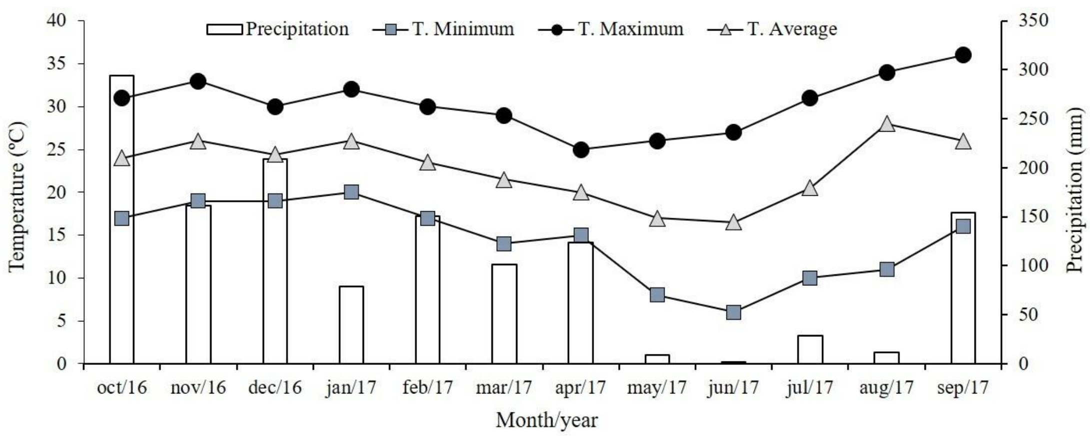


**Figure 1.** Monthly precipitation and average, maximum and minimum temperatures recorded in the weather station during the experiment

The soil of the area was classified as a typical dystrophic Tb haplic Cambisol (Santos et al., 2018a). Since 2007, the area has been cultivated with coffee plants of the variety Obatan, with spacing of 3.5 m between rows and 0.8 m between plants (3,571 plants $ha^{-1}$). In 2009, tree species were introduced into the system, with spacing of 16 m between rows and 14 m between plants (44 trees·$ha^{-1}$). The area was managed with agricultural machinery and implements. Coffee plants were fertilized with urea (four times a year), potassium chloride (twice a year), reactive phosphate, boron and compost based on bovine manure, chicken bed and coffee plant mulch (once a year).

The experimental design was completely randomized, with six replications. The treatments were determined according to the tree species intercropped with the coffee crop: (1) *Anadenanthera falcata* (Benth.) Speg ("angico-do-cerrado"); (2) *Peltophorum dubium* (Speg.) Taub. (canaphistula) and (3) *Cassia grandis* L.f. (pink shower). Leaf litter mass deposition of the coffee crop (eight coffee shrubs between each pair of tree species) was determined (Figure 2). The samplings were carried out both in the tree planting row (TPR) and in the tree planting interrow (TPI). Four leaf litter deposition points were sampled in the TPR, spaced apart at 1.5, 3.0, 4.5, and 6.0 m from the tree trunks and four points in the TPI distributed parallel to the TPR points, also spaced apart at the same distances. Each sampling point was performed in duplicate (right and left side), and the material was collected in a single sample per point, with six replications (Figure 2). Statistical analyses were carried out separately for the species (trees and coffee trees) and for the distances (1.5, 3.0, 4.5, and 6.0 m)

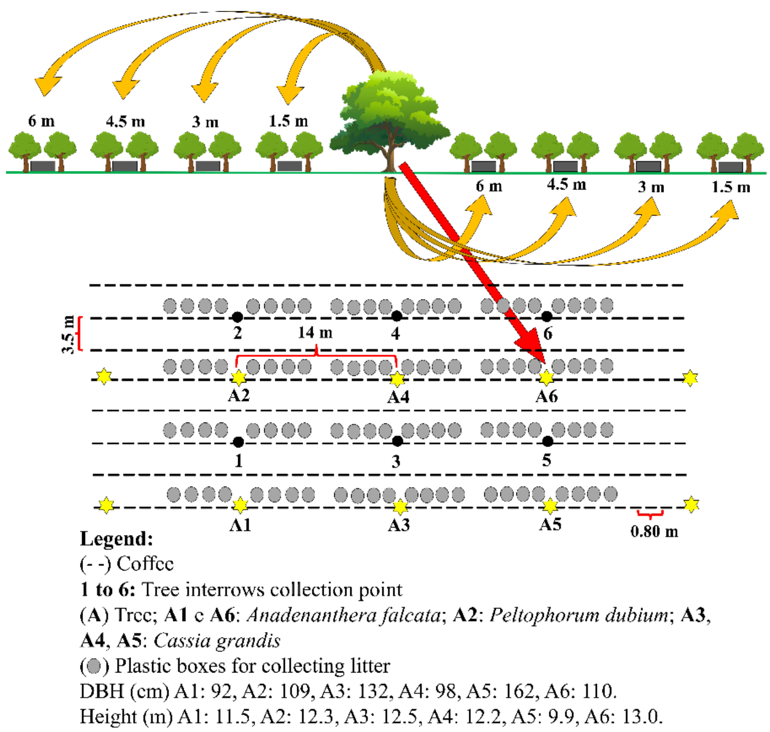


**Figure 2.** Schematic representation of the shaded coffee crop area and detail of litter sampling points in the tree planting row. DBH: diameter at breast height (cm)

The litter of trees and coffee shrubs was collected according to the methodology adapted from Jaramillo et al. (2008), which involves using a nylon net on the ground between the rows of coffee trees to collect the litter. In this study, plastic boxes were used to collect the material. The boxes, with dimensions of 0.52 m long, 0.35 m wide and 0.17 m high, were placed on the soil, under the projection of the coffee tree canopy. The collection boxes were positioned so as not to hinder the mechanized cultural practices of the area, because it is a commercial crop.

Nine litter samplings were carried out at thirty-day intervals, from November 2016 to September 2017 (except June and July). In the months of June and July 2017, no samplings were carried out because it was time for coffee harvest (semi-mechanized; thus, the collection boxes would have prevented the harvest). The plant material of each box was stored in plastic bags, and subsequently separated by tree species or coffee and left to dry in a forced air circulation oven at 65°C for 72 hours, to determine the dry mass by species, month, and total, at each sampling point in the TPR and the TPI.

The dry material was weighed on an analytical balance. Total litter deposition (sum of all months of sampling) in the TPR and TPI were determined by sampling point ($t \cdot ha^{-1}$); monthly litter deposition in the TPR and TPI, by sampling point ($t \cdot ha^{-1} \cdot month^{-1}$); and monthly litter deposition by tree species and coffee ($t \cdot ha^{-1}$ month), adding up the litter deposited monthly at all the sampling points in the TPR and TPI per tree species and coffee. For the monthly total litter of the species *A. falcata* and *C. grandis*, which presented two and three individuals, respectively, the average deposition per individual was used for the evaluations.

To determine the nutrient contents for litter dry weight, all samples collected during the experiment (nine samplings) were separated by species (coffee, *A. falcata*; *P. dubium* and *C. grandis*) at each sampling point (TPR and TPI, 1.5, 3.0, 4.5 and 6 m). Subsequently, these samples were homogenized, generating a sample composed by the species, with six replications. The samples were processed in a Willey mill to determine nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S) contents, following the method used by Malavolta et al. (1997).

Total nutrient accumulation in the litter was calculated by multiplying the nutrient content of each species ($g \cdot kg^{-1}$) by the average amount of dry weight deposited per tree individual and by the total dry weight of coffee trees ($t \cdot ha^{-1}$). To quantify the contribution of each species to the input of nutrients via litter, the ratio between the total accumulation of the elements and the accumulation observed in the litter of each species was calculated, and the results expressed as a percentage. The calculations were performed for each macronutrient in isolation and for the sum of all nutrients.

The data were submitted to tests of normality of error distributions (Shapiro-Wilk) and homogeneity of variances (Bartlett), and, when the assumptions of variance analysis (ANOVA) were not met, they were transformed into $\sqrt{x}$. After the assumptions were met, the data were submitted to ANOVA and the means were compared by Tukey's test ($p \leq 0.05$), except for the data from the sampling point in relation to the tree species (TPR and TPI), whose means were compared by Student's t test ($p \leq 0.05$).

## RESULTS AND DISCUSSION

A significant difference was observed in the total amount of litter produced as a function of the site of sampling in the shaded coffee crop (Figure 3A). However, the distance from the trunk of the trees did not influence the total amount of litter (Figure 3B).

Total deposition ($t\ ha^{-1}$) was higher in the tree planting row (TPR). The TPR contributed 8.7 $t \cdot ha^{-1}$, while the value for the TPI was 4.3 $t \cdot ha^{-1}$ (Figure 3A). Alonso et al. (2015) argued that there is a positive relationship between litter and tree canopy cover index, with higher deposition in denser spacing. Silva et al. (2019), evaluating the density and occupation of the canopy by tree species at the same site of this study, found low canopy density in the tree planting interrows, which decreases the potential of litter production.

In the months of May, August and September, there was a higher deposition of litter in the TPR and in the TPI (Figure 4). The lowest amounts were found to occur in November and December in the TPI. On the other hand, the lowest deposition of litter occurred in March.

The TPR accumulated a greater amount of litter in all sampling periods. The pattern of litter deposition during the months of the year was more strongly related to climatic variations such as temperature and rainfall (Figure 1) than to the location of trees (Figure 3B). In general, the highest contributions by the coffee plants and the trees occurred in the driest months, as also found by other authors (Paudel et al., 2015; Guimarães et al., 2017; Asigbaase et al., 2021), who reported a strong influence of seasonality on litter deposition. This result is linked to the characteristics of the trees, which are deciduous to semi-deciduous species; therefore, they lose the leaves during the coldest and drier season. This is due to the physiological response of trees to water deficit (Guimarães et al., 2017) and the inability of plants to provide water to the leaves and avoid desiccation and damage to their structures (Descheeemaker et al., 2006). Thus, when leaves fall off, plants reduce the loss of water by perspiration. The highest contribution of litter in the dry period is an important tool in nutrient cycling, since nutrients are immobilized and then released at the beginning of the rainy season, when decomposition is more intense (Sayer and Tanner, 2010). This time coincides with the time when coffee plants have the highest demand for nutrients.

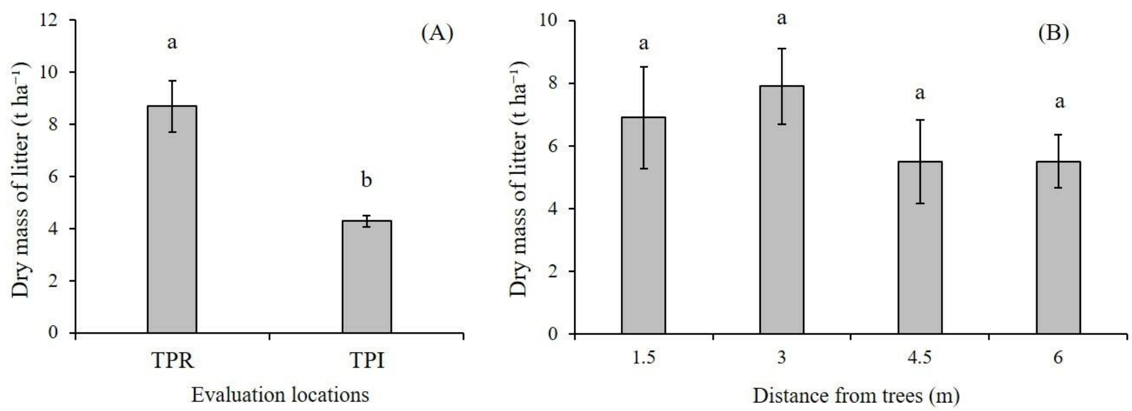


**Figure 3.** Total deposition of litter in the shaded coffee crop from October 2016 to September 2017 (sum of nine samplings), depending on the sampling sites (A) and distances between trees (B). Means followed by the same letter in the bars do not differ by Student's t test (A) and Tukey's test (B), at 5% probability. The error bars represent the standard error of the means

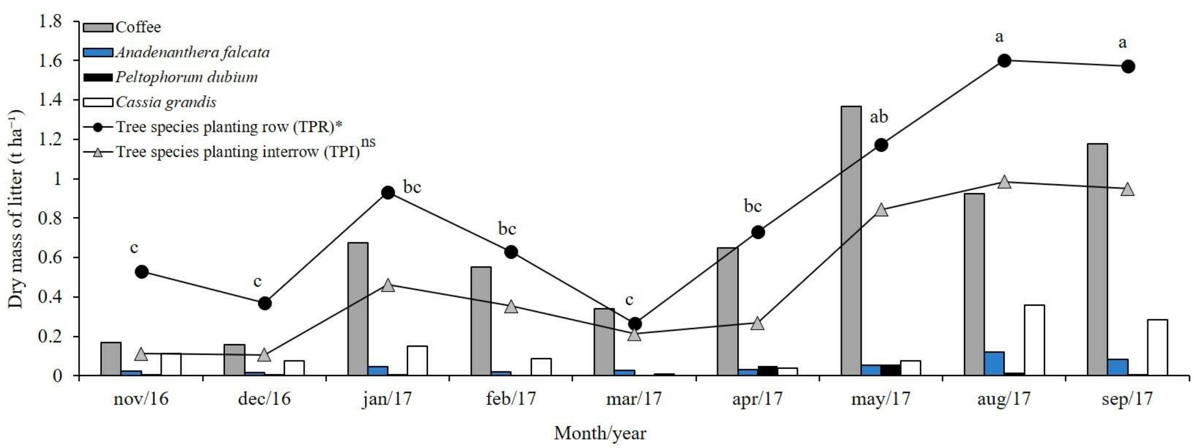


**Figure 4.** Monthly deposition of litter according to species (trees and coffee tree) and location of sampling. TPR: Tree species planting row; TPI: Tree species planting interrow. *Means followed by different letters on the markers (circles) differ by Tukey's test at 5% probability. ns: non-significant

The species that contributes most to the increase in litter was the coffee crop (Figure 4), and this finding can be attributed to the largest number of coffee plants in comparison to forest trees. Another reason is the characteristic of shade trees, which have smaller leaves when compared to coffee tree leaves. Neves et al. (2022) attributed lower litter deposition to sites where tree species have small leaves.

The lowest rainfall and temperatures occurred between the months of May and August (Figure 1), which contributed to a greater deposition of litter, mainly of coffee plants, which contributed 78% of the total litter. Deposition by the coffee plants increased from May onwards. Campanha et al. (2007) also found higher litter deposition in May, attributing the result to the fall of coffee leaves. In Brazil, the dormancy of ripe buds and the maturation of coffee fruits occur in May and the subsequent months, (Matiello et al., 2020), causing leaf fall. Therefore, the ripening phase of the fruits is a strong drain for photoassimilates (Thomaziello et al., 2000). Also, owing to the form of harvest, coffee trees lose a large number of leaves (Campanha et al., 2007), increasing the deposition of litter in the driest months of the year.

Among the forest tree species, *C. grandis* was the one that most produced litter, contributing 15% of the total. *A. falcata* and *P. dubium* contributed 5% and 2% of total deposition, respectively. The analysis of deposition of litter by species showed that *C. grandis* produced 11.87 $kg \cdot plant^{-1}$, *A. falcata* 4.17 $kg \cdot plant^{-1}$ and *P. dubium* 0.16 $kg\ plant^{-1}$. *C. grandis* and *A. falcata* produced more litter in the months of August and September. On the other hand, *P. dubium* had higher deposition in April and May (Figure 4). The highest deposition by *C. grandis* may be due to the largest diameter at breast height (DAP) found in the species (Figure 2). Positive relations between amount of litter and DAP of forest species have already been reported in other studies (Molffi et al., 2020; Kassa et al., 2022). According to Negash and Starr (2013), DAP is the easiest and most reliable tree biometric parameter to measure and was the best parameter to estimate the annual leaf litter production of trees.

Nutrient content of litter varied among species (Table 1). These differences can be due to several factors, e.g., age and density of the species; amount of litter produced; spatial variation of nutrients in the soil; interception capacity of one species over the other, and phenology of the species (Morinigo et al., 2017; Kassa et al., 2022).

The coffee crop litter showed the highest levels of K and Mg in comparison to that of the tree species (Table 1). For N content, the coffee crop litter outperformed *P. dubium* and *C. grandis*, but it had a similar result to that of *A. falcata*. On-site fertilization is performed on the soil under the projection of the coffee tree canopy, causing different fertility gradients, with higher concentration of nutrients in the areas near the coffee trees. This may have increased nutrient absorption efficiency, and consequently, the contents in the litter, especially N and K, which are the most required by the coffee crop, and Mg, which plays a fundamental role in photosynthesis (Tränkner et al., 2018; Hauer and Tränkner, 2019).

**Table 1.** Content and accumulation of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) for litter dry weight of the leaves of the tree crop and the coffee species.

| Species | N | P | K | Ca | Mg | S |
|---|---|---|---|---|---|---|
| | Content of nutrients ($g \cdot kg^{-1}$) | | | | | |
| Coffee | 23.93 a[1] | 0.39 a | 15.53 a | 12.06 bc | 3.53 a | 1.88 a |
| *A. falcata* | 20.23 ab | 0.42 a | 7.85 b | 13.43 b | 2.45 b | 1.30 b |
| *P. dubium* | 17.25 b | 0.12 b | 6.50 b | 9.78 c | 1.68 c | 1.70 ab |
| *C. grandis* | 16.57 b | 0.29 a | 6.61 b | 19.80 a | 1.39 c | 2.03 a |
| CV (%) | 8.51* | 32.95 | 15.98* | 6.53* | 6.19* | 14.81 |
| | Accumulation of nutrients ($kg \cdot ha^{-1}$) | | | | | |
| Coffee | 88.38 a | 1.46 a | 56.70 a | 44.53 a | 13.03 a | 6.96 a |
| *A. falcata* | 4.39 b | 0.10 bc | 1.90 b | 3.27 c | 0.59 b | 0.32 c |
| *P. dubium* | 1.68 b | 0.01 c | 0.65 b | 0.95 c | 0.16 b | 0.17 c |
| *C. grandis* | 11.48 b | 0.20 b | 4.58 b | 13.72 b | 0.96 b | 1.40 b |
| CV (%) | 11.39* | 12.47* | 15.07* | 6.81* | 6.66* | 8.52* |

[1]Means followed by the same letter in the column do not differ by Tukey's test, at 5% probability. Means of six replicates per species. *Data transformed into $\sqrt{x}$.

There was high average N content in the coffee crop litter and the forest species. This may have been due to the influence of the trees, which can reduce losses (Getachew et al., 2023) and improve the utilization of N that is applied to the soil through fertilization. The presence of a nodulating legume (*A. falcata*), that is, establishing symbiosis with $N_2$-fixing bacteria, may also explain the high levels of N in the litter, since part of the biologically fixed N can be provided to coffee trees and other trees by means of the fall and decomposition of litter (Mamani et al., 2012).

The species *P. dubium* had the lowest P content ($0.12 \cdot g \cdot kg^{-1}$) compared to the other species, which did not differ among themselves, ranging from 0.29 $g \cdot kg^{-1}$ to 0.42 g $kg^{-1}$. The low levels of P (0.12-0.42 $g \cdot kg^{-1}$) in the litter of the coffee crop and the shade trees suggest that this may be the limiting nutrient in the agroecosystem, a fact also reported by Notaro et al. (2014) and Kassa et al. (2022). This is due to the characteristics of P fixation in soils, which limits its availability to plants, especially in soils with higher clay content. Another explanation for the low P content is its translocation from senescent tissues to other parts of the plant (Notaro et al., 2014).

*Cassia grandis* had higher Ca content (19.80 $g \cdot kg^{-1}$) than other forest species and the coffee crop. Finally, S content in the coffee crop (1.88 $g \cdot kg^{-1}$) and in *C. grandis* (2.03 $g \cdot kg^{-1}$) had the highest values compared to *A. falcata* (1.30 $g \cdot kg^{-1}$), but it was similar to that of *P. dubium* (1.70 $g \cdot kg^{-1}$) (Table 1). It is worth noting that *C. grandis* had less Mg and K. On the other hand, the species with more K and Mg (coffee crop and *A. falcata*) contained less Ca compared to *C. grandis*. The concentration of Ca can be inhibitory to Mg and K and vice versa. Ca, Mg and K are antagonistic, thus the concentration of one can affect that of the others. It is plausible that this influenced the rate of absorption, which resulted in the accumulation dynamics of these nutrients in the forest species litter and the coffee tree. Ramírez et al. (2020) demonstrated that the absence or excess of one of these cations can alter the absorption dynamics of the coffee tree. The authors found that owing to the lower absorption of Ca, the coffee trees compensated for it by absorbing other cations (K and Mg), increasing their concentrations in the tissues. In our study, K accumulation was preferred over Ca by the coffee crop; because K is the second nutrient most required by this crop (Santos et al., 2021b; Rodrigues et al., 2023). This may have kept Ca in the soil solution, which may at least partly explain the higher Ca content in *C. grandis*.

The nodulating species *(A. falcata*) showed lower S content in the litter, and this may be due to the higher demand for S in N-fixing legumes, because the element is essential in biological fixation and may be a limiting factor in symbiosis. According to Divito and Sadras (2014), nodules are more sensitive to S deficiency in comparison to the shoot; therefore, S assimilation in tissues is reprogrammed during symbiosis (Becana et al., 2018), which increases the concentration S in the nodules in comparison to the leaves (Divito and Sadras, 2014) and helps explain the results found in this study.

The highest accumulations for all nutrients were found in the coffee crop litter, especially N and K, which are the most required by such crop (Matiello et al., 2010; Clemente et al., 2015). Coffee litter accounted for 71.26% (Ca) to 88.82% (K) of nutrient inputs and 81.74% of total return. Comparable results were reported by Asigbaase et al. (2021), who found that the commercial crop litter (*Theobroma cacao* L.) was the main source of nutrients in shade-grown systems.

*Cassia grandis* showed higher levels of Ca and S in the litter and was, among the forest species, the one that returned the most nutrients (Table 1), especially Ca and N. Except for K, there was little variation between the contents in the litter of the coffee crop and the other tree species. This result suggests that the highest nutrient inputs by the coffee crop and *C. grandis* are related to litter deposition. This finding is similar to that of other studies, whose nutrient inputs were determined by the leaf litter fall pattern (Paudel et al., 2015), since the probability of nutrient inputs is higher as deposition increases.

In general, our results suggest that the trees have a smaller direct effect on litter-induced nutrient cycling, since the coffee trees account for the highest production of litter. This may be related to the choice of forest species, which was made particularly for the sake of microclimate protection (shading) of the coffee crop. Studies conducted in the same place indicated that afforestation brought benefits, e.g., higher photosynthetic efficiency of coffee crops (Silva et al., 2019), improvement in coffee drink quality (Silva et al., 2018) and higher microbiological activity of the soil (Guimarães et al., 2017). On the other hand, Morinigo et al. (2017), on the same site, found that trees increase soil resistance to penetration and contribute little to soil fertility; for some nutrients, there is greater competition, especially against coffee trees located in the same tree planting row. According to Getachew et al. (2023), the level of complementary use of resources and competition will depend on the selection of tree species, which must be careful to maintain the biogeochemical parameters of the soil in coffee agroecosystems.

## CONCLUSIONS

The distance from the trunk of the forest species did not influence the pattern of litter deposition in the coffee agroecosystem. The largest amounts of litter teal occurred in the tree planting row, owing to the low projection of the canopy between the rows.

Seasonality influences litter inputs, with the highest deposition occurring in the driest and coldest months of the year, which in Brazil coincide with the ripening season of the fruits and rest of the floral buds of the coffee trees. This results in greater loss of leaves. Because the shade trees are deciduous and semi-deciduous species, they provide more litter in the driest periods.

The return of nutrients in the agroecosystem is related to the pattern of litter fall. The coffee trees were the main source of macronutrient inputs. The trees had little influence on nutrient cycling especially because of the reduced litter deposition in comparison to that of the coffee trees. Among the forest species, *C. grandis* produced more litter and concentrated more Ca and S; thus, it was the tree species that contributes the most to nutrient cycling in the coffee crop.

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