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RESEARCH ARTICLE

# Contribution of Pruning Residues to Carbon and Nutrient Cycling in Cacao Monocultures and Agroforestry

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**Abstract**
*Background and aims* Cacao in agroforestry systems can benefit from improved nutrient cycling, since shade trees could transfer nutrients through litterfall and pruning residues. Additionally, shade trees could affect decomposition processes of these residues. Studies on nutrient release from pruning residues and on the effect of shade trees on decomposition processes are scarce. We aimed to determine how cropping systems (agroforestry, monocultures) affect the decomposition of pruning residues and quantify nutrient release by these residues.

*Methods* Litterbags with two mesh sizes (0.1 and 2 mm), containing leaf mixtures, were placed under five cropping systems (conventional and organic monocultures, conventional and organic agroforestry, successional agroforestry) in a long-term trial in Alto Beni, Bolivia. Carbon, phosphorus, nitrogen, potassium, cellulose, and lignin were measured in fresh leaves and litterbags at 4, 8, and 12 months after laying.

*Results* Nitrogen was higher under conventional agroforestry than under the other systems at 4 months after laying. Phosphorus was higher under agroforestry than under monocultures at 8 months after laying. Litterbags with 2 mm mesh size contained lower amounts of carbon and nutrients at 4 months after laying than litterbags with 0.1 mm mesh size. Release of nutrients from pruning residues was estimated.

*Conclusions* The effect of shade trees on decomposition processes was limited to changes in nitrogen and phosphorus contents in litterbags. Larger mesh litterbags likely favoured microbial colonization and nutrient transfer through leaching. The nutrient input from pruning residues could meet the potassium and nitrogen demands of cacao but is insufficient for phosphorus.

**Keywords** Agroforestry · Nutrients · Leaching · Immobilisation · Nitrogen · Phosphorus

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## Abbreviations

| | |
|---|---|
| AFS | Agroforestry systems |
| CA | Conventional agroforestry |
| CM | Conventional monoculture |
| OA | Organic agroforestry |
| OM | Organic monoculture |
| SA | Successional agroforestry |

## Introduction

Cacao is one of the most important tree species cultivated in the tropical regions of South America (Imbach et al. 2015). While Bolivia contributes only to 6% of South America's cocoa production, this commodity serves as the primary source of income for smallholder farmers in the Alto Beni region (Ortiz and Somarriba 2005; te Velde et al. 2006). In the wild, cacao (*Theobroma cacao*) thrives as understory plant in tropical rainforests, receiving low levels of light. Consequently, cacao cropping proves possible within agroforestry systems (AFS). However, the species' phenotypic plasticity also allows for successful growth under full-sun conditions in monoculture (Jaimes-Suárez et al. 2022). Compared to AFS, monoculture typically gives higher yields in the initial years. However, the longevity of cacao in monocultures is often shorter than in AFS, primarily due to photooxidative stress (Jaimes-Suárez et al. 2022), requiring earlier renewal of trees than in shaded conditions (Andres et al. 2016). Moreover, monocultures require more external fertilizer inputs than AFS, and decrease in yields can also be due to soil exhaustion caused by inappropriate fertilization practices (Vaast and Somarriba 2014). In contrast, cultivating cacao within AFS has the potential to provide numerous ecosystem services. These include, for instance, compensating lower cacao yields by timber and fruit production, enhancing carbon sequestration through shade tree biomass, buffering microclimatic conditions, preserving higher biodiversity (Niether et al. 2020), while shade trees contribute to nutrient cycling (Mortimer et al. 2018). Moreover, cultivation within AFS can have positive effects on soils which include: reduced erosion (Muchane et al. 2020), increased organic matter content and nutrient availability, and more dynamic microbial processes (Dollinger and Jose 2018), compared to monocultures.

Shade trees can contribute directly to nutrient cycling by acting as nutrient sources for crops, potentially reducing or even eliminating the need for external fertilization (Fontes et al. 2014; Froufe et al. 2020; Asigbaase et al. 2021). For example, Hartemink (2005) reported that the quantities of nitrogen, phosphorus and potassium in cacao AFS litter and rainwash across different locations, soil types, cacao tree densities and shade trees species were higher than the amounts of these nutrients lost in cacao beans. Although this does not imply sustainability of AFS, as nutrient losses by leaching and immobilisation in plant biomass also occur, the nutrient inputs due to litter and throughfall should be considered when evaluating the nutritional status of AFS (Hartemink 2005). Shade trees could obtain nutrients from deeper soil layers and transfer them to cacao through litter decomposition while nitrogen-fixing trees could promote biological nitrogen fixation and transfer this nutrient to the crop. However, shade trees could also compete for nutrients and some nitrogen fixers might increase phosphorus immobilisation (Mortimer et al. 2018). The role of shade trees in facilitating nutrient uptake or competing with cacao depends on the system design (Mortimer et al. 2018) and specific species (Sauvadet et al. 2020). Additionally, shade trees could have indirect effects on nutrient release from cacao litter by increasing decomposer communities through higher biodiversity (Udawatta et al. 2019) and by providing more favourable microclimatic conditions in AFS respect to monocultures. Hence, further research is required on the role of shade trees and biodiversity in nutrient cycling to find generalizable trends.

In some AFS, management includes the pruning of cacao and shade trees. Pruning is labour intensive but can improve cacao yields by controlling shade levels (Esche et al. 2023). Moreover, pruning residues could increase carbon and nitrogen stocks in soil (Schneidewind et al. 2019). Pruning residues consist of fresh material which have higher nutrient contents than senescent leaves found in litterfall (Hartemink 2005). Pruning and mulching frequency was positively related to higher nutrient stocks in litter (Steinfeld et al. 2024). Therefore, it is necessary to determine what are the nutrient inputs due to the pruning residues in AFS and include these inputs into the economic evaluation of AFS management practices that include pruning. Additionally, determination of decomposability and rate of nutrient release of these residues can give insights for better management of pruning activities to better align nutrient availability with plant requirements.

The decomposition of plant litter comprises fragmentation, leaching and catabolism by decomposers, which are interlinked processes (Cotrufo et al. 2010a). Fragmentation includes the breaking down of litter carried out by edaphic fauna and the physical displacement of these fragments into soil layers (Cotrufo et al. 2010b). Leaching involves the downward movement of nutrients (Lehmann and Schroth 2002) and soluble carbon molecules (Cotrufo and Lavallee 2022) from litter to soil driven by water. Catabolism, carried out by soil fauna and microorganisms, implies the breakdown of molecules into $CO_2$, $H_2O$ and mineral components, producing energy and incorporation of elements or molecules into decomposer biomass. Mostly for microorganisms, immobilization processes in microbial biomass have been reported. For example, when nitrogen in plant litter is low, microorganisms obtain additional nitrogen from the environment and immobilise it in their biomass, increasing temporarily the amount of nitrogen in litter (Robertson and Groffman 2024).

The decomposition and mineralization processes depend on substrate characteristics, decomposer communities and environmental conditions such as soil properties and microclimate (Manzoni et al. 2010). Respect to substrate characteristics, the C:N relationship and total nutrients are proposed as drivers of decomposition rates (Zhang et al. 2008). In AFS, pruning residues consist of material from various tree species with different decomposition rates. By then, there is a possibility of positive or negative interactions between the decomposition processes of these mixed residues (Cuchietti et al. 2014; Porre et al. 2020). Decomposition was enhanced in mixtures containing both cacao leaves and leaves from accompanying species, compared to cacao leaves alone (Saj et al. 2021). Respect to decomposers, systems with increasing complexity are expected to have more diverse decomposer communities (Udawatta et al. 2019) and tree species richness has shown positive effects on nutrient cycling (Steinfeld et al. 2024). Additionally, conventional and organic management of systems can have an effect on microbial communities (Hartmann et al. 2015; Lori et al. 2022). Besides microbial communities, invertebrates also contribute to nutrient turnover although the extent of their effect is system-specific (Chassain et al. 2021). Finally, AFS can provide different microclimatic conditions compared to monocultures (Niether et al. 2018) potentially influencing decomposer communities.

We conducted our research at the long-term SysCom trial in Bolivia, where cacao is cultivated under five different cropping systems varying in plant diversity and management (organic and conventional) (Schneider et al. 2017). Using litterbag experiments, we aimed at determining the effects of these systems on the decomposition and nutrient release from green leaves resulting from pruning of cacao and of accompanying species. We hypothesized that the decomposition and nutrient release: (i) would be facilitated under agroforestry or organic management compared to monoculture or conventional systems; (ii) would be enhanced in leaf mixtures compared to cacao leaves alone; (iii) would be more efficient when mesofauna is not excluded.

## Methods

### Study site

The SysCom trial is located at"Sara Ana"in the Alto Beni region of the La Paz department, Bolivia. It is situated on an alluvial terrace on the north-eastern side of the Andes (15°27′36.60″S, 67°28′20.65″W). The soils are Lixisols and Luvisols according to the FAO classification (Schneider et al. 2017). The altitude ranges between 380 and 400 m above sea level. The mean annual temperature of the area is 26 °C, and the mean annual rainfall is 1519 ± 220 mm, with the majority occurring between October and March.

The trial started in 2008 with the clearing of a secondary forest that had been established for twenty years, characterized by *Guadua* spp. among other species. Five cacao cropping systems are being compared: (1) conventional monoculture (CM), (2) organic monoculture (OM), (3) conventional agroforestry (CA), (4) organic agroforestry (OA), (5) successional agroforestry system (SA), using a randomized block design with 4 repetitions. The plot size is 48 m × 48 m. Cacao trees are planted at intervals of 4 m × 4 m (625 trees $ha^{-1}$). The OA and CA systems exhibit a permanent shade provided by trees such as leguminous species (e.g., *Erythrina* spp. and *Inga* spp.), timber species (e.g., *Swietenia macrophylla*), and fruit species (e.g., *Theobroma grandiflorum*) growing between the cacao trees, with a total density of about 304 trees ha$^{-1}$. The SA system includes the same species but also additional cultivated crops (e.g., ginger, curcuma), trees (e.g., peach palm), and spontaneous species from natural regeneration. The total density of associated trees is approximately 1180 trees ha$^{-1}$.

In the CM systems, mineral fertilizers (Ntotal-$P_2O_5$-$K_2O$-MgO) were applied twice a year (March and December) at a dose of 18–12-24–4 kg ha$^{-1}$. The CA received half of this dose also twice a year. Both CM and CA received herbicides 4–5 times per year, mainly glyphosate. In OM, compost prepared with the following proportions (in fresh weight): around 21% banana pseudostems, 21% cacao, coffee, and banana peels, 21% topsoil, 7% chicken manure, and 10% sludge, was applied around the cacao tree trunk once a year (December), at the rate of 3400 kg dry weight. ha$^{-1}$. Mean composition of compost was: organic matter 22%, total nitrogen 0.6%, total phosphorus 0.3%, potassium 0.6%, and total magnesium 0.4%. OA and SA systems were not fertilized. No chemicals against pest or disease were used in OM, OA and SA.

## Litterbag experiments

The decomposition process of leaves in the five cropping systems was assessed using litterbags (Chassain et al. 2021). Litterbags with dimensions 20 cm × 20 cm and with two mesh sizes were employed: 0.1 mm to exclude soil mesofauna (exclusion litterbags) and 2 mm which allows the entry of soil mesofauna (inclusion litterbags) (Menta 2012). Fresh leaves from cacao and accompanying species were randomly collected from plants across the whole study area and leaves were placed into both exclusion and inclusion litterbags. We used complete leaves, or if necessary, leaves were cut to pieces that could fit into the litterbags, but they were not cut to small fragments or shredded. Cacao litterbags were prepared with 15 g of fresh cacao leaves. Mixture 1 (M1) litterbags were prepared with 10 g of cacao, 3 g of *Erythrina* sp., 1 g of *Musa paradisiaca*, and 1 g of Inga sp leaves. Mixture 2 (M2) litterbags were prepared with 8 g of cacao, 1.5 g of *Garcinia* sp., 1 g of *Inga* sp., 1 g of *Musa paradisiaca*, 2.5 g of *Swartzia* sp., and 1 g of *Theobroma grandiflorum* leaves. M1 and M2 leaf contents were defined based on the mean percentage of fresh leaf weight from each tree species found in the pruning residues of the CA/OA plots and SA plots, respectively.

Table 1 shows which were the litterbags used for testing the different hypotheses. For laying the litterbags, two cacao trees were randomly chosen from each plot. The litterbags were placed in the litter layer, at 1-m distance from each tree trunk. Six cacao litterbags (3 inclusion and 3 exclusion litterbags) were placed near each chosen tree in all plots, making a total of 240 cacao litterbags. In plots corresponding to agroforestry systems (CA,OA), we additionally placed M1 litterbags (3 exclusion and 3 inclusion litterbags) making a total of 96 M1 litterbags. In SA plots, we placed a total of 48 M2 litterbags following the same scheme.

**Table 1** Litterbags used for testing the study hypotheses

| Hypothesis | Litterbags |
|---|---|
| Cropping system and/or mesofauna influence the loss of mass, carbon, lignin, cellulose and nutrients from litter generated by pruning of cacao trees | Litterbags with two different mesh sizes (0,1 mm that excludes mesofauna and 2 mm that allows entry of mesofauna) and contained only cacao leaves were placed across all cropping systems (CM, OM, CA, OA, SA) |
| For agroforestry systems (CA, OA), the cropping system, mesofauna and/or nature of leaves influence the loss of mass, carbon, lignin, cellulose and nutrients from litter generated by pruning of cacao and shade trees | Additional litterbags with the two different mesh sizes and mixture of leaves M1 were placed in plots of CA and OA |
| For successional agroforestry systems (SA), the presence of mesofauna and/or nature of leaves influence the loss of mass, carbon, lignin, cellulose and nutrients from litter generated by pruning of cacao and shade trees | Additional litterbags with the two different mesh sizes and mixture of leaves M2 were placed in plots of SA |

To facilitate locating the litterbags during collection, each group of litterbags was strung on a thin wire, which was secured to an iron rod. In CM and OM plots, two rods were positioned on opposite sides of the trunks (Fig. 1, left). One rod was attached to a wire with three exclusion cacao litterbags, while the other rod held three inclusion cacao litterbags. In CA, CA and SA plots, four rods were placed (Fig. 1, right). These rods were connected to wires holding cacao exclusion and inclusion litterbags, as well as M1 or M2 exclusion and inclusion litterbags. All litterbags were placed in the plots in April 2021.

We collected the litterbags from the plots every four months (August 2021, December 2021, and April 2022). At each sampling time, for each plot and each tree, we collected one litterbag of each category, that means one litterbag from each wire (one inclusion and one exclusion cacao litterbag in monocultures, one inclusion and one exclusion cacao litterbag plus one inclusion and one exclusion of M1 or M2 litterbags in agroforestry). Hence, for each sampling time, a total of 128 litterbags were collected which means 8 replicates for each combination of variables (cropping system, mesh size and leaf material).

### Analysis of fresh cacao leaves and mixtures

The moisture content and the concentration of carbon, nutrients, cellulose and lignin of fresh cacao leaves and of fresh M1 and M2 mixes was determined in samples taken from the pool of leaves or of leaf mixtures that was later used for preparing the litterbags.

Moisture content of the cacao leaves and mixtures was determined by comparing fresh and dry weight after drying at 70 °C for three days. The initial concentrations of organic carbon, total phosphorus, and potassium were determined in 14 samples of cacao leaves, 14 samples of mixture M1, and 14 samples of mixture M2. From each of these groups, 8 samples were randomly selected to measure cellulose and lignin content. Additionally, 4 samples from each group were analysed for potassium content.

### Chemical analysis in litterbags

The collected litterbags were dried at 65 °C for around three days until reaching constant dry weight, which was recorded. Subsequently, the collected samples were pulverized and homogenized by passing them through a 0.5mm mesh. In all samples collected at 4 and 12 months after laying, we analysed inorganic elements (nutrients), organic carbon, cellulose and

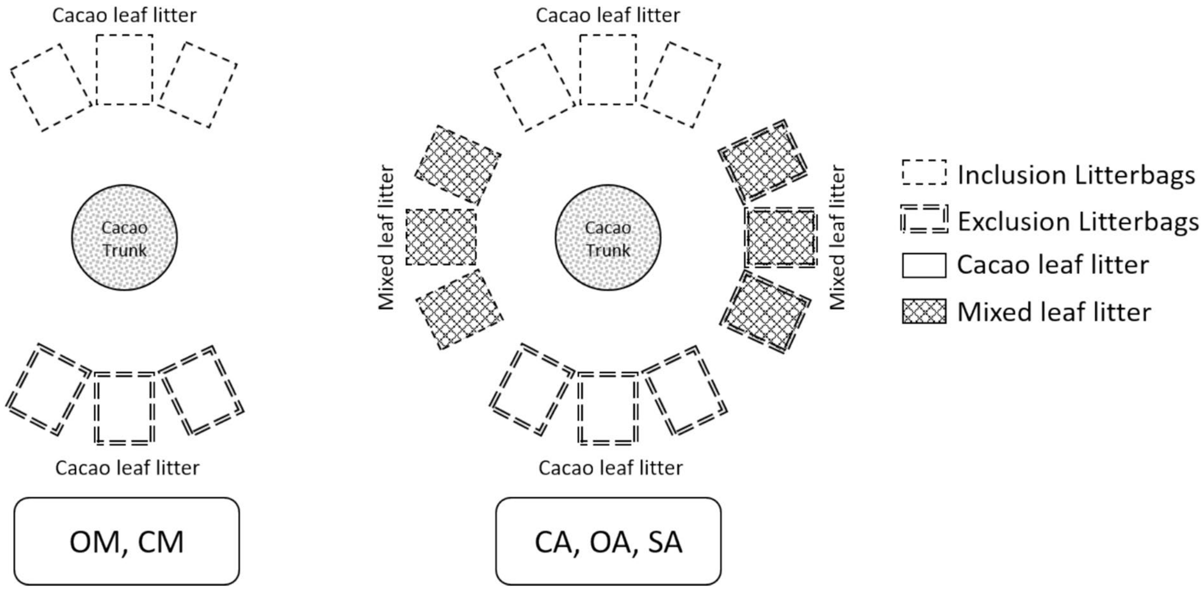

**Fig. 1** Location of litterbags around cocoa trees in the different plots

lignin. For samples collected at 8 months after laying, we only determined organic carbon and phosphorous.

### *Inorganic elements (nutrients)*

Total nitrogen was determined using the Kjeldahl method adapted for plant material as described by Baker and Thompson (1992). Phosphorus content was determined using the procedure described by Flindt and Lillebø (2005). To determine potassium content, 0.1 g of each sample was burnt to ashes. Then, 1 mL of 18% HCl was added to the ash, and the mixture was heated until dry. The residue was dissolved in 10 mL of 0.2 M HCl and diluted to 50 mL with distilled water. The potassium concentration of the resulting solutions was measured using flame photometry, following EPA method 258.1 (EPA, 1971).

### *Organic carbon, lignin and cellulose*

Organic carbon was determined using a modified version of the Walkey-Black method (Nelson and Sommers 1982). Briefly, 5 mL of 0.167 M $K_2Cr_2O_7$ were added to 0.02 g of each sample. Next, 10 mL of $H_2SO_4$ were added and the mixtures were shaken and left to react for 30 min at room temperature. Afterward, 100 mL of distilled water and drops of ferroin indicator were added. Finally, the samples were titrated with 0.5 M $FeSO_4$.

Quantification of cellulose and lignin was carried out using a method modified from Van Soest (1963). For this, 0.3 g of pulverized material was boiled in a $H_2SO_4$/CTAB solution (20 g CTAB in 1 Lt $H_2SO_4$ 0.5 M) with drops of isoamylic acid as antifoaming agent, for one hour under reflux, and filtered. The filtration residue was washed with three aliquots of 50 mL boiling water, then rinsed with acetone until the material no longer released colour. The residue was then dried at least 5 h at 70ºC and weighed after cooling. This first residue (ADF: acid and detergent resistant fibre) contains cellulose, lignin and ash. Then, 3 mL of $H_2SO_4$ 72% was added to ADF and allowed to react for one hour, after which 82 mL of distilled water were added. The resulting mixture was autoclaved for one hour. Subsequently, it was filtered and the absorbance of the filtrate was measured at 280 nm to determine the amount of acid-soluble lignin. The second filtering residue (which contains acid-resistant lignin and ash) was dried for at least 5 h at 70 °C and weighted. Finally, the filtered solid was incinerated at 550 °C and the weight of the resulting ash was determined.

### Calculation of the mass of nutrients, organic carbon, cellulose and lignin in litterbags, and determination of nutrient losses

The presence of ash in all litterbags was determined by heating the litterbag contents at 550 °C for six hours. The obtained values were used for correcting the dry weight of litterbag contents in case of contamination with soil or dust. The remaining mass of nutrients or of cellulose and lignin was calculated as follows:

$$m = (DWf - ash)Cf$$

m: remaining mass of nutrient, organic carbon, cellulose or lignin (g)
DWf: final dry weight in litterbag (g)
Ash: mass of ashes in samples (g)
Cf: final concentration of the nutrient, organic carbon, cellulose or lignin ($g_{nutrient}/g_{Litter}$)

The percentages of loss for each nutrient were calculated for each litterbag as follows:

$$EL = \frac{(DWi \text{ x} Ci) - (\text{DWf x } Cf)}{DWixCi} x100$$

EL: Element or nutrient loss
DWi: initial dry weight of litter placed in litterbag (g)
Ci: initial concentration of the nutrient in litter ($g_{Nutrient}/g_{Litter}$)
DWf: final dry weight of litter placed in litterbag, corrected for ash (g)
Cf: final concentration of the nutrient in litter ($g_{Nutrient}/gL_{itter}$)

The calculation of nutrient release per kg of litter was done as follows:

$$NutrientRelease = \frac{(DWi \text{ x} Ci) - (\text{DWf x } Cf)}{DWi} x1000$$

DWi initial dry weight of litter placed in litterbag (g).
Ci initial concentration of the nutrient in litter ($g_{nutrient}/g_{litter}$).

DWf final dry weight of litter placed in litterbag, corrected for ash (g).

Cf final concentration of the nutrient in litter ($g_{nutrient}/g_{litter}$).

## Statistical analyses

The initial chemical characteristics of the different leaf materials that were introduced into cacao (C), mixture M1 and mixture M2 litterbags were compared by using linear models. We compared the initial dry weight and the initial contents of nutrients, organic matter, cellulose and lignin in litterbags with the values obtained at 4, 8, and 12 months after laying with the Wilcoxon signed-rank test.

Initial models that aimed to test the effects of decomposition time, cropping system, litterbag mesh size and leaf composition on the chemical characteristics of decomposing material showed interactions between the time of decomposition and the other predictor variables. Therefore, we analysed the effect of the cropping system, the leaf material and the mesh size within each sampling time.

For each sampling time, we assessed the influence of the cropping system, the litterbag mesh size and the interactions between these factors on dry weight and chemical characteristics for cacao litterbags with mixed effect linear models with the plot as a random factor. For agroforestry systems (CA, OA) we tested models that comprised cropping system, litterbag mesh size, nature of leaves (C or M1) as fixed effects factors and plot as a random factor. Finally, for SA, we tested models with litterbag mesh size and nature of leaves as fixed effects and plot as random variable. All mixed effects linear models were done with lmr() function of lme4 package.

We selected the simpler models based on the Akaike information criterion (AIC), calculated using the dredge command from the MuMin package. In cases where significant differences were detected between cropping systems, marginal means were estimated using the emmeans package, and pairwise comparisons were conducted using Tukey´s HSD with the multcomp package.

For all selected models, the distribution of residuals was assessed using the DHARma package. All analyses were conducted in RStudio version 2025.05.1–513.

## Results

### Initial chemical characteristics of cacao leaves and of mixtures M1 and M2 that were placed in litterbags

The initial chemical characteristics of cacao leaves an d of mixtures M1 and M2 that were placed in litterbags are shown on Table 2. The initial chemical characteristics were not significantly different across cacao leaves, M1 and M2 mixtures.

### Overall evolution of dry weights and chemical characteristics in litterbags

The results obtained from the Wilcoxon signed-rank test that compared dry weight and contents of different nutrients, organic carbon, cellulose and lignin at initial time and at 4, 8 and 12 months after laying showed that, for all sampling times, final values were significantly lower than initial values (Fig. 2, Fig. 3).

### Effect of the cropping system and mesh size of litterbags on decomposition of cacao leaves

Four months after laying, only the mass of nitrogen in cacao litterbags was affected by the cropping system, with values significantly higher for litterbags placed in CA respect to the other systems ($p = 0.002$) (Fig. 3.A). This higher nitrogen content for CA was also reflected in the C:N ratio (Fig. 4). Inclusion litterbags (mesh size 2 mm) showed significantly lower contents of organic carbon ($p = 0.004$), phosphorus ($p = 0.004$), nitrogen($p = 0.003$) and potassium ($p = 0.012$) (Fig. 2 C, 2 E, 3 A, 3C) than exclusion litterbags (mesh size 0.1 mm).

**Table 2** Initial chemical characteristics (mean ± standard deviation) by leaf material (cacao, mixture M1, mixture M2)

| Litterbag | Cacao | M1 | M2 |
|---|---|---|---|
| Organic carbon (%) | 50.8 ± 3.8 | 51.6 ± 3.0 | 50.9 ± 3.4 |
| Phosphorous (%) | 0.19 ± 0.03 | 0.19 ± 0.03 | 0.20 ± 0.03 |
| Nitrogen (%) | 1.3 ± 0.4 | 1.4 ± 0.4 | 1.4 ± 0.5 |
| Potassium (%) | 5.6 ± 1.2 | 5.6 ± 1.0 | 5.9 ± 0.9 |
| Cellulose (%) | 21.6 ± 5.4 | 22.4 ± 5.5 | 23.1 ± 6.2 |
| Lignin (%) | 34.0 ± 6.8 | 35.8 ± 8.1 | 33.8 ± 6.8 |
| C/N | 43 ± 18 | 44 ± 25 | 40 ± 17 |

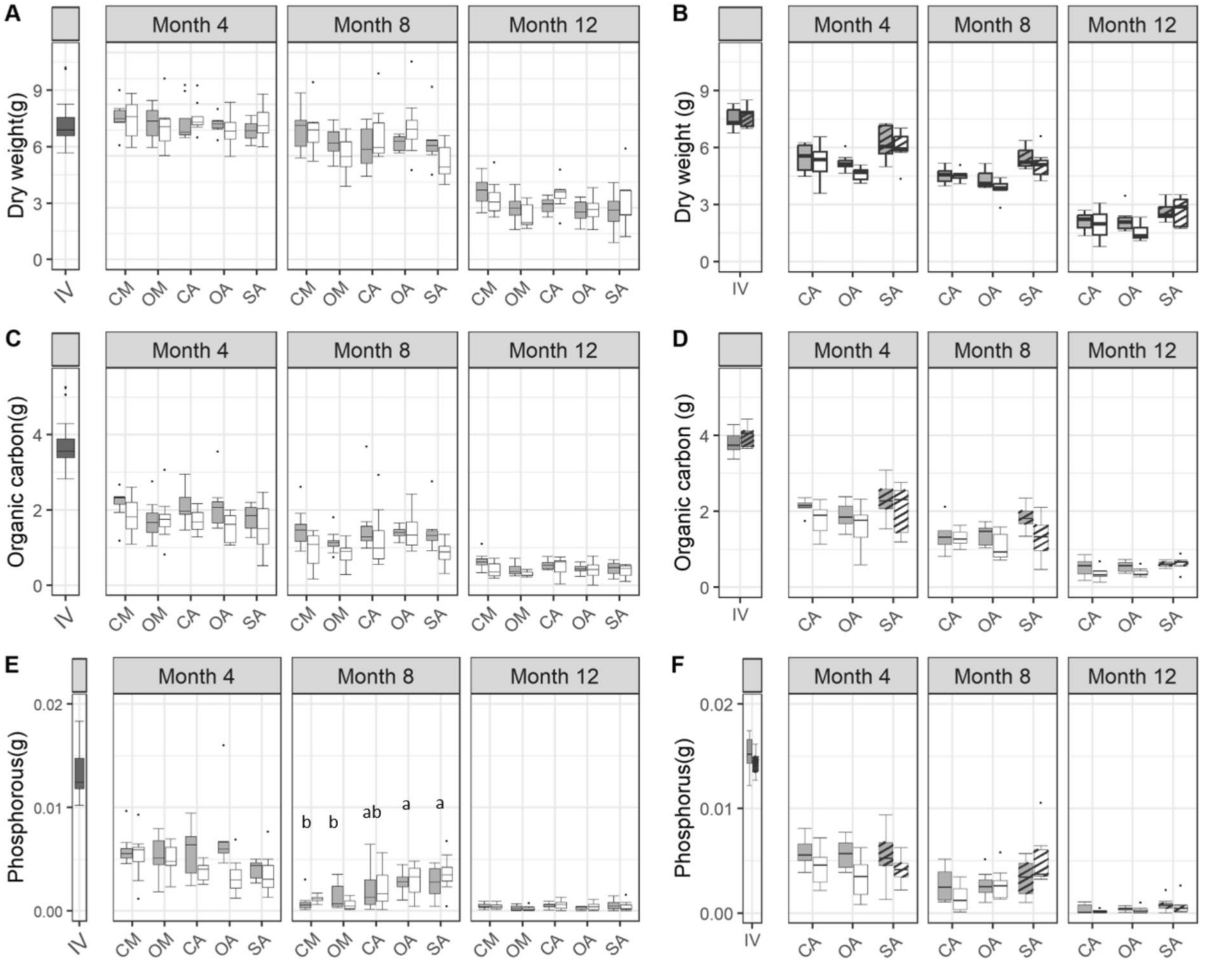

**Fig. 2** Temporal evolution of dry weight (A, B), carbon (C, D) and phosphorus (E,F) contents in litterbags containing cacao leaves (A,C,E) and leaf mixtures (B,D,F); non-striped boxes denote mixture M1 and striped boxes denote mixture M2. Light grey boxes correspond to exclusion bags, white boxes to inclusion bags. The system abbreviations stand as: IV, initial values, CM, conventional monoculture; OM, organic monoculture; CA, conventional agroforestry; OA, organic agroforestry; SA successional agroforestry. Small letters indicate significant differences between cropping systems

Eight months after laying, the cropping system had a significant effect on phosphorus contents of litterbags ($p=0.02$) with litterbags from SA and OA showing significantly higher phosphorus masses than litterbags from monocultures. Phosphorus contents in litterbags from CA had intermediate values between the SA or OA and monocultures (Fig. 2 D). At this time point, the mass of organic carbon was significantly lower in inclusion than in exclusion litterbags ($p=0{,}001$).

For cacao litterbags collected after 12 months of laying, the cropping system had a significant effect only on lignin contents, which was significantly higher in litterbags from CA respect to litterbags from OA and SA (Fig. 3.G). Carbon contents were still significantly lower in inclusion respect to exclusion litterbags ($p=0.025$) (Fig. 2 C).

The C:N ratio in cacao litterbags decreased gradually with time (Fig. 4). For M1 and M2, the C:N ratio decrease was found significant only between 0 and 4 months.

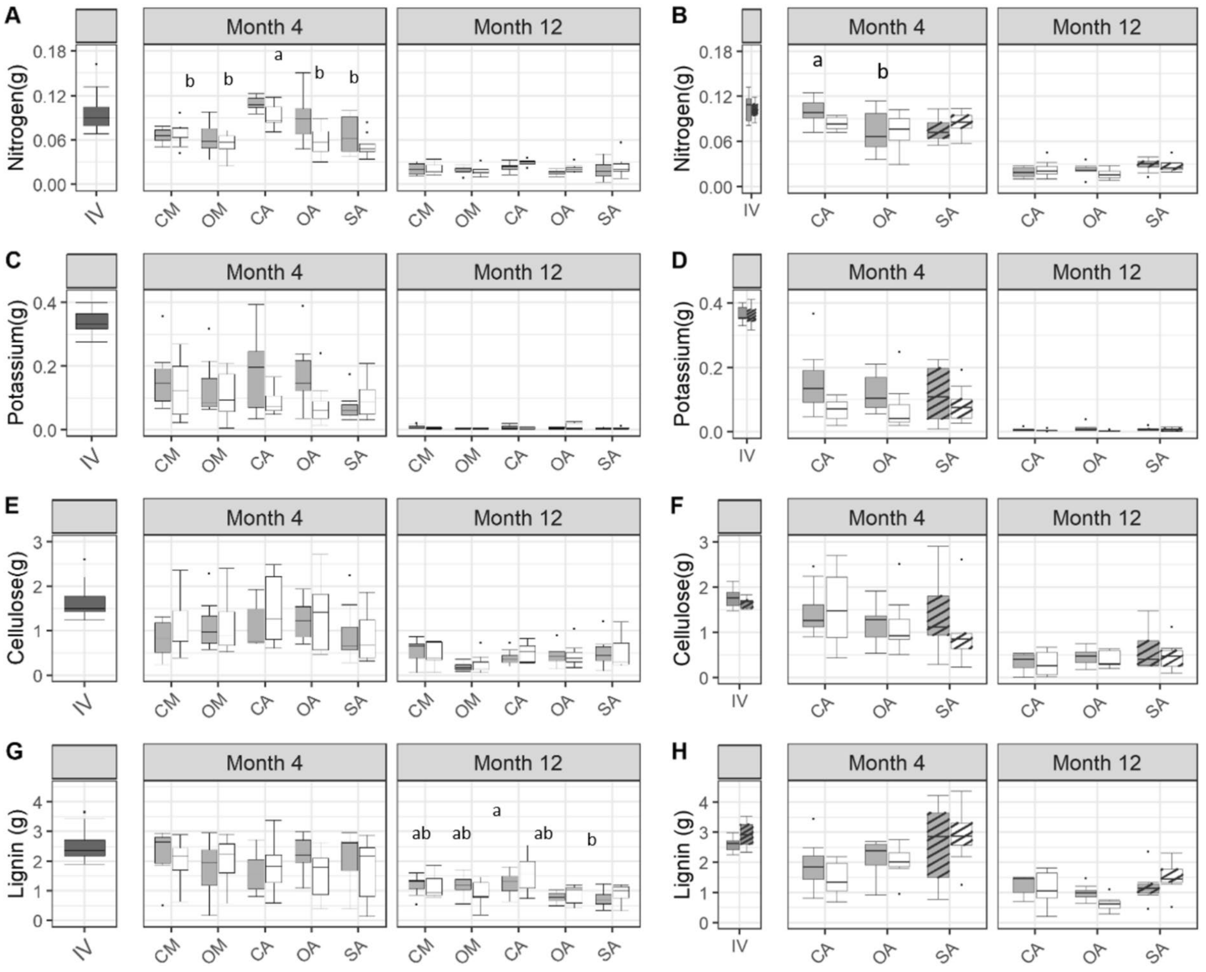

**Fig. 3** Temporal evolution of nitrogen (A,B), potassium (C,D), cellulose (E,F) and lignin (G,H) contents in litterbags containing cacao leaves (A, C, E,G) and leaf mixtures (B,D,F, H; non-striped boxes denote mixture M1 and striped boxes denote mixture M2). Light grey boxes correspond to exclusion bags, white boxes to inclusion bags. The system abbreviations stand as: IV, initial values, CM, conventional monoculture; OM, organic monoculture; CA, conventional agroforestry; OA, organic agroforestry; SA successional agroforestry. Small letters indicate significant differences between cropping systems

### Effect of the cropping system, mesh size and leaf material on decomposition in agroforestry systems

At four months after laying, nitrogen contents of litterbags from CA was significantly higher than nitrogen contents in litterbags placed in OA ($p=0.007$, Fig. 3B). The mesh size had a significant effect on carbon ($p=9.10^{-5}$, Fig. 2D), phosphorus ($p=8.65.10^{-6}$, Fig. 2F), nitrogen ($p=0,02$, Fig. 3B) and potassium ($p=7.10^{-5}$, Fig. 3. D) with contents of these nutrients significantly lower in larger sized mesh litterbags.

For bags collected at 8 months after laying, no significant effects of cropping system or mesh size were observed on the measured parameters. In the case of litterbags collected at 12 months after laying, litterbags from CA showed significantly higher nitrogen ($p=0.0184$, Fig. 3B) and lignin ($p=3.48.10^{-5}$, Fig. 3H) contents than litterbags from OA plots. Mesh size affected carbon contents, with lower values in inclusion bags ($p=0.026$, Fig. 2.D).

Across all sampling times, no significant effect of litterbag leaf material (cacao or M1) was observed for any of the measured parameters.

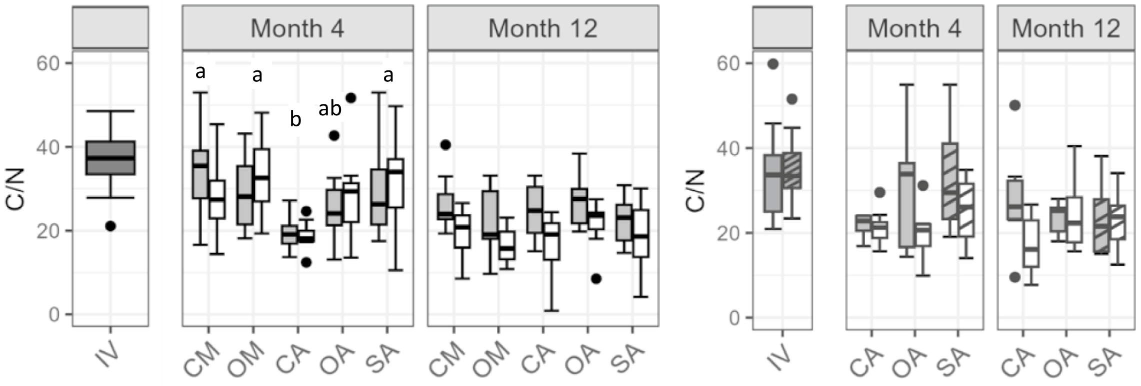

**Fig. 4** Temporal evolution of C:N ratio in litterbags containing cacao leaves (left) and leaf mixtures (right; non-striped boxes denote mixture M1 and striped boxes denote mixture M2). Light grey boxes correspond to exclusion bags, white boxes to inclusion bags. The system abbreviations stand as: IV, initial values, CM, conventional monoculture; OM, organic monoculture; CA, conventional agroforestry; OA, organic agroforestry; SA successional agroforestry. Small letters indicate significant differences between cropping systems

### Effect of mesh size and leaf material on decomposition in successional agroforestry systems

For litterbags placed under successional agroforestry systems (SA), mesh size only affected dry weight, carbon and phosphorus contents at eight months after laying. Dry weight (p = 0.029, Fig. 2B) and carbon (p = 0.002, Fig. 2D) showed lower values in inclusion respect to exclusion bags. In case of phosphorus, higher values were measured in inclusion bags (p = 0.0378, Fig. 3.D).

Leaf material in M2 litterbags showed significantly higher dry weight (p = 0.0005, Fig. 2 B), organic carbon (p = 0.007, Fig. 2D), nitrogen (p = 0.02, Fig. 3B) and lignin (p = 0,0139, Fig. 3H) than cacao litterbags. For month 8, M2 litterbags still shower higher dry weight (p = 4,5.10–5, Fig. 2B) and carbon (p = 0,003, Fig. 2. D) content than cacao litterbags. The tendency was similar after 12 months of laying with M2 litterbags showing higher dry weight (p = 0.04, Fig. 2B), carbon (p = 0.0013, Fig. 3D) and lignin (p = 0,002, Fig. 3H).

### Estimation of carbon and nutrient loss in litterbags

The relative loss of organic carbon and nutrients from cacao, M1 and M2 litterbags, estimated at 4 and 12 months after laying, are shown in Table 3. At 4 months after laying, most samples had lost more than 40% of organic carbon. Negative values were obtained for nitrogen losses, notably under CA, indicating nitrogen increase. Although highly variable, average losses of phosphorus and potassium were over 50%.

At twelve months after laying, organic carbon losses were over 80%. Nitrogen losses were a bit lower, around 75%. Practically all phosphorus and potassium were lost (losses over 95%).

An estimation of the mass of carbon and of nutrients released by mass of pruning residues is presented in Table 4. These values allow to determine how pruning residues contribute to soil fertilization.

## Discussion

### Initial composition of fresh leaves and evolution of chemical characteristics during decomposition

The values obtained for nutrient contents in green (non-senescent) cacao leaves were similar to those observed by Agbotui et al. (2024), except for potassium contents that were significantly higher in our samples. Nutrient contents can vary quite widely with the cacao variety, season and soil characteristics (Hosseini Bai et al. 2017; Quintino R. De et al. 2020). The high potassium contents in our samples can be related to high exchangeable potassium (between 0.6 and 1.1 meq per 100 g soil) in upper layers of soils of our study area (Schneider et al. 2017). These soil

**Table 3** Percentage of carbon and nutrient loss from initial values (mean ± standard deviation) for litterbags with two mesh sizes containing different leaf material (cacao, M1 and M2 mixtures), and placed in the different cropping systems. The mesh size abbreviations stand as: E, exclusion (mesh size 0.1 mm); I, inclusion (mesh size 2 mm). The system abbreviations stand as: CM, conventional monoculture; OM, organic monoculture; CA, conventional agroforestry; OA, organic agroforestry; SA successional agroforestry

| Leaf material | Cacao | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| System | CM | | OM | | CA | | OA | |
| Mesh size | E | I | E | I | E | I | E | I |
| **4 months after laying** | | | | | | | | |
| Carbon | 42 ± 11 | 50 ± 16 | 50 ± 17 | 48 ± 19 | 42 ± 18 | 54 ± 8 | 42 ± 20 | 58 ± 11 |
| Nitrogen | 23 ± 15 | 19 ± 23 | 22 ± 28 | 31 ± 19 | −27 ± 21 | −8 ± 12 | −6 ± 45 | 33 ± 21 |
| Phosphorus | 54 ± 9 | 58 ± 18 | 56 ± 16 | 58 ± 13 | 54 ± 21 | 70 ± 8 | 43 ± 33 | 75 ± 13 |
| Potassium | 54 ± 24 | 63 ± 25 | 60 ± 27 | 66 ± 24 | 47 ± 38 | 74 ± 12 | 38 ± 43 | 77 ± 20 |
| **12 months after laying** | | | | | | | | |
| Carbon | 83 ± 5 | 89 ± 6 | 88 ± 5 | 91 ± 2 | 85 ± 3 | 86 ± 9 | 87 ± 4 | 89 ± 7 |
| Nitrogen | 75 ± 10 | 77 ± 12 | 75 ± 7 | 80 ± 6 | 77 ± 9 | 73 ± 6 | 85 ± 3 | 81 ± 6 |
| Phosphorus | 96 ± 2 | 97 ± 2 | 97 ± 2 | 98 ± 2 | 96 ± 2 | 96 ± 3 | 98 ± 1 | 97 ± 3 |
| Potassium | 97 ± 24 | 99 ± 1 | 99 ± 1 | 99 ± 0 | 98 ± 1 | 99 ± 0 | 99 ± 1 | 97 ± 2 |
| Leaf material | | | M1 | | | | M2 | |
| System | SA | | CA | | OA | | SA | |
| Mesh size | E | I | E | I | E | I | E | I |
| **4 months after laying** | | | | | | | | |
| Carbon | 53 ± 10 | 61 ± 15 | 43 ± 5 | 52 ± 11 | 49 ± 10 | 57 ± 16 | 40 ± 15 | 48 ± 17 |
| Nitrogen | 24 ± 32 | 42 ± 18 | 16 ± 15 | 30 ± 8 | 39 ± 24 | 39 ± 23 | 28 ± 18 | 21 ± 16 |
| Phosphorus | 54 ± 9 | 75 ± 13 | 63 ± 9 | 72 ± 12 | 64 ± 9 | 78 ± 13 | 60 ± 19 | 72 ± 10 |
| Potassium | 54 ± 24 | 74 ± 16 | 68 ± 21 | 86 ± 7 | 75 ± 11 | 85 ± 15 | 52 ± 46 | 75 ± 17 |
| **12 months after laying** | | | | | | | | |
| Carbon | 89 ± 5 | 90 ± 4 | 86 ± 7 | 90 ± 4 | 85 ± 4 | 89 ± 11 | 84 ± 3 | 84 ± 4 |
| Nitrogen | 80 ± 13 | 76 ± 13 | 79 ± 8 | 75 ± 10 | 75 ± 10 | 81 ± 8 | 69 ± 9 | 69 ± 8 |
| Phosphorus | 96 ± 4 | 97 ± 3 | 97 ± 3 | 54 ± 9 | 97 ± 2 | 98 ± 3 | 94 ± 4 | 95 ± 6 |
| Potassium | 99 ± 1 | 98 ± 1 | 98 ± 1 | 54 ± 24 | 97 ± 3 | 99 ± 1 | 98 ± 1 | 98 ± 1 |

potassium contents are considered as excessive for cacao (Li et al. 2015). When supply of potassium is high, the concentration of this element increases in vegetative parts of cacao (Hartemink 2005; Li et al. 2015).

Loss of carbon in litter is attributed to production of $CO_2$ and release of soluble organic molecules that can leach into soil (Cotrufo and Lavallee 2022). Part of litter carbon is incorporated into microbial biomass, remaining in the litterbags. Microbial biomass contain a series of nitrogen-containing organic compounds which lower the C:N stoichiometry (Gul and Whalen 2022) and by then loss of nitrogen during decomposition is lower than carbon loss, as was also observed in our samples (Tab. 2). Our data showed a temporal increase in nitrogen contents of some samples at four months after laying (Tab. 1, Fig. 3. A and B). Temporal increase in nitrogen contents of litter can be due to nitrogen mining from the environment (Paul 2016) and its immobilisation in microbial biomass.

We measured two fractions of plant cell wall polymers following the gravimetric method proposed by Van Soest (1963), and we referred to these fractions as “cellulose” and “lignin”. However the “cellulose” fraction, also contains hemicelluloses and pectins (Godin et al. 2014). Cellulose and hemicelluloses are not susceptible to leaching since they are not soluble and, in the case of hemicelluloses, a complex set of enzymes is required for degradation (Berg and

**Table 4** Carbon and nutrient release ($g_{nutrient}.kg_{litterDW}^{-1}$, mean ± standard deviation) from litterbags with two mesh sizes containing different leaf material (cacao, M1 and M2 mixtures), and placed in the different cropping systems. The mesh size abbreviations stand as: E, exclusion (mesh size 0.2 mm); I, inclusion (mesh size 2 mm). The system abbreviations stand as: CM, conventional monoculture; OM, organic monoculture; CA, conventional agroforestry; OA, organic agroforestry; SA successional agroforestry

| Leaf material | Cacao | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| System | CM | | OM | | CA | | OA | |
| Mesh size | E | I | E | I | E | I | E | I |
| **4 months after laying** | | | | | | | | |
| Carbon | 215 ± 57 | 258 ± 82 | 259 ± 85 | 247 ± 99 | 217 ± 94 | 276 ± 42 | 215 ± 106 | 301 ± 55 |
| Nitrogen | 3 ± 15 | 2 ± 3 | 3 ± 3 | 4 ± 2 | −3 ± 3 | −1 ± 1 | −1 ± 5 | 4 ± 3 |
| Phosphorus | 1.0 ± 0.2 | 1.1 ± 0.3 | 1.0 ± 0.3 | 1.0 ± 0.2 | 1.0 ± 0.4 | 1.3 ± 0.2 | 0.8 ± 0.6 | 1.3 ± 0.2 |
| Potassium | 26 ± 12 | 31 ± 12 | 29 ± 13 | 32 ± 12 | 23 ± 18 | 36 ± 6 | 18 ± 21 | 37 ± 10 |
| **12 months after laying** | | | | | | | | |
| Carbon | 407 ± 40 | 422 ± 27 | 389 ± 106 | 418 ± 51 | 387 ± 26 | 423 ± 72 | 425 ± 72 | 443 ± 46 |
| Nitrogen | 9 ± 1 | 11 ± 3 | 9 ± 1 | 11 ± 2 | 11 ± 3 | 12 ± 1 | 13 ± 2 | 13 ± 1 |
| Phosphorus | 1.7 ± 0 | 1.9 ± 0.2 | 1.8 ± 0 | 1.9 ± 0.1 | 1.9 ± 0.1 | 2.0 ± 0.1 | 2.0 ± 0.1 | 2.0 ± 0.1 |
| Potassium | 47 ± 1 | 55 ± 9 | 48 ± 0 | 55 ± 9 | 58 ± 9 | 65 ± 0 | 60 ± 8 | 64 ± 1 |
| Leaf material | | | M1 | | | | M2 | |
| System | SA | | CA | | OA | | SA | |
| Mesh size | E | I | E | I | E | I | E | I |
| **4 months after laying** | | | | | | | | |
| Carbon | 276 ± 50 | 315 ± 77 | 213 ± 24 | 261 ± 53 | 245 ± 52 | 285 ± 79 | 210 ± 80 | 249 ± 87 |
| Nitrogen | 3 ± 4 | 5 ± 2 | 3 ± 2 | 5 ± 1 | 6 ± 4 | 6 ± 4 | 4 ± 3 | 3 ± 2 |
| Phosphorus | 1.3 ± 0.1 | 1.3 ± 0.2 | 1.0 ± 0.2 | 1.5 ± 0.2 | 1.3 ± 0.2 | 1.6 ± 0.3 | 1.1 ± 0.4 | 1.4 ± 0.2 |
| Potassium | 39 ± 7 | 36 ± 8 | 56 ± 5 | 56 ± 5 | 49 ± 7 | 56 ± 10 | 23 ± 21 | 34 ± 8 |
| **12 months after laying** | | | | | | | | |
| Carbon | 402 ± 42 | 444 ± 36 | 444 ± 36 | 464 ± 22 | 441 ± 20 | 462 ± 18 | 435 ± 13 | 434 ± 22 |
| Nitrogen | 11 ± 2 | 11 ± 2 | 9 ± 1 | 9 ± 1 | 9 ± 1 | 10 ± 1 | 8 ± 1 | 8 ± 1 |
| Phosphorus | 1.8 ± 0.1 | 1.8 ± 0.1 | 1.7 ± 0.1 | 1.8 ± 0.1 | 1.7 ± 0 | 1.8 ± 0 | 1.7 ± 0.1 | 1.7 ± 0.1 |
| Potassium | 45 ± 1 | 44 ± 0 | 47 ± 1 | 50 ± 6 | 47 ± 1 | 48 ± 0 | 47 ± 1 | 54 ± 1 |

McClaugherty 2014). This explains slower degradation of "cellulose" and "lignin" materials in comparison to total organic carbon (Fig. 2 and Fig. 3). Furthermore, molecules placed under the"cellulose" and "lignin" categories can include native lignin initially present in leaves but also newly formed microbial products (Prescott and Vesterdal 2021).

The main forms of phosphorus in plants are inorganic phosphate, phosphate sugars, nucleic acids and phospholipids (Hawkesford et al. 2012; Suriyagoda et al. 2023). Inorganic phosphorus and soluble phosphorus-containing molecules can be released during decomposer catabolism and easily leached from litter (Berg and McClaugherty 2014). We observed a significant decrease in phosphorus contents after four months of decomposition. The rapid decline of phosphorus proportions in cacao litter after initial months was also observed by Froufe et al. (2020) and Agbotui et al. (2024). However, in our data, at 8 months after lying, values observed under OA and SA suggest temporal phosphorus immobilisation in microbial biomass.

Potassium ions are highly soluble and are present in leaf cell cytoplasm and leaf fluids (Britto and Kronzucker 2008). Therefore, potassium is a non-structural element and can be lost by leaching at a faster rate than litter mass loss (Coleman et al. 2018). We observed this rapid loss of potassium from cacao leaves and mixtures, since more than 50% of potassium was lost 4 months after laying and practically all of it was lost at 12 months after laying (Fig. 3. C and D, Tab. 3).

The loss of litterbag weight, nitrogen, cellulose and lignin contents was faster from month 8 to month 12 than in previous months. This is in line with the fact that the time interval between months 8 and 12 corresponds to the rainy season and warmer months (December 2021 to April 2022).

### Effect of cropping system on litter decomposition and nutrient release

The cacao cropping system could affect decomposition through changes in decomposer communities and in environmental conditions (Manzoni et al. 2010). Significant differences in decomposition were expected at least between agroforestry systems and monocultures which were highly different in tree densities and vegetation diversity. Higher fungal richness was observed under agroforestry systems than under monocultures, while higher bacterial richness and diversity was observed under organic than under conventional management for soil samples taken from our study area (Lori et al. 2022). Considering that litter is colonized at least partially by soil microorganisms, microbial communities in litter are expected to vary with the cropping system. However, we could not observe any significant effect of the cropping system on dry weight, organic carbon, cellulose and potassium during the experiment, and on lignin in samples collected 4 months after laying.

For nitrogen contents, we observed significantly higher values for CA compared to all other cropping systems, both for cacao and M1 litterbags after four months of laying, suggesting higher immobilisation in microbial biomass for CA. Both CA and CM received added nitrogen through fertilizers. However, nitrogen immobilisation was mostly observable in CA. This suggests that a combination of added nitrogen and specific microbial communities causes this immobilization. It is interesting to note that, 12 months after laying, litterbags in CA contained higher proportions of polymers classified as « lignin» than litterbags in other systems, suggesting that nitrogen immobilisation gave rise to microbial polymers.

Eight months after laying, litterbags in SA and OA (which showed higher soil fungal diversity, Lori et al. 2022) had significantly lower phosphorus proportions than in monocultures (which showed lower soil fungal diversity, Lori et al. 2022). The relationship between this apparent temporal phosphorus immobilisation in microbial biomass and fungal diversity needs further investigation.

Environmental conditions can affect microbial communities and leaching phenomena. Before pruning activities in September, the percentage of rain throughfall was lower in agroforestry compared to monocultures, monocultures presented larger mean temperature amplitudes and lower annual mean relative humidity (Niether et al. 2018). These microclimatic variations between cropping systems did not seem to affect leaf decomposition, which is in line with Saj et al. (2021), who found no correlation between cacao decomposition and microclimatic variables.

### Effect of litterbag mesh size on decomposition

Litterbags with two mesh sizes were used to investigate the role of mesofauna in leaf decomposition. However, mesh size can influence decomposition by causes other than presence of mesofauna. For instance, larger mesh sizes may enhance leaching and facilitate the entry of soil particles and fine roots. The entry of external material can promote microbial colonization of the litter, further accelerating decomposition processes (Chassain et al. 2021).

Limachi et al. (2024), using litterbags that were identical to our litterbags and that were placed around the same trees at the same time, reported the presence of mesofauna in 2 mm mesh litterbags. Of all mesofauna individuals, around 80% were oribatid mites, 6.8% were gasteropods, 3.4% were diptera, 3,2% were isopopods, 2.7% and 1.4% were diplopods. Abundance of individuals was higher in samples taken in December (humid months) compared to samples taken in April (dry months). The effect of mesofauna on litter is complex and it does not necessarily accelerate decomposition (Frouz 2018). Moreover, Chassain et al. (2021) report that the effect of mesofauna under tropical conditions is less important than in temperate climates.

At four months after laying, organic carbon and nutrients contents were significantly lower in inclusion than in exclusion litterbags. However, the initial four months correspond to dry season, when mesofauna was less abundant (Limachi et al. 2024). Additionally, the percentages of insoluble polymers (cellulose and lignin) were not affected by mesh size. All this information suggests that microbial colonisation and facilitated leaching, but not mesofauna caused higher release of nutrients from inclusion litterbags in the first months of decomposition.

### Effect of the nature of the leaf material on decomposition

Across all sampling times, for CA and OA, no significant effect of the leaf material (cacao, M1) on carbon and nutrient contents of litterbags was observed. Schneidewind et al. (2022) report that the degradation of *Erythrina* sp leaves is twice as fast as degradation of cacao leaves in the same study area and under conditions very similar to those of the current assay. Similarly, Kaba et al. (2021) report that pruning residues from *Gliciridia* sp, which is also nitrogen-fixing, decompose and release nutrients at higher rates than cacao leaves. M1 contained a high proportion of cacao leaves and a relative low proportion of leaves from leguminous trees such as Erythrina, Swartzia and Inga (M1 contained 67% of cacao leaves and 27% of leaves from leguminous trees). This high proportion of cacao leaves could explain the lack of differences in decomposition between cacao and M1 litterbags. Matos et al. (2020) reported that high quality litter (lower C:N ratio) gave rise to more abundant microbial biomass, more arthropod abundance, and higher potassium and phophorus contents in soil suggesting stimulated decomposition. Since cacao leaves and M1 had similar C:N ratio, this could also influence in the lack of differences during decomposition.

In contrast, in SA, M2 litterbags tended to have higher dry weight, carbon and nitrogen contents than cacao litterbags. M2 litterbags contained lower proportion of cacao leaves but a similar C:N ratio as cacao litterbags. Some of the leaves present in M2 seem to have had a different decomposition dynamic than cacao leaves. Results from a experiment with diverse litters and soil microbial diversities showed that litter composition was a more important driving factor than soil biodiversity for loss of litter mass (Liu et al. 2023). This aligns with results obtained with M2 litter and could partially explain the lack of differences between cropping systems.

The decomposition of leaf-mixtures can be additive, synergic or antagonistic. Synergy can result from various factors, including the transfer of nitrogen from high-nitrogen litter to more recalcitrant litter, as well as increased chemical diversity, which may promote richer bacterial and fungal communities (Porre et al. 2020). Under our conditions, apparently there are no significant synergetic effects of leaf mixtures on decomposition. This is in line with Porre et al. (2020) who report that additivity of decomposition rates is more common than interaction between litter from different species. Rapidly growing nitrogen-fixing shade trees are normally included in agroforestry systems because they could replace nitrogen lost in harvest and can develop on nitrogen-deficient soils, transferring nitrogen to crops mostly through residue decomposition, release and uptake of root exudates and transfer through mycorrhiza (Munroe and Isaac 2014). Our data suggest that under our working conditions, transfer of nitrogen through decomposition of leaf residues is not very significant (Matos et al. 2020).

### Estimating nutrient release from pruning

The calculation of nutrient losses requires knowing the initial nutrient contents of each litterbag. Since initial values were determined in additional leaf samples, the nutrient losses shown on Table 3 are estimates.

Data on Table 4 allow us to approximate the quantity of nutrients released by pruning residues over a year. Considering that dry weight of residues goes from 1039 to 8000 kg.ha$^{-1}$ (Morales-Belpaire et al. 2024), there is a yearly release of 2–14 P kg ha$^{-1}$, 9–72 N kg ha$^{-1}$ and 48–376 K kg ha$^{-1}$. Given that the soils in our study area contain an average of 0.1% nitrogen, 0.85 ppm of potassium (Schneider et al. 2017) and around 4 ppm of phosphorus (Morales-Belpaire et al. 2024), and following recommendations from Snoeck and Dubos (2018), the recommended fertilizer rates are: N 30 kg.ha$^{-1}$, $P_2O_5$ 90 kg.ha$^{-1}$ (equivalent to 39,2 P kg.ha$^{-1}$), with no potassium addition. Under our conditions, pruning residues could supply most of annual nitrogen demand and 5–35% of the phosphorus demand.

### Limitations of the litterbag method

Although the litterbag method is one of the most used for studying litter decomposition, it has serious limitations as described by Cotrufo et al. (2010b). One of the limitations is the exclusion of edaphic macrofauna, which have a fundamental role in fragmentation. Seibold et al. (2021) found that, under temperature and precipitation conditions similar to ours, insects and other invertebrates accelerate annual mass loss of deadwood by 30–40%. Land use and management can affect edaphic fauna. For example Matos et al. (2020) reported that macrofauna was significantly different between pasture, agroforestry and forest. Moreover, Silva et al. (2024) observed a positive correlation between abundance, richness and diversity of trees and diversity of soil dwelling arthropods. The lack of significant effects of the cropping system could be, at least partially, affected by the exclusion of macrofauna, which could be expected to vary across the cropping systems.

Litterbags were placed among the standing litter with limited contact with soil. Pauli et al. (2011) reported that the litter layer has relatively low invertebrate density as compared to upper layers of soil. Also variations of soil microbial biomass and enzymatic activities have been reported to vary with land use and cropping systems (Matos et al. 2020; Morales-Belpaire et al. 2024). Lack of contact of litterbags with soil might have also caused a sub-estimation of decomposition time and a lack of significant differences in many measured chemical properties.

Another problem of the litterbag method is the estimation of soil or dust contamination. One of the common methods to account for this contamination is washing the litterbag contents, but this procedure could have eliminated soluble molecules and has low repeatability (Potthoff and Loftfield 1998). By then, we corrected dry weights by substracting ash content. However, we are aware that a small fraction of ash could correspond to inorganic contents of leaf material.

## Conclusions

Under our experimental conditions, the only significant effects of the cropping systems on cacao and M1 leaves was observed for nitrogen contents in conventional agroforestry after 4 months of laying, and for phosphorus contents in agroforestry systems after 8 months of laying. These findings suggest that some conditions under agroforestry systems could favour the increase in microbial biomass that temporarily immobilises these elements.

Larger mesh litterbags showed lower contents of elements that have soluble forms (carbon, nitrogen, phosphorous, potassium) than smaller mesh litterbags at four months after laying. However, this seems to be caused more by facilitated microbial colonization and leaching than by presence of mesofauna.

M1 and M2 litterbags contained a high proportion of cacao and had similar values of the C:N ratio as cacao litterbags. Although M1 litterbags showed no relevant differences with cacao litterbags, the M2 litterbags showed different decomposition behaviour than cacao litterbags, suggesting that criteria other than C:N ratio should be considered. No evidence of synergistic effects of residues from shade trees could be observed.

Under the conditions of the field trial, the nutrient input from pruning residues could meet the potassium and nitrogen demands of cacao crops, but is insufficient for phosphorus.

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**Data availability** The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

### Declarations

**Competing interests** The authors declare none.

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