Agroforest Syst
https://doi.org/10.1007/s10457-023-00876-6

Total litterfall and leaf-litter decomposition of *Theobroma grandiflorum* under different agroforestry systems in the western Colombian Amazon

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Received: 4 December 2022 / Accepted: 7 July 2023

Abstract The change in land use from forest to pasture has generated negative effects on the biological, physical and chemical attributes of the soil in the Amazon in recent years. Agroforestry systems (AFS) can increase biomass production and increase the rate of litter decomposition. The objective of this study was to quantify the amount of litter accumulated on the soil and the rate of decomposition in multistrata successional agroforestry systems with *Theobroma grandiflorum* as mainly crop, compared to forest in the western Colombian Amazon. Samples were collected for one year every 15 days starting in August 2013 using four collection traps distributed systematically in each AFS. In each trap the amount of total biomass was calculated (Mg ha^{-1}) and for each component leaves, branches, flowers, fruits and seeds. To determine *k*, litterbags containing *Theobroma grandiflorum* leaves were located in each land use and were collected every 15 days from November 2013 up to 150 days, for a total of 840 litterbags (6 land uses × 10 monitoring periods × 2 mesh size × 7 replications). The annual average litterfall production was 50.8% higher in AFS (6.5 Mg ha^{-1}) than in forestry (3.2 Mg ha^{-1}), with leaves and branches being the major contributors with 5.2 ± 0.5 and 0.7 ± 0.2 Mg ha^{-1}, respectively. The residence time (1/*k*) of the SF were higher than the average of the AFS. The time needed to rich a decomposition of 50% (t_{50}) in AFS was higher than SF. In this sense an average of 185 days are required to decompose 50% of the remaining dry mass (RDM%) while in SF is 95 days. Agroforestry systems generated a higher annual mean contribution of biomass than that presented in the forest (6.5 vs. 3.2 Mg ha^{-1}), however, under the forest there was a high value of *k*. requiring 125 and 95 days to decompose 50% of the remaining

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Published online: 23 July 2023

dry mass. The leaf was the main contributor to the total biomass supplied to the soil.

Keywords Litter accumulated · Litter residence time · Litterbag · Mesh size

Introduction

In different regions of continental Amazonia, and especially in Colombia, deforestation attributed to the expansion of grasslands stands out (Armenteras et al. 2006). Due to inadequate grassland management, highly degraded pasture lands prevail and cattle graze freely on very unproductive pastures, generating high environmental pollution related to CO_2 emissions generated by slash-and-burn as well as CH_4 emissions generated by livestock farming (Etter et al. 2006; Landholm et al. 2019; Vargas et al. 2019). In the Amazon region many pastures are degraded supporting low stocking rates, and its contribution to ecosystem services related to nutrient cycling, erosion control and many others is poor (Silva et al. 2022; Rodríguez et al. 2021a).

Agroforestry systems (AFS) are one of the practices implemented in degraded landscapes of the deforested Amazon (Álvarez et al. 2023; Lavelle et al. 2016) that have allowed for improved soil fertility conditions and increased ecosystem services (de Souza et al. 2019; Gervazio et al. 2019). AFS can improve soil fertility and structure from leaf nutrient cycling (Che et al. 2020; Cherubin et al. 2019; Froufe et al. 2019; Guo et al. 2018). However, this ability to improve soil characteristics depend on the amount and decomposition rate of (provided) biomass (Pérez-Flores et al. 2018; Wang et al. 2014; Das and Das 2010; Montagnini et al. 1993; Heuveldop et al. 1988).

Different values of biomass contribution to the soil have been reported ranging from 1.6 to 61.2 Mg ha^{-1} under different AFS such as home gardens and multistrata agroforestry arrangements (Sari et al. 2022; Verma et al. 2022; Froufe et al. 2019; Pérez-Flores et al. 2018; Fontes et al. 2014; Das and Das 2010; Arato et al. 2003). As for the decomposition rate (*k*, i.e. decomposed dry mass per day) estimated using single negative exponential regression (Olson 1963; Guo et al. 2022), as the remaining dry mass (RDM%) of litterfall in AFS, it may vary depending on the leaf species and the type of agroforestry structure, as much as environmental factors and biotic communities (Swift et al. 1979; Heal et al. 1997; Anderson and Ingram 1982; Anderson and Domsch 1985). In this regard, Hasanuzzaman and Hossain (2014a) found 0.9 and 2.1 k year^{-1} for different species of *Mangifera indica*, *Zizyphus jujuba*, *Litchi chinensis,* and *Artocarpus heterophyllus*, that make up a home garden in Bangladesh. Similarly, Leblanc et al. (2006) report the decomposition of fresh leaves of *Inga samanensis* and *Inga edulis* under alley cropping values of 0.0981 and 0.1478 k week^{-1}. Under other AFS such as coffee, Villavicencio-Enriquez (2012) in Mexico reports *k*-values of 2.3, 2.0 and 1.8 under a Coffee AFS, rustic coffee system and medium forest, respectively. Under a silvopastoral system (SSP) in India a *k* value between 0.5 and 1.8 was recorded (Tripathi et al. 2013). Other studies of leaf litter decomposition of *Theobroma cacao*- *Cordia alliodora* and *T. cacao-Erythrina* sp. mixtures in Cocoa AFS under shade trees (*Cordia alliodora* and *Erythrina poeppigiana*) showed RDM values between 45.2 and 48.9% (Heuveldop et al. 1988). Similarly, leaf litter decomposition studies of twelve forest species under AFS in Bangladesh recorded a mass loss between 11 and 63% (Hasanuzzaman and Hossain 2014b). In the Colombian Amazon region, there is a lack of knowledge regarding leaf litter and its fractions and decomposition rate to maintain surface soil cover and nutrient supply to the soil as a strategy for the recovery of degraded soils. This gap compromises our ability to predict the impact of agroforestry arrangements as litterfall contributors and in the improvement of soil fertility.

The studies carried out in the western Colombian Amazon under AFS have been based mainly on biological soil studies (Rodríguez et al. 2018), soil macro-aggregates (Rodríguez et al. 2019; 2021a), and typologies of agroforestry systems associated with *Theobroma cacao* (Suárez et al. 2018). Therefore, it is necessary to evaluate leaf litter production and the decomposition on AFS as a mechanism of nutrient cycling involved in improving soil fertility and recovering degraded soils due to grazing pressure (Sari et al. 2022; Piza et al. 2021). The aim of this research is to measure the total amount of litterfall, and its fractions contributed to the soil, as well as to evaluate the decomposition process under different agroforestry systems and adjacent natural regeneration areas. In this sense, we propose to answer the following questions: (i). What is the contribution of biomass from the different leaf litter fractions under land uses? and (ii). What is the incidence of the different land uses on the rate of leaf litter decomposition? These questions raise the need to know the amount of leaf litter that an AFS can provide and the rate with which it decomposes, as part of the nutrient cycling service that AFS can generate as a restoration strategy for degraded soils in the Amazon. Therefore, the evaluation of litter production and decomposition of multistrata AFS is important to understand the mechanisms involved in the sustainability and soil fertility of these land use systems as restoration strategies for degraded pastures.

Materials and methods

Study site and description of the evaluated land use types

The study was developed in five agroforestry systems with no intervention (manage or inputs) for 20 years) which were compared to near secondary forest (SF) areas located at the Centro de Investigaciones Amazonicas CIMAZ Macagual—Universidad de la Amazonia (Table 1) at approximate coordinates 1°30′4.87" N and 75°39′47.16" W, located in the Amazon and the Andes transition (east of the Andes mountains) at an altitude of 360 m, in a humid area with an average annual precipitation of 3793 mm and a monomodal rainfall. The maximum precipitation is distributed between April and September, with solar brightness of 1.707 h year^{-1}, average temperature of 25.5 °C and relative humidity of 84.3% (IGAC 2014). The CIMAZ Amazonian research center is located in southern Colombia towards the foothills of the eastern cordillera (Fig. 1). CIMAZ is an experimental center of 380 ha where the plots with the five AFS and the SF evaluated were located. There was only one plot for each PFS (not repeated). The SF and the land uses were less than 900 m apart and the physiognomy and soil type is quite homogeneous, presenting a sandy loam texture. The five SAF and the SF had different species (deciduous and evergreen) and different origin (native or exotic) and their age is approximately 25 years while SF had an age of 40 years (Table 1). The soils of the different agroforestry systems evaluated (Table 2), classified as Acrisols (Quesada et al. 2011) are acidic with pH values ranging from 2.64 to 5.02, aluminum saturation levels of 84% and very high Fe levels ranging from 437 to 912 mg kg^{-1}, average exchangeable acidity of 2.5 meq100g^{-1} and effective cation-exchange capacity averaging 3.7 meq100g^{-1}, and low carbon organic (1.7%) and organic matter (2.9%) contents in the soil. Total bases in the soil average 1.2 meq100g^{-1} and the fertility level is low, with N and P contents not exceeding 0.8 and 2.6 mg kg^{-1}, respectively. The geology of the area corresponds to conglomerates, clays, and poorly consolidated sandstones with a hilly landscape. Soil mineralogy shows high quartz contents followed by feldspars and predominance of kaolinite (IGAC 2014).

In total, six land use types (Table 3) were investigated and their structure was composed by an average 537 trees, more frequently by *Hevea brasiliensis, Theobroma cacao, Eugenia stipitata, Cariniana pyriformis*, among others. Likewise, these land uses contained leguminous tree species such as *Acrocarpus fraxinifolius, Cedrelinga cateniformis, Inga minutula and Schizolobium amazonicum*, fruit trees such as *Bactris gasipaes, Borojoa patinoi, Eugenia stipitata, Theobroma bicolor, T. cacao, T. grandiflorum* and timber trees such as *Acrocarpus fraxinifolius, Anacardium excelsum, Calycophyllum spruceanum, Cordia alliodora,* among others. These land uses have high levels of shade that exceed 70% for some of them, with dasometric measurements such as diameter at breast height with an average of 15.1 cm and tree heights of 8.4 m.

Litter production

The samples of litterfall were collected for one year every 15 days from August 2013. Four collection traps (1 m^2 area) were placed at a height of 30 cm above the ground and distributed in a systematic way in each land use to consider the intra-variation. The traps were made of polyshade mesh and 1/2 inch diameter PVC pipe. All samples were dried (70 °C) in paper bags to a constant weight and separated into leaves (LV), branches (BR), flowers (FW), fruits (FR) and seeds (SD). Then they were weighed on a dry basis (g m^{-2}, converted to Mg ha^{-1} later) in an OhausTM balance with 0.01 g precision.

Table 1 Description of dominant vegetation, microclimatic parameters, area and location of study sites

Land use types	Description[1]	Average temperature (°C)	Relative Humidity (%)	Area (ha)	Location
CFP1	Agroforestry system established for 24 years, with a predominance of a type of rubber tree ([*Hevea brasiliensis* (Willd. ex A. Juss; D, Nt) Müll. Arg.] characterized by its broad leaves, associated with the fruit trees copoazú [*Theobroma grandiflorum* (Willd. ex Spreng.) K.Schum.] (E, Nt) and arazá (*Eugenia stipitata* McVaugh) (E, Nt)	33	66	3.0	N 01°29´42.7 W 75°39´15.3
STC	Agroforestry system established for 24 years, which combines the trees paricá (*Schizolobium amazonicum* Huber ex Ducke) (D, Nt), rubber [*Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg.], and peach palm (*Bactris gasipaes* Kunth) (E, Nt) with the fruit tree copoazú [*Theobroma grandiflorum* (Willd. ex Spreng.) K.Schum.]	30	65	3.5	N 01°29´53.7 W 75°39´11.8
CA2	Agroforestry system established for 25 years, in which the tree seed were sown in rows with a predominance of the species peach palm (*Bactris gasipaes* Kunth) and rubber [*Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg.], achapo [*Cedrelinga cateniformis* (Ducke) Ducke] (D, Nt) is found at a low density, yarumo (*Cecropia peltata* L.) (E, Nt), and ice cream bean (*Inga minutula* (Schery) T.S. Elias (E, Nt); between the rows are cacao (*Theobroma cacao* L.) (E, Nt), arazá (*Eugenia stipitata* McVaugh) and copoazú [*Theobroma grandiflorum* (Willd. ex Spreng.) K.Schum.]	29	67	2.0	N 01° 29´47.9 W 75°39´9.9
CFP3	Agroforestry system implemented for 21 years, composed of the species huito (*Genipa Americana* L.) (D, Nt), bilibil [*Guarea guidonia* (L.) Sleumer] (E, Nt), higuerón (*Ficus enormis* (Mart. ex Miq.) Mart.) (E, Ex), wild cashew [*Anacardium excelsum* (Kunth) Skeels] (E, Nt), Honduran mahogany (*Swietenia macrophylla* King.) (D, Nt), laurel [*Cordia alliodora* (Ruiz & Pav.) Oken)] (E, Nt), tachuelo (*Lacmellea standleyi* (Woodson) Monach.) (E, Nt), Juan soco (*Couma macrocarpa* Barb.Rodr.) (E, Nt), and sangre toro [*Virola elongata* (Benth.) Warb] (E, Nt), associated with the fruit trees copoazú [*Theobroma grandiflorum* (Willd. ex Spreng.) K.Schum.], arazá (*Eugenia stipitata* McVaugh), and plantain (*Musa paradisiaca* L.) (E, Ex). The system is geogaphically located near water bodies. Some areas of the system experience floods during periods of maximum precipitation	30	49	2.0	N 01°29´55.6 W 75°39´46.6
HG	Agroforestry system implemented for 26 years that combines diverse fruit trees such as copoazú [*Theobroma grandiflorum* (Willd. ex Spreng.) K.Schum.], pataxte (*Theobroma bicolor* Bonpl.) (E, Nt), custard apple (*Annona cherimola* Miller), borojó (*Borojoa patinoi* Cuatrec.) (E, Nt), cacao (*Theobroma cacao* L.), mango (*Mangifera indica* L.) (E, Ex), and peach palm (*Bactris gasipaes* Kunth); Colombian mahogany (*Cariniana pyriformis* Miers) (E, Nt), wild cashew [*Anacardium excelsum* (Kunth) Skeels], chingale [*Jacaranda copaia* (Aubl.) D. Don.] (E, Nt), and capirona (*Capirona decorticans* Spruce) (E, Nt) are found in low densities	31	46	2.0	N 01°30´6.7 W 75°39´49.2

Table 1 (continued)

Land use types	Description[1]	Average temperature (°C)	Relative Humidity (%)	Area (ha)	Location
SF	*Cedrela odorata* (C, Nt)*, Laurus nobilis* L. (P. Ex), *Inga sp., Miconia appendiculata* Triana (E, Nt), *Miconia elata* (Sw.) DC. (E, Nt) *Cecropia peltata, Cedrelinga cateniformis* among others. Natural system of approximately 40 years without any type of human intervention	28	75	55	N 01°29´42.9 W 75°39´14.2

Alley cropping 2—CA2; Cropping in forest plantation 3—CFP3; Cropping in forest plantation 1—CFP1; Home garden—HG; Secondary Forest—SF; Shade trees for crops—STC. Evergreen—E; Deciduous—D; Native—Nt; Exotic—Ex. Sources: www.tropical.thefernsinfo (useful tropical plants) and www.iucnredlist.org/search. [1]From Rodriguez et al. 2018

Decomposition of litterfall

The litterbag approach was used to study the dynamics of decomposition (Bocock and Gilbert 1957, Karberg et al. 2008). To determine the effect of land uses on the rate of leaf litter decomposition, a litterbag (20 × 15 cm) containing 20 g of *Theobroma grandiflorum* leaves was used because it was present in all land uses studied. *Theobroma grandiflorum* leaves had a carbon content of 49.3% (Walkley and Black method), nitrogen content of 1.1% (Kjeldahl method) and phosphorus content of 1.0% (Bray II method). At the base level, *Theobroma grandiflorum* leaves presented a content of 0.4% calcium, 0.3% potassium and magnesium and 231.5 mg kg^{-1} of sodium (Atomic absorption method). The lignin content was 46.9%, the cellulose and hemicellulose content were 18.9% and 5.2%, respectively, and the lignocellulosic index was 0.7. Lastly, the total phenol content was of 0.1% (Folin–Ciocalteau method). This initial weight of the litterbag was recorded and bags were closed with staples.

The effect of the soil macrofauna community on the litter decomposition rate for each land use was evaluated in 2 mm and 20 mm mesh size litterbags, made of nylon plastic and metal mesh, respectively (70 litterbags per mesh size) with seven repetitions. This difference in pore size attained the objective of inferring the incidence of the agroforestry system on the decomposition rate, since depending on the design, composition, and structure of the AFS, the populations of soil macrofauna can vary and therefore the decomposition (Toro et al. 2015; Bradford et al. 2002). Twenty litterbags (10 monitoring periods × 2 mesh size) were placed in each of the 7 groups (replications) by land use. The replications were systematically allocated in each land use to consider intra-variation.

The litterbags were place on top of soil after remove the litter. After that, the remove litter was put over the litterbags to simulate the natural condition of decomposition. The litterbags were collected at random, one for each replication, every 15 days from November 2013 up to 150 days, for a total of 840 Litterbag. The litterbags were placed in a three-factor (6 land uses × 2 mesh size × 10 monitoring periods) experiment with 7 replications in a complete randomized design. The material obtained in each bag was dry-weighed on an OhausTM scale with an accuracy of 0.01 g.

Data analysis

A non-linear regression model of the remaining dry mass (RDM) percentage as a function of time per mesh size under each land use was fitted, corresponding to a simple exponential decay model (Olson 1963; Casanoves et al. 2022). The RDM (%) = $DM_t/DM_0 \times 100$, where DM_t is the remaining dry matter at the t sampling time, and DM_0 is the initial dry matter of the litter bags for decomposition (Bahamonde et al. 2012). The decomposition rate constant (k) of litter residues was estimated following single exponential model (Olson 1963) as indicated: $DM_t/DM_0 = \alpha\, e^{(-kt)}$, where α is the intercept, k is the value of the decomposition constant ($k > 0$) and t is the evaluation time. Based on these developed models, it was calculated time at 50% RDM (t_{50}), time at 95% RDM (t_{95}) and time at 99% RDM (t_{99}) (Songwe et al. 1995).

Linear Models (LM) were adjusted to analyze the differences between litterfall production data (Mg ha^{-1} $year^{-1}$) and decomposition constant (k) among the

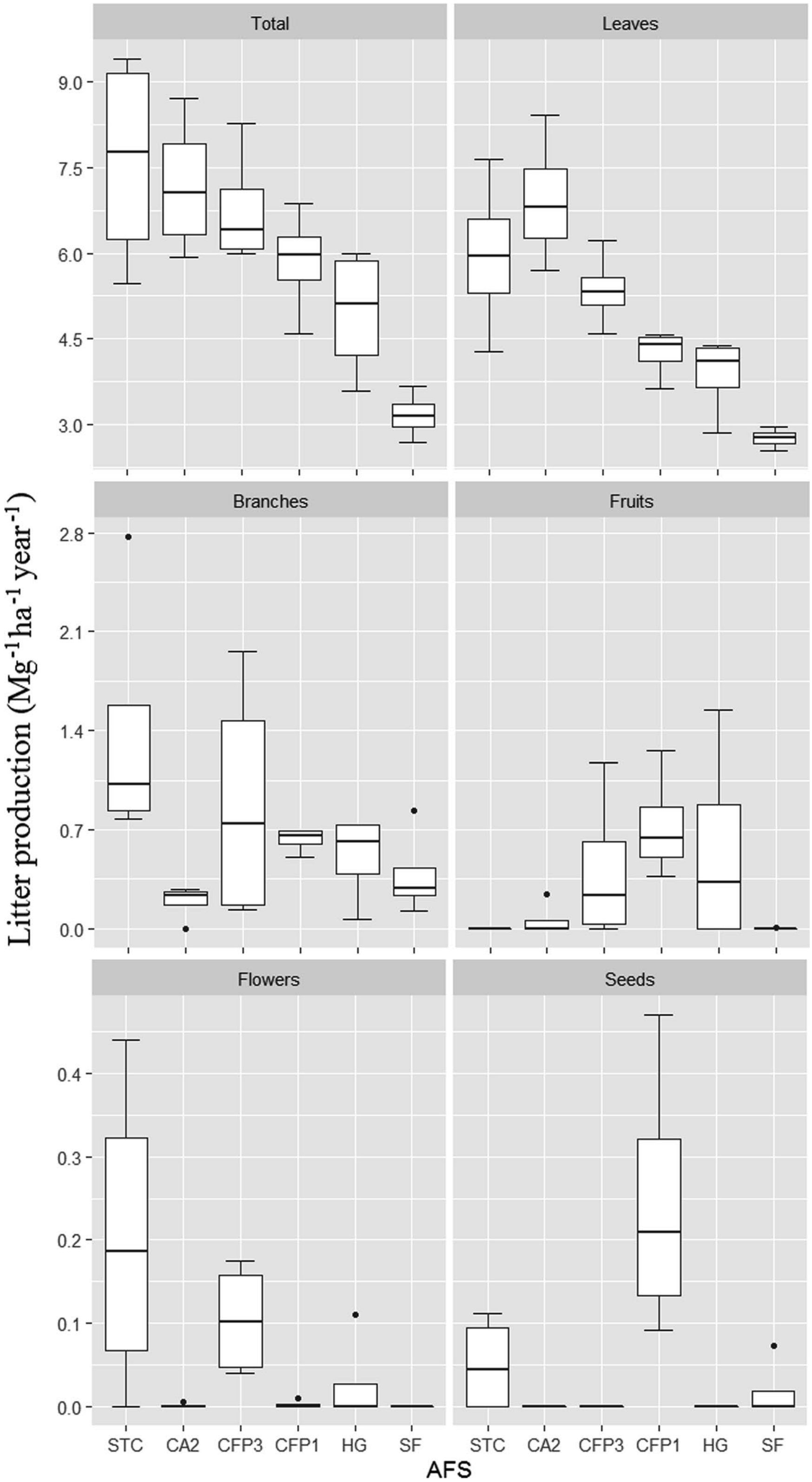

Fig. 1 Total amount of litterfall components produced under six land use types collected for one year from August 2013. Secondary forest—SF, Shade trees for crops—STC, Alley cropping 2—CA2, Crops in forest plantation 3– CFP3, Crops in forest plantation 1– CFP1 and Home garden—HG

Table 2 Soil chemical composition in the six land use types evaluated in the western Colombian Amazon

Soil attribute	Unit	SF	STC	CA2	CFP3	CFP1	HG
pH		2.64 ± 0.36	3.58 ± 0.28	3.52 ± 0.1	5.02 ± 0.24	3.26 ± 0.23	4.34 ± 0.06
OC	%	1.77 ± 0.17	1.47 ± 0.3	1.77 ± 0.17	1.14 ± 0.19	1.62 ± 0.29	2 ± 0.15
OM	%	3.06 ± 0.3	2.53 ± 0.53	3.06 ± 0.3	1.97 ± 0.32	2.79 ± 0.5	3.46 ± 0.26
N	%	0.86 ± 0.01	0.86 ± 0.02	0.81 ± 0.04	0.69 ± 0.03	0.86 ± 0.03	0.83 ± 0.01
P	mg kg^{-1}	3.15 ± 0.01	2.41 ± 0.11	2.48 ± 0.09	2.33 ± 0.03	2.53 ± 0.11	3.3 ± 0.11
K	meq 100 g^{-1}	0.04 ± 0.01	0.04 ± 0.01	0.07 ± 0.01	0.03 ± 0.01	0.04 ± 0.01	0.05 ± 0.01
Ca	meq 100 g^{-1}	0.5 ± 0.11	0.7 ± 0.1	0.33 ± 0.05	0.7 ± 0.11	0.43 ± 0.13	0.71 ± 0.22
Na	meq 100 g^{-1}	1.02 ± 0.4	0.43 ± 0.06	0.74 ± 0.18	0.25 ± 0.09	0.14 ± 0.08	0.32 ± 0.07
Mg	meq 100 g^{-1}	0.06 ± 0.01	0.12 ± 0.04	0.14 ± 0.03	0.26 ± 0.02	0.05 ± 0.02	0.22 ± 0.05
TB	meq 100 g^{-1}	1.62 ± 0.45	1.3 ± 0.19	1.28 ± 0.23	1.24 ± 0.16	0.67 ± 0.16	1.3 ± 0.24
Zn	mg kg^{-1}	1.07 ± 0.04	1.5 ± 0.32	1.88 ± 0.3	4.21 ± 1.57	1.26 ± 0.2	2.25 ± 0.27
Cu	mg kg^{-1}	0.45 ± 0.03	1.28 ± 0.05	0.74 ± 0.09	2.6 ± 0.78	0.97 ± 0.15	2.03 ± 0.35
Fe	mg kg^{-1}	912.22 ± 8.89	748.78 ± 95.38	860.08 ± 31.25	811.96 ± 46.2	841.14 ± 17.39	654.05 ± 49.87
Mn	mg kg^{-1}	2.63 ± 0.61	10.51 ± 7.26	8.86 ± 2.51	26.37 ± 1.18	7.03 ± 3.11	19.34 ± 1.32
EA	meq 100 g^{-1}	5.29 ± 0.12	1.8 ± 0.78	4.05 ± 0.4	0.13 ± 0.06	3.63 ± 0.26	0.34 ± 0.09
ECEC	meq 100 g^{-1}	6.91 ± 0.49	3.1 ± 0.6	5.33 ± 0.4	1.37 ± 0.16	4.3 ± 0.34	1.64 ± 0.16
BS	%	6.27 ± 1.17	9.3 ± 1.09	5.45 ± 0.63	10.45 ± 2.11	3.17 ± 0.71	5.72 ± 1.73
AlS	%	77.44 ± 4.34	49.6 ± 15.32	75.85 ± 3.72	9.68 ± 5.23	84.73 ± 3.00	22.84 ± 8.23

Mean ± Standard error. Secondary Forest– SF; Shade trees for crops—STC; Alley cropping 2—CA2; Cropping in forest plantation 3—CFP3; Cropping in forest plantation 1– CFP1; Home garden—HG. OC: Organic carbon; OM: Organic matter; SB: Sum of bases; EA: Exchangeable acidity; ECEC: effective cation-exchange capacity; BS: Base saturation; AlS: Aluminum saturation

Table 3 Composition and structure of the six land use types evaluated in the western Colombian Amazon

Land use types	Tree density (Trees ha^{-1})	Aboveground biomass (Mg ha^{-1})	Number of species	DBH[1] (cm)	Total height[1] (m)	Shade level (%)
STC	492	45.1	4	14.2	9.2	75
CA2	468	41.4	8	14.5	6.4	70
CFP3	473	44.3	12	13.5	5.1	85
CFP1	399	127.8	3	27.6	11.4	65
HG	1292	61.6	11	7.9	5	85
SF	102	41.7	6	10.6	12	45

DBH: average value of diameter at breast height. [1]mean. Secondary Forest—SF, Shade trees for crops—STC, Alley cropping 2—CA2, Cropping in forest plantation 3—CFP3, Cropping in forest plantation 1– CFP1, Home garden—HG

different land uses. The model for litterfall production data considered the fixed effect of land uses and the ANOVA was obtained for each collection type (leaves LV, branches BR, flowers FW, fruits FR and seeds SD) and for the total litterfall. The model for decomposition constant considered the fixed effect of land uses, bag size and its interaction. Assumptions of normality and homogeneity of variance were evaluated by an exploratory residual analysis. Mean values were compared using Fisher's LSD post-hoc test ($\alpha = 0.01$). The selection of the fitted models was based on Akaike (AIC) and Bayesian (BIC) Information Criteria (Littell et al. 1996) and on likelihood ratio tests (LRT). Analyses were performed using the *gls* function (Pinheiro et al. 2012) in R language software, version 4.2.0 (R Core Team. 2022), using the interface in InfoStat (Di Rienzo et al. 2022).

Results

Litterfall production

The average annual production under AFS was 6.5 ± 0.3 Mg ha^{-1} of litter with maximum and minimum values of 4.5 and 7.6 Mg ha^{-1} for STC and HG, respectively, while in the SF, the annual litter production was 3.2 Mg ha^{-1} (Fig. 1). The *Theobroma grandiflorum* litter fall percentage in each AFS was CFP3 = 9.6%, HG = 15.7%, CA2 = 0.9%, CPF1 = 13.7% y STC = 3.3%.

During study litterfall period there was decrease of rainfall between august-2013 to april-2014 and increase in average temperature (Fig. 2A). We registered high litter production during first quarterly 2014, which it was associated to low rainfall and high average temperature (Fig. 2B). The land use STC showed high litter in march 2014 associated with low rainfall respect to the others AFS evaluated. On the other hand, land uses CA2 and CFP3 showed slightly increase in litterfall production when increase rainfall.

We registered high litter production during first quarter of 2014, which was associated with low rainfall and high average temperature (Fig. 2A). The land use STC showed higher litterfall in march 2014, associated with low rainfall. Among components, leaves and branches were the largest contributors to total production with 5.27 ± 0.5 and 0.72 ± 0.2 Mg ha^{-1}, respectively (Fig. 1).

Decomposition of litterfall

The residual mass of the litter decreased exponentially over time under all land uses evaluated (AFS's and SF), with an effect on the decomposition rate (k). There was a significant interaction between land uses and mesh sizes ($p = 0.0017$). When comparing land

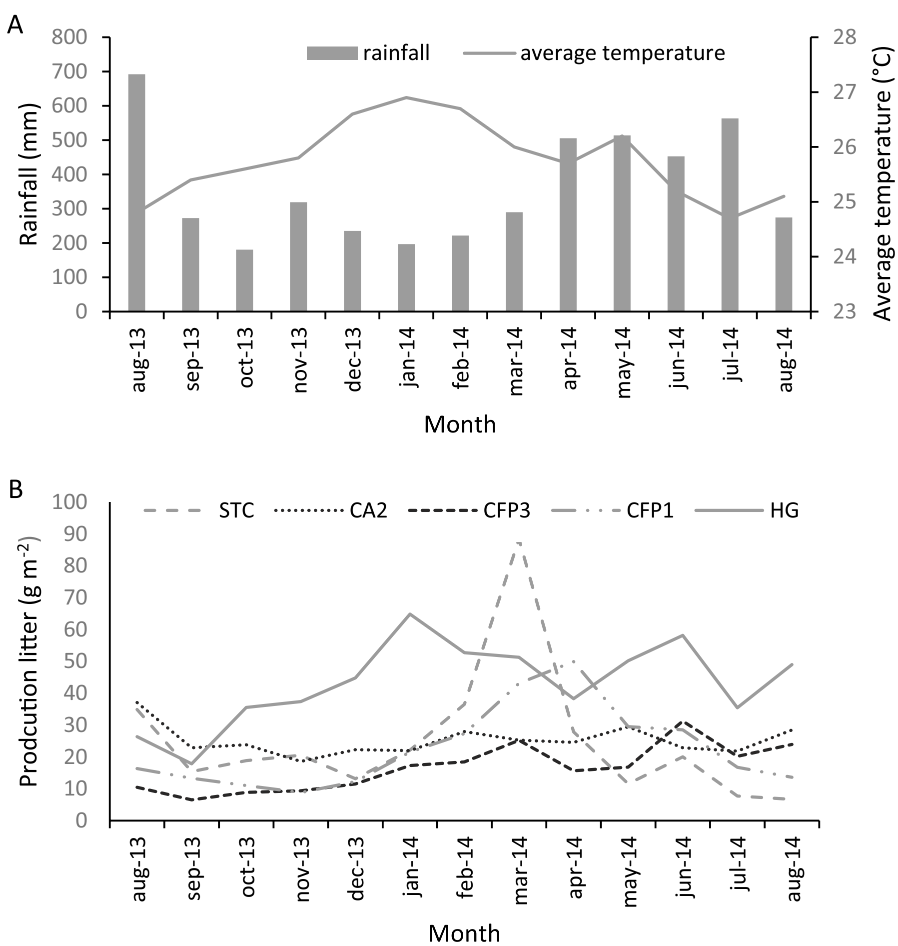

Fig. 2 **A**. Monthly variation of rainfall and average temperature during study period of litterfall among land use types evaluated. Source: http://www.ideam.gov.co/ **B**. Monthly variation in litter production among land use types evaluated. Secondary forest—SF, Shade trees for crops—STC, Alley cropping 2—CA2, Crops in forest plantation 3– CFP3, Crops in forest plantation 1– CFP1 and Home garden—HG

uses, the SF presented a higher k value compared to the AFS, but in SF there were not differences between mesh sizes (Table 4). The effect of land use and mesh size affected the rate of decomposition, for example, in the SF the decomposition rate was higher compared to AFS (Fig. 3) in the different times evaluated (t_{50}, t_{95} and t_{99}; Table 4). Overall, the soil macrofauna under all land uses evaluated increased the litter decomposition rate by 27.2%, reducing the time to decompose 99% of RDM by 92 days. When comparing AFS under CFP3 in a mesh size of 20 mm there is a higher rate of decomposition (Table 4) which affects the remaining dry mass (Fig. 3). With all the Table 4 results variables we perform a principal component analysis to ordinate the AFS´ in relation with SF, getting the following order: SF > HG > STC > CFP 1 > CFP3 > CA2.

Discussion

Litter production

The inverse relationship observed in several AFS between litter production and rainfall was similar to studies made in Brazil (Lima et al. 2015; Sanches et al. 2009). However, trees leave deposition does not always show an evident inverse relationship with rainfall as we seen in land uses CA2 and CFP3 (Fig. 2), indicating in some cases that litterfall is dependent on the plant species (Fernandes et al. 2006; Barlow et al. 2007). On the other hand, under Amazonian conditions, agroforestry systems presented a higher biomass contribution to the soil compared to the SF. This is due, among other things, to the fertility of the soil (Wood et al. 2006) since it promotes the contribution of biomass. The characteristics of the soil in which the SF was found were a very high acidity condition with a pH of 2.64 ± 0.36 and very high levels of Fe and Al as well as exchangeable Al, which probably influenced the development of the biomass above the soil. In this sense, it has been reported that biomass production in the forest is very variable, for example in a lowland tropical forest it reached between 2.3 to 13.9 Mg ha^{-1} year^{-1}, or in an upland tropical forest a biomass production between 3.7 to 14.3 Mg ha^{-1} year^{-1} (Zapata et al. 2007) and in a humid tropical forest as in the present study a biomass production of 2.8 to 15.6 Mg ha^{-1} year^{-1} (Collantes et al. 2014). However, in the Amazon, forests depend solely on nutrient cycling to meet their nutritional requirements, so the rate of nutrient supply depends on species composition and diversity (Lagemann et al. 2022; Lips and Duivenvoorden 1996).

Table 4 Decomposition constants (k calculated for $t = 365$ day, litterfall residence time ($1/k$) in a year) and time required ($t = d$) for loss of 50%, 95% and 99% of initial leaf dry weight in decomposition litterbags under six land use types in the western Colombian Amazon

Site	Mesh size (mm)	k (days^{-1})	t_{50}	t_{95}	t_{99}	1/k	RDM_{150dd}
STC	2	0.0034 ± 0.0003^{c}	202 ± 19	705 ± 75.1	921.7 ± 99.1	292 ± 20.3	58 ± 2.5
	20	0.0044 ± 0.0006^{d}	166 ± 27	601 ± 116	788.4 ± 154	229 ± 28.4	50 ± 3.8
CA2	2	0.0027 ± 0.0004^{c}	266 ± 34	930 ± 120	1216 ± 158	366 ± 34.5	64 ± 3.2
	20	0.0041 ± 0.0007^{d}	167 ± 28	642 ± 119	846.9 ± 159	243 ± 28.7	49 ± 4
CFP3	2	0.0029 ± 0.0003^{c}	230 ± 26	827 ± 102	1083 ± 135	346 ± 26.5	61 ± 1.8
	20	0.0094 ± 0.0005^{a}	82.1 ± 4.1	257 ± 13	332.5 ± 16.9	107 ± 5.1	27 ± 1.9
CFP1	2	0.0029 ± 0.0003^{c}	218 ± 15	806 ± 71.8	1059 ± 97.4	342 ± 15.5	60 ± 1.7
	20	0.0040 ± 0.0003^{d}	176 ± 11	591 ± 40.4	769.1 ± 53.6	249 ± 11.6	55 ± 2.2
HG	2	0.0039 ± 0.0003^{c}	187 ± 12	621 ± 44.3	808.3 ± 58.3	260 ± 13.0	57 ± 2.3
	20	0.0044 ± 0.0004^{d}	164 ± 15	547 ± 52	711.9 ± 68	227 ± 15.8	52 ± 2.7
SF	2	0.0062 ± 0.0005^{b}	108 ± 8.4	377 ± 28.1	492.2 ± 36.7	162 ± 9.4	38 ± 2.5
	20	0.0062 ± 0.0004^{b}	95.5 ± 6.8	364 ± 26	479.5 ± 34.5	162 ± 7.8	36 ± 2.2

Mean ± Standard error. RDM: remaining dry mass. dd: decomposition days. Means with a same letter are not different (Fisher's LSD, $p > 0.05$). Secondary Forest—SF, Shade trees for crops—STC, Alley cropping 2—CA2, Cropping in forest plantation 3– CFP3, Cropping in forest plantation 1– CFP1 and Home garden—HG

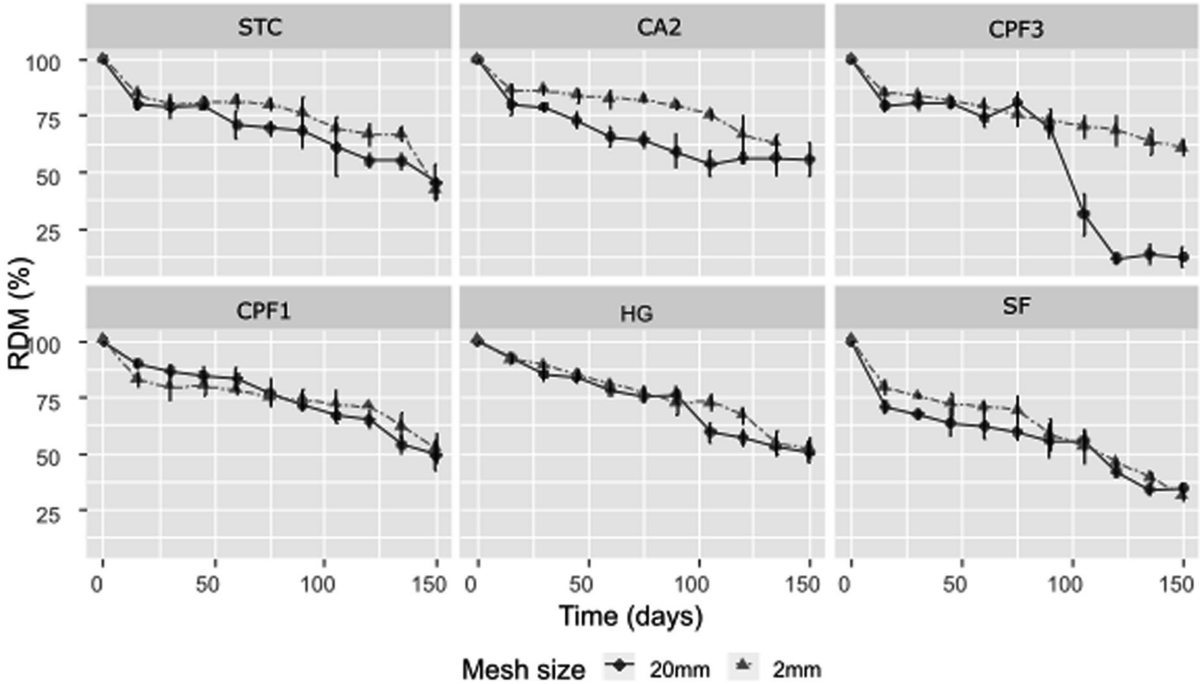

Fig. 3 Decomposition rate of *Theobroma grandiflorum* in litterbags with different mesh size under six evaluated land use types. Secondary forest—SF, Shade trees for crops—STC, Alley cropping 2—CA2, Cropping in forest plantation 3—CFP3, Cropping in forest plantation 1– CFP1, Home garden—HG. Remaining Dry Mass (RDM; n = 7). The segments represent standard errors

Thus, when we compared the biomass production of agroforestry systems, they provided more biomass compared to that of the SF. For example, in agroforestry systems associated with cocoa cultivation, it has been reported that the biomass contribution to the soil reaches between 1.7 to 8 Mg ha^{-1} year^{-1} (Saj et al. 2021, 2022; Asigbaase et al. 2021a; Pérez-Flores et al. 2018; Schneidewind et al. 2018; Fontes et al. 2014; Muoghalu and Odiwe 2011; Tridiati et al. 2011; Fassbender et al. 1991), and under a coffee agroforestry system between 2.6 to 9.1 Mg ha^{-1} year^{-1} (Nesper et al. 2019; Villavicencio-Enríquez 2012; Beer 1988). The above findings depend on the complexity of the agroforestry design in terms of its structure (density of individuals) and the species composition, which has a significant impact on biomass contribution (Verma et al. 2022). For example, under the STC agroforestry system, a greater biomass of leaf litter was produced due to the presence of the Paricá tree species (*Schizolobium parahyba var. amazonicum*), which is a legume native to the Amazon with a high adaptation to acid soils, with biomass production reaching 4.51 Mg ha^{-1} year^{-1} (Gonzalez et al. 2021; Leal-Silva et al. 2011) and which has been used for the restoration of degraded soils in the Amazon region (Rosário et al. 2014; Gazel et al. 2007). In the case of the CA2 agroforestry system, a high biomass production of more than 7 Mg ha^{-1} year^{-1} was also found due to its composition of species such as *Bactris gasipaes* to produce peach palm fruit (Chontaduro). Annual production for this species has been reported, when 53% of weight corresponded to leaflets and 47% to rachis (Ribeiro et al. 2020; McGrath et al. 2000). When we analyzed the biomass production by components, we found a predominance of leaf litter (68.4—95.7%) which is within the range reported by several authors (Saj et al. 2022; Sari et al. 2022; Costa et al. 2017; Tripathi et al. 2009; Gupta et al. 2010) who mention ranges of leaf litter production between 65—76% of the total biomass produced. However, the reproductive material (flowers and fruits) in the studied AFS (< 13%) was lower than that recorded for the AFS in Brazil (20.07%) (Arato et al. 2003).

Litter decomposition rate of *Theobroma grandiflorum*

Although the SF did not produce more biomass in the soil compared to the agroforestry systems, it had a greater degradation of aboveground biomass in both pore sizes. This is due to extrinsic factors, e.g., litter consumption by termites and earthworms (Asigbaase et al. 2021b; Durán-Bautista et al. 2020). This increase in the decomposition rate constant is due to the density and diversity of individuals of macrofauna communities present in the SF compared to that found in agroforestry systems (Rodríguez et al. 2018), which significantly reduced the days in which total biomass degradation is required (t_{99}).

As the objective was to measure the incidence of macrofauna populations (exclusion of the effect of the mesh size Bradford et al. 2002), as a product of the effect of agroforestry systems on the rate of decomposition, leaves of the same species were used to analyze this effect. In this sense, the same chemical indicators of litter quality were maintained, mainly related to nitrogen content, C:N ratio, lignin, polyphenol content, characteristics that can predict decomposition rates (Siqueira et al. 2022). Thus, under the agroforestry systems the value of *k* increased 39.9% as a result of the activity of macrofauna populations (0.00526 for 20 mm mesh size vs. 0.00316 for 2 mm mesh size), this difference being greater under the CFP3 agroforestry system (69.1%). However, when we compared the value of *k* between the agroforestry systems and the SF, the latter increased the value of *k* by 32.1%. This is an evident proof that the design and composition of the AFS do not only influence the biomass contribution but also the macrofauna populations which impact the litter decomposition rate (Pech et al. 2022; Rodríguez et al. 2018; Durán et al. 2018; Suárez et al. 2015; Toro et al. 2015). When analyzing *k* at the tree species level, Negash and Starr (2021) mention variations of *k* from 2.58 $year^{-1}$ (0,0071 day^{-1}) for *Persea americana* to 6.1 yr^{-1} (0.0167 day^{-1}) for *Millettia ferruginea*, differences that are mainly due to variations in the chemical composition of the leaf (Cissé et al. 2021). However, the decomposition rate presented in our study was relatively low, perhaps due to the high values of lignin (46.9%) and C:N ratio (44.4) present in the *Theobroma grandiflorum* leaf.

According to the decomposition rate categories described by Gimenes et al. (2010), it was found that the leaves of *Theobroma grandiflorum* in agroforestry systems STC, AC2, CFP3, CFP1 and HG in 2 mm mesh size, as well as leaves from CFP1 and HG in 20 mm mesh size had a low *k* (<0.005 day^{-1}). Leaf SF at 2 mm mesh size and STC, CA2 and SF at 20 mm mesh size were a medium *k* (0.005—0.010 day^{-1}) and CFP3 at 20 mm mesh size a fast rate in decomposition value ($k>0.010$ day^{-1}). The decomposition rate in 20 mm mesh size can be overestimate for small litter fractions losses. However, some authors have used 10 mm, 15 mm y 50 mm mesh size (Rubio et al. 2016, Zúñiga-Céspedes et al. 2018, Darmawan et al. 2021 respectively). In this sense, when we compared the value of *k* and the decomposition behavior presented, it was found that the values of the for plantations and tropical forests according to those described by León and Osorio (2014) and are slightly higher than the values of *k* (0.00167—0.00403 day^{-1}, simple exponential model) of the litterfall of the simple montane rainforest (Bothwell et al. 2014).

Although CFP3 showed the lower soil macrofauna abundance and richness also it presented the highest *k* value in decomposition bag with a pore size of 20 mm due to some event that generated a greater decomposition of the leaf litter on the 70th day. These changes during the process of leaf litter decomposition may be due to fauna present in the tree canopy that by phenomena such as heavy rains or wind gusts can lead to the fall of ant nests to the ground (Yusah et al. 2012).

Under agroforestry systems, mean residence time has been reported between 2 to 3 years, being higher values than those recorded in the present study (0.2—0.8 years) which depend on the availability of radiation (Hairiah et al. 2006) as well as on the conditions of each site and especially on the recalcitrant condition of tree leaves (Tangjang et al. 2015). In our study the value of 1/*k* was lower in the SF compared to that found under agroforestry systems, a situation similar to that reported by Dawoe et al. (2010) who mention that the forest presented values of 2.8 years compared to 4.4 years in cocoa crops. A study of decomposition under agroforestry systems who used bags with 1 mm mesh size, recorded values for RDM of 58% in *Theobroma cacao*, 10% in *Gmelina arborea*, 60% in *Cedrela odorata* and 25% in *Gliricidia sepium* during a period of four months (Rojas et al. 2017), observing that cacao leaves have a slower decomposition than legumes. Schwendener et al. (2007) found a time of

2.4 years to have the total biomass of the *T. grandiflorum* litter decomposed in in AFS, meanwhile en in our case, between 1.7 and 3.8 years were required for 99% of the litter to disappear in different AFS.

Conclusions

We found that the annual biomass input was 50.8% higher in AFS (6.5 Mg ha^{-1}) than in SF (3.2 Mg ha^{-1}), with leaves being the main contributor to the total biomass input to the soil. However, under SF the litter decomposition rate was higher compared to the other land uses, requiring between 95 and 125 days to decompose 50% of the remaining dry mass, respectively. Overall, the soil macrofauna under all land uses could potentially increase the litter decomposition rate by 27.2%, reducing the time to decompose 99% of the remaining dry matter by 92 days. (Multistrata) Agroforestry systems can be a strategy for the recovery of degraded soils in the Amazon as they increase the nutrient cycling as well as the rate of litter decomposition, when compared to SF.

Author contribution All authors contributed to the conception and design of the study. Material preparation, data collection and analysis were performed by all authors. The first draft of the manuscript was written by Juan Carlos Suárez and all authors commented on earlier versions of the manuscript. All authors read and approved the final manuscript.

Declarations

Competing interests The authors declare no competing interests.

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