Biomass decomposition dynamic in agroforestry systems with *Theobroma cacao* L. in Rionegro, Santander (Colombia)

Dinámica de descomposición de la biomasa en sistemas agroforestales con *Theobroma cacao* L., Rionegro, Santander (Colombia)

Jairo Rojas M.[1], **Víctor Caicedo**[2], **and Yeirme Jaimes**[1]

ABSTRACT

The study was carried out in an agroforestry system (AFS) with cacao trees already established in *La Suiza* Research Center, Corpoica, located in Rionegro, Santander (Colombia). The objective was to evaluate biomass input and nutrient release rate of the species that comprise the AFS (*Gmelina arborea*, *Gliricidia sepium*, *Cedrela odorata*, *Theobroma cacao*). The plant material decomposition process of the species was monitored with decomposition bags after 8, 15, 23, 84 and 113 days, evaluating remnant weight and nitrogen, phosphorous, potassium, calcium and magnesium content. Results showed significant differences in plant material decomposition of the species considered. The largest weight loss was found in *G. arborea* (87.55%) and the lowest in *C. odorata* (40.01%). The highest nutrient release value was found in *G. arborea* followed by *G. sepium*, and the lowest in *T. cacao* and *C. odorata*. Therefore, depending on the species that comprise the AFS there is a differential leaf biomass decomposition dynamic and hence, of the nutrient input to the soil. Of the species evaluated the highest input of new organic matter to the soil in this AFS comes from *G. arborea*. Altogether, the litter generated by the species evaluated contributed with 10% of the nutrients required for a cacao harvest.

Key words: plant litter, nutrient release, organic matter, shade trees, cacao crop.

RESUMEN

El estudio se realizó en un sistema agroforestal (SAF) con cacao establecido en el C.I. La Suiza, Corpoica, Rionegro, Santander (Colombia). En este trabajo se evaluó el aporte de biomasa y la tasa de liberación de nutrientes de las especies del SAF (*Gmelina arborea*, *Gliricidia sepium*, *Cedrela odorata*, *Theobroma cacao*). El proceso de descomposición del material vegetal por especie se monitoreó con bolsas de descomposición los días 8, 15, 23, 84 y 113, evaluando el peso remanente y contenido de nitrógeno, fosforo, potasio, calcio y magnesio. Los resultados mostraron diferencias significativas en la descomposición del material vegetal de las especies. La mayor pérdida de peso se observó en *G. arborea* (87,55%) y la menor en *C. odorata* (40,01%). La mayor tasa de liberación de nutrientes la presentó *G. arborea* seguida de *G. sepium*, y las menores *T. cacao* y *C. odorata*. Por tanto, dependiendo de las especies utilizadas, se presenta una dinámica diferencial de descomposición de biomasa foliar y por ende del aporte de nutrientes al suelo. La mayor entrada de nueva materia orgánica al suelo proviene de *G. arborea*. La hojarasca de todas las especies evaluadas juntas aportó 10% de los nutrientes requeridos para una cosecha de cacao.

Palabras clave: hojarasca, liberación de nutrientes, materia orgánica, árboles sombrío, cultivo de cacao.

Introduction

The reduction of nutrient and organic matter content in soils is a serious threat for agricultural production and food security in many tropical countries (Hossain *et al*., 2011). In this sense, agroforestry provides a sustainable opportunity to counteract this threat due to its potential to reestablish degraded or marginal soils. According to Oelbermann *et al*. (2004) agroforestry systems (AFS) improve soil quality through the input of organic matter from harvest and litter residues maintaining or increasing organic matter in the soil.

Organic matter added through litter, usually improves soil quality as it enhances its water holding capacity, water filtration, biodiversity, soil microorganism activity and nutrient concentration (Ngora *et al*., 2006; Hossain *et al*., 2011). Among litter types, leaf litter has comparatively the highest nutrient concentrations and also returns the largest amounts of nutrients to the soil, in essence it is the major source of soil nutrients (Hossain *et al*., 2011).

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[1] Colombian Corporation for Agricultural Research (Corpoica), La Suiza Research Center. Rionegro, Santander (Colombia). jrojas@corpoica.org.co
[2] Universidad de Nariño. Pasto (Colombia). vituquito20@hotmail.com

In this context, the combination of cacao trees with non-timber species, e.g. plantain and cassava, and with shade trees like *Erythrina glauca* Willd. and *Gliricidia sepium* (Jacq.) Kunth ex Walp. are excellent examples of compatibility and complementarity among different species, as well as of sustainability of a multistrata system with significant litter production (Somarriba, 2006; Fontes *et al.*, 2014). However, the litter produced by each species has very particular characteristics influencing the quantity and the time in which the nutrients are released to the soil during the decomposing process (Beer *et al.*, 1990; Schroth *et al.*, 2001; Mendonça and Stott, 2003).

These nutrient deposition, decomposition and release rhythms to the soil must be synchronized with the crop´s nutritional needs and the maintenance of the soil`s biological functionality and activity (Beer *et al.*, 1990; Schroth *et al.*, 2001; Mendonça and Stott, 2003). For this reason, it is important to know and compare the litter`s nutrient and biomass input from each species that compose the AFS with cacao. Therefore, in this study the litter decomposition dynamic from leaves and petioles of the species *Gmelina arborea* Roxb., *Gliricidia sepium* (Jacq.) Kunth ex Walp., *Cedrela odorata* L., and *Theobroma cacao* L. that comprise an AFS in the municipality of Rionegro, department of Santander was established. Moreover, nutrient input and economic assessment per species was also determined.

Materials and methods

Study site description

The research was carried out in an agroforestry system with cacao at the farm El Encanto located in the municipality of Rionegro, department of Santander, Colombia. The farm is located on western flank of the Eastern Cordillera of Colombia at 07°24´51.0" N and 73°11´33.6" W, and 825 m of altitude. The region has an annual average rainfall of 2,500 mm, a mean temperature of 25°C, 80% relative humidity and an annual solar radiation of 1,700 h. Acording to Holdridge (1967) it is located in the life zone classified as tropical humid forest (bh-T) and also placed in the Kv agroecological zone, characterized by having alluvial soils, clay loam and sandy loam textures. These terrains are distinguished by having a steep relief with slopes higher than 50% that are characteristic of Colombia`s eastern mountain range (ICA-IGAC, 1985).

Sample collection and processing

The study was carried out with the species *G. arborea*, *G. sepium*, *C. odorata* and *T. cacao* that are traditional elements of AFS with cacao in the municipality of Rionegro. The decomposing rate was measured using the decomposing bag technique describe by Bärlocher (2005) during four months. Plant material samples from each species, i.e. fresh leaves and petioles, are taken directly from the plants in order to know the exact time that the decomposing period starts and schedule further monitoring. Each tissue sample (100 g) was placed in a polyethylene bag of 30 × 20 cm with mesh openings of 1.0 × 1.0 mm.

The bag method was consisted in close a sample of vegetal tissue with know weight and nutrient content inside of a porous bag that allows the exchanges between the soil and the vegetal tissue. This method was used to determinate the rate of decomposition and nutrient release.

Fifteen samples were placed in the field at a depth of 2 cm from the litter in a completely random design with an area of 0.5 ha. Three bags per species were collected after 8, 15, 23, 84 and 113 d of being placed in the site. The material collected was dried in an oven at 75ºC for approximately 72 h until reaching a constant weight. After being dried, the samples were weighed in a precision balance.

Mass loss

The decomposition of the material was evaluated through dry weigh loss per each degradation time. The residual dry weight percentage (%*RDW*) was calculated considering the dry weight coefficient in the oven of the residual material per period (*RMP*), over the dry weight in the oven of the initial material (*DWI*), as follows:

$$\% RDW = 1 - (RMP/DWI) \times 100 \quad (1)$$

With the RDW value the decomposition rate of each vegetal material was determined. According to Oelbermann *et al.* (2004), the relative decomposition rate or transfer rate to the soil was calculated as follows:

$$Y_f = Y_0 e^{-kt} \quad (2)$$

Where, Y_f is the residual dry weight percentage; Y_0 is the initial dry weight percentage; k is the relative decomposition rate or decomposition speed of vegetal material; and t is the time (days). To evaluate the release or nutrient transfer, a single exponential model was implemented (Oelbermann *et al.*, 2004b; Farfán 2009), as follows:

$$W_f = W_0 e^{-kt} \quad (3)$$

Where, W_f is the remaining amount of each nutrient; W_0 is the mineral amount of each nutrient; k is the nutrient release constant; and t is the decomposition litter time (days).

Nutrient content measurements

To measure nutrient content, the following methods were used: the organic nitrogen (N) by the Kjeldahl digestion method, based on wet oxidation of organic matter using H_2SO_4 and a digestion catalysis (Horneck and Miller, 1998); the phosphorous (P) by the molybdovanadate colorimetry method using a spectrophotometer; and the potassium (K), calcium (Ca) and magnesium (Mg) by the method of Walsh with atomic absorption spectrophotometry (Unigarro *et al.*, 2009).

Statistical analysis

Litter quality was evaluated through the comparison between residual dry weight percentage and the nitrogen, phosphorous, potassium, calcium and magnesium content measured in percentage. The data obtained were compared and assessed between species using an analysis of variance (ANAVA). A Tukey test was carried out to compare the differences between the species when the F values of the ANAVA showed significant differences ($P \leq 0.05$).

Economic analysis

Nutrient input to the soil from different treatments or species used as shade in cacao plantations was assessed in economic terms, considering as a base the equivalent prices of conventional fertilizers in the market according to the availability as commercial formulations or as simple elements.

Results and discussion

Quality of the materials

Regarding the nitrogen levels in plant tissue to be decomposed, *C. odorata* contributed with the lowest levels (8.2 g kg^{-1}) and *G. sepium* with the highest levels (16.2 g kg^{-1}). Regarding phosphorous, due to the low levels found, this element could have been immobilized as the levels of all the species evaluated showing values beneath 2.5 g kg^{-1}. The highest levels of potassium were found in *G. sepium* and in *G. arborea* (Tab. 1). According to the calcium and magnesium levels found, the contribution per species in ascending order were *G. sepium* < *G. arboreum* < *T. cacao* < *C. odorata*, and *C. odorata* < *G. sepium* < *G. arboreum* < *T. cacao*, respectively (Tab. 1). Taking into account the levels established by Palm (1995), all the species evaluated showed a concentration below the critical N and P levels, i.e. 20 to 25 g kg^{-1} and less of 2.5 g kg^{-1}, respectively. According to the same author, this event could have caused an immobilization of these elements.

TABLE 1. Chemical characteristics of the species used in the decomposition experiment.

Treatment	Nutrient (g kg^{-1})				
	N	P	K	Ca	Mg
T. cacao	9.16	0.92	5.8	8.4	2.2
G. sepium	16.2	1.16	8.44	4.2	0.92
G. arboretum	11.96	1.2	6.72	7.8	1.36
C. odorata	8.2	0.8	3.4	11.88	0.88

Decomposition patterns

The residual weight (%) varied significantly in time and within the evaluated species ($P \leq 0.05$) (Tab. 2). Eight days after initiating the litter decomposition process, *G. sepium* showed the highest residual weight loss (31.39%) followed by *T. cacao* (17.73%) with highly significant differences between the species evaluated (P=0.0007) (Tab. 2; Fig. 1). The species *G. sepium* maintained the weight loss behavior after 15, 23, 84 and 113 d, reaching 74.80% in weight loss (Fig. 1). Although in the first samples (8 d) *G. arborea* did not show the highest weight loss values, at day 15, 23, 84 and 113 the weight loss reached considerable values, showing the highest weight loss values in days 84 and 113 (Fig. 1), with significant differences compared with the other species evaluated (P=0.0004 and $P \leq 0.0001$, respectively) (Tab. 2). Regarding the species with the lowest weight loss,

TABLE 2. Anova of the residual dry weight percentage (%RDW) for *T. cacao, C. odorata, G. arboea* and *G. sepium* at days 8, 15, 23, 84 and 113 in the municipality of Rionegro, department of Santander during 2010- 2011.

		8 d		15 d		23 d		84 d		113 d	
S.V	**D.F**	**M.S**	***P*-value**	**M.S**	***P*-value***	**M.S**	***P*-value**	**M.S**	***P*-value**	**M.S**	***P*-value**
Model	3	232.20	0.0007	275.39	0.0151	416.45	0.0002	724.28	0.0004	1627.44	<0.0001
Treatment	3	232.21	0.0007	275.39	0.0151	416.46	0.0002	724.28	0.0004	1627.44	<0.0001
Error	8	13.24		42.00		16.48		35.35		1627.44	
Total	11										

Significant differences: $P \leq 0.05$.

C. odorata and *T. cacao* showed the lowest values during the assessment period (Fig. 1). In these species, the highest weight loss was found between day 8 and 23, reaching values of 31.28% in *C. odorata* and 35.23% in *T. cacao*, showing maximum values in day 113 (41.57% and 43.88%, respectively) (Fig. 1).

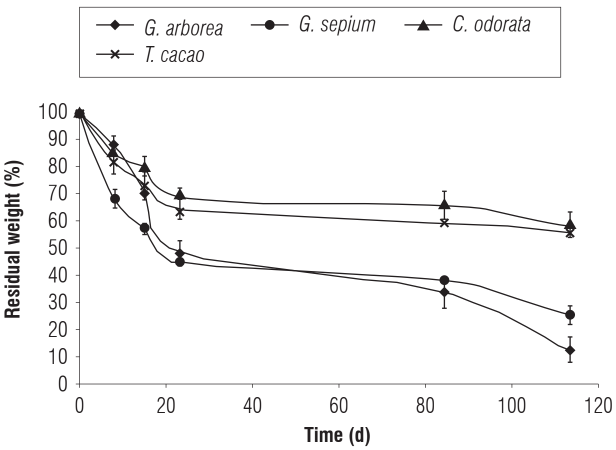

FIGURE 1. Residual biomass weight of *T. cacao, C. odorata, G. arborea* and *G. sepium* during the decomposition process. The values shown are an average of three samples ±SD.

Nutrient release percentage

Nitrogen, phosphorous, potassium, calcium and magnesium release from the aerial biomass of the different species evaluated in this study did not show significant differences. However, the highest release was found in *G. sepium*, followed by *G. arborea* (Fig. 2a-2e). Due to the fact that nutrients input are measured in terms of N and P mineralization (Mafongoya *et al*., 1997), in the AFS evaluated in this study *G. sepium* is considered a high quality source of nutrients as it has the highest content of these elements in its initial plant material content, and a higher nutrient release in the decomposing process (Fig. 2a and 2b). The leaves of *G. sepium* have a high N content and a low amount of lignin and polyphenols, so these can therefore be decomposed much faster (Mafongoya *et al*., 1997).

According to Munguía (2003) similar tendencies were found in the Verde Vigor farm, located in Pérez Zeledón canton, Costa Rica, working with litter from *Erythrina poeppigiana* (Walp.) O. F. Cook, *Eucalyptus deglupta* Blume and *Coffea arabica* L. In this study, *E. poeppigiana* showed to be the shade species that had the fastest N release, although it differs in the percentage and time required (65% in 24 d). Moreover, *E. deglupta* showed the slowest release rate, i.e. it did not release this element on its own but only when combined with *C. arabica* (2% in 24 d). Otherwise, Montenegro (2005) found that of the shade species evaluated in a coffee ASF in Turrialba (Costa Rica) the legume species were the ones that generated the highest nutrient release, concurring with the results found in this study. Likewise, both studies found that *G. sepium* showed the best behavior in relation to nutrient release. Moreover, regarding the low nutrient release showed by *T. cacao* and *C. odorata*, this can be due to various factors. Normally, this low nutrient release is related with big quantities of reactive polyphenols or structural lignin in the tissues of species associated to insoluble proanthocyanidins (Mafongoya *et al*., 1997).

The species evaluated showed a quick N, P and K release off in the first lixiviation phase during the decomposition process (Fig. 2a-2c). Anderson and Ingram (1993) mentioned that during the plant tissue decomposition process the release and mineralization of N and other elements frequently show a very fast initial phase. In this phase, the microorganisms that comprise the soil´s biomass degrade the litter, and secondary products as cellulose and hemicellulose, constituents of the cellular walls, are obtained. At the same time this new biomass and its metabolic products become substrates for the second phase. This second phase is characterized by being slower due to the increase of recalcitrant fractions and is mainly regulated by the lignin content in decomposing tissue.

Additionally, potassium release was found to occur in all species evaluated between days 8 and 23 with release rate values (k) between -0.051 and -0.116 depending on the species (Fig. 2c, Tab. 3). This is attributed to the high K mobility and its fast lixiviation on the initial phases of the litter decomposition process (Zaharah and Bah, 1999). However, these results are contrary to the ones found by Munguía (2003) regarding K release in litter of *E. poeppigiana*, where in only 24 d 39% of this nutrient was released, and after 213 d 99% was released with a rate of -1.55 per day, obtaining a higher value compared to other treatments and nutrients. The results in this same study also showed that *E. deglupta* litter released in 24 d 17% of the K, and after 213 d 88% had been released, showing a k of -0.49 per day, i.e. the lowest value found.

The calcium showed a fast release in the species *C. odorata* during the period from day 8 to 23 and decreased after 84 and 113 d with a total release of 9.84%. However, the species *G. arborea* had the highest release constant during all the evaluation period for a total of 10.26% (Fig. 2d, Tab. 3). Munguía (2003) reports for *E. poeppigiana* a 67% calcium release in 213 d with a rate (k) of -0.5 d^{-1}, meanwhile a treatment with *E. deglupta* + *C. arabica* + *E. poeppigiana* and

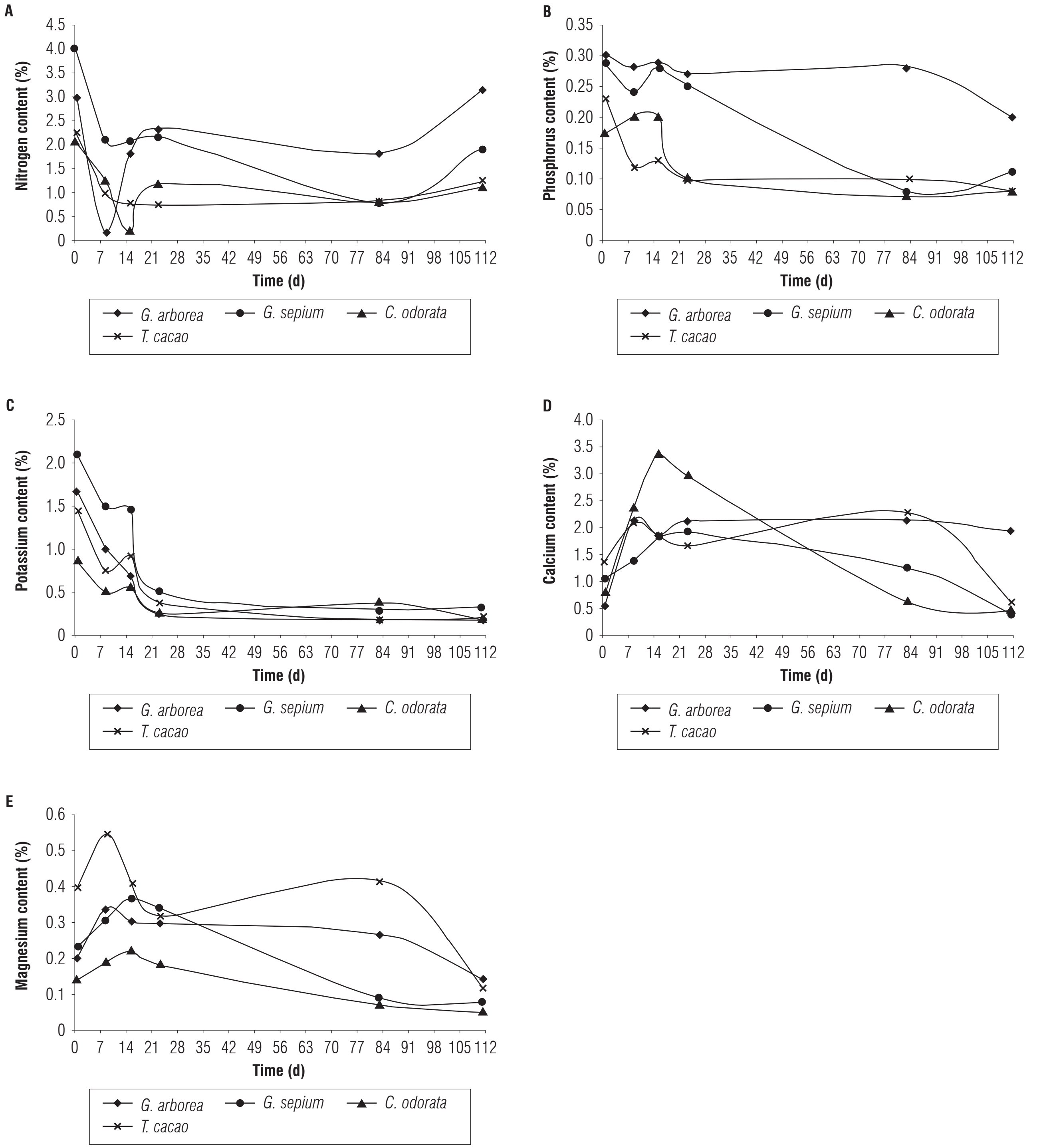

FIGURE 2. Nitrogen (A), phosphorous (B), potassium (C), calcium (D) and magnesium (E) content in litter from *G. arborea*, *G. sepium*, *C. odorata* and *T. cacao* during the decomposition process.

another one with a mixture of *E. deglupta* + *E. poeppigiana* begin calcium release from day 100 with a release rate (k) of -0.13 and -0.14 per day, respectively (Tab. 3). This slow release is due to the type of link that this element generates with other elements in the cellular wall.

Regarding magnesium, the highest release was shown by *T. cacao* from day 8 to 113 with a total of 1.82% followed by *G. arborea* with a release of 1.35%, being the species *C. odorata* and *G. sepium* the ones with the lowest release percentages in the evaluation period, i.e. between 0.71%

TABLE 3. Nutrient release rates per sampling period of different leaf materials according to the species evaluated under field conditions.

Nutrient release rate / Species	Sampling period (d)				
	8	15	23	84	113
Nitrogen release rate (k_N d^{-1})					
G. arborea	- 0.076	- 0.055	- 0.041	- 0.019	- 0.018
G. sepium	- 0.132	- 0.083	- 0.062	- 0.031	- 0.019
C. odorata	- 0.082	- 0.051	- 0.058	- 0.016	- 0.027
T. cacao	- 0.130	- 0.093	- 0.067	- 0.018	- 0.011
Phosphorous release rate (k_P d^{-1})					
G. arborea	- 0.024	- 0.025	- 0.036	- 0.014	- 0.022
G. sepium	- 0.071	- 0.040	- 0.041	- 0.027	- 0.021
C. odorata	- 0.040	- 0.015	- 0.046	- 0.017	- 0.013
T. cacao	- 0.106	- 0.058	- 0.055	- 0.016	- 0.014
Potassium release rate (k_k d^{-1})					
G. arborea	- 0.080	- 0.082	- 0.116	- 0.039	- 0.038
G. sepium	- 0.091	- 0.061	- 0.098	- 0.034	- 0.029
C. odorata	- 0.072	- 0.051	- 0.052	- 0.020	- 0.018
T. cacao	- 0.107	- 0.051	- 0.078	- 0.031	- 0.022
Calcium release rate (k_{Ca} d^{-1})					
G. arborea	- 0.002	- 0.026	- 0.028	- 0.012	- 0.029
G. sepium	- 0.011	- 0.000	- 0.008	- 0.009	- 0.021
C. odorata	- 0.003	- 0.029	- 0.074	- 0.024	- 0.021
T. cacao	- 0.078	- 0.028	- 0.029	- 0.005	- 0.016
Magnesium release rate (k_{Mg} d^{-1})					
G. arborea	- 0.053	- 0.031	- 0.037	- 0.016	- 0.026
G. sepium	- 0.010	- 0.005	- 0.018	- 0.023	- 0.022
C. odorata	- 0.039	- 0.028	- 0.036	- 0.019	- 0.018
T. cacao	- 0.064	- 0.039	- 0.042	- 0.009	- 0.019

and 1.19%, respectively (Fig. 2e). These results do not coincide with the outcomes reported by Munguía (2003) as the magnesium release values found for *E. poeppigiana* were 7% in 24 d and 97% in 213 d, showing a release rate (k) of -1.02 per day. Meanwhile, for *E. deglupta* in only 24 d there was no magnesium release and after 213 d there was a 19% release rate (k) of -0.013 per day.

Economic analysis

According to the nutrient input of each species evaluated and with the traditional fertilization levels used in the municipality of Rionegro, department of Santander, the study showed that to produce 1,000 kg ha^{-1} of dry grain of cacao, the species *G. arborea* contributes with the highest nitrogen and phosphorous quantities in the AFS studied with 9.37% and 1.32%, followed by *G. sepium* with 8.99% and 0.96%, respectively (Tab. 4). Altogether, the litter produced by the four species that comprise the system contributed with 27.44% of the nitrogen and 3.46% of the phosphorous that is usually employed in an AFS with cacao. Regarding potassium input, the litter produced by *G. sepium* contributed with 4.97% of the K that was relatively superior to the other species assessed and that ranged from 1.85 to 2.43% (Tab. 4). In total, the litter generated by the four species evaluated contributed with 10.65% of the K that is normally required to fertilize the AFS (Tab. 4).

These contributions from the litter produced by the species that comprise the AFS, allow the optimization of the producer´s finances, as currently the main fertilization source for these systems are synthesis fertilizers known as *Triple-15* that provide N, P and K to the soil with a market price of 75,000 COP (ca. 25 USD) for 50 kg, plus application wage costs of up to 25,000 COP (ca. 8-9 USD). According to the results obtained in this research, with the contribution of the litter produced by the species assessed that constitute

TABLE 4. The nutrient release percentage of *T. cacao, C. odorata, G. arborea* and *G. sepium* in the municipality of Rionegro, department of Santander during 2010- 2011.

Traditional fertilization	*T. cacao* nutrient input	*C. odorata* nutrient input	*G. arborea* n utrient input	*G. sepium* nutrient input	Total input of the four species considered in the AFS
(kg/harvest)		(% at day 113)			
Nitrogen 31-40	4.56	4.52	9.37	8.99	27.44
Phosphorous 5-6	0.53	0.65	1.32	0.96	3.46
Potassium 54-86	2.43	1.85	2.3	4.07	10.65
Calcium 5-8	8.56	9.84	10.26	6.8	35.46
Magnesium 5-7	1.82	0.71	1.35	1.19	5.07

the AFS, the fertilization costs can be reduced 10% in average as well as the use of synthesis fertilizers and the amount of labor during fertilization processes.

The amount of nutrients extracted in kilograms to produce and harvest 1000 kg of dry cacao per ha during a year in the municipality of Rionegro are: nitrogen 31-40, phosphorous 5-6, potassium 54-86, calcium 5-8 and magnesium 5-7. Considering that part of the fertilizers are lost due to solubility problems, washing, microorganism absorption and that most of the nutrient content extracted by the plant are not part of the cacao almonds, the application of these element should be higher (Mejía, 2000). In this sense, the litter contributes greatly to the cycling system. This demonstrates the sustainability of the productive potential in agroforestry systems with cacao that is directly linked to the conservation of soil fertility, and is being directly influenced by the nutritional quantity and quality of the plant residues that are annually returned to the soil through litter.

Conclusions

The species *G. arborea* showed the highest plant material decomposition with an average indicator in residual weight of 87.55% after 113 d, meanwhile *C. odorata* (timber specie) showed the lowest residual weight 40.01%.

G. arborea showed the highest nutrient release followed by *G. sepium*, and the lowest was shown by *T. cacao* and *C. odorata*.

Calcium is the nutrient that shows the highest release percentage followed by nitrogen with a better release behavior compared to potassium and magnesium, meanwhile it also showed to be the nutrient with the slowest release.

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