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Artículo de investigación

Agroforestry systems of *Theobroma cacao* L. affects soil and leaf litter quality

Sistemas agroforestales de *Theobroma cacao* L. afectan la calidad del suelo y la hojarasca

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Abstract

The objective of this study was to determine the effect of Agroforestry systems (AFS) and non-AFS of *Theobroma cacao* L. on soil and leaf litter quality, during rainy (RS) and dry (DS) seasons in a tropical zone. The treatments were *T. cacao* crop (CC), Yopo forestry (*Anadenanthera peregrina* L.) Speg. (YF), Acacia forestry (*Acacia mangium* Willd.) (AF), Agroforestry system of *T. cacao* + Yopo forestry (CYF), Agroforestry system of *T. cacao* + Acacia forestry (CAF), arranged in random design in the field. Leaf litter production was highest in CC (0.79 and 0.73 ton.ha^{-1}) during RS and DS, respectively. CC and AFS improved soil fertility, less Mg in CC; AFS leaf litter quality, CAF in DS and CYF in both seasons, less B and S in DS. AFS can be a solution in tropical zones to solve the problems of low soil fertility.

Keywords: biotechnology, soil fertility, soil organic matter, nutrients, tropical soils.

Resumen

El objetivo de este estudio fue determinar el efecto de los sistemas agroforestales (AFS) y no AFS de *Theobroma cacao* L. en la calidad del suelo y la hojarasca, durante las épocas de lluvia (RS) y sequía (DS) en zona tropical. Los tratamientos fueron cultivo de *Theobroma cacao* (CC), forestal de Yopo (*Anadenanthera peregrina* L.) Speg. (YF), forestal de Acacia (*Acacia mangium* Willd.) (AF), sistema agroforestal de *T. cacao* + forestal de Yopo (CYF), sistema agroforestal de *T. cacao* + forestal de Acacia (CAF), en un diseño completamente al azar en el campo. La producción de hojarasca fue más alta en CC (0.79 y 0.73 ton.ha^{-1}) en RS y DS, respectivamente. CC y AFS mejoró la fertilidad del suelo, menos Mg en CC; AFS la calidad de la hojarasca, CAF en DS y CYF en ambas épocas, menos el B y S en DS. Los AFS pueden ser una solución en zonas tropicales para solventar los problemas de baja fertilidad de los suelos.

Palabras clave: biotecnología, fertilidad del suelo, materia orgánica del suelo, nutrientes, suelos tropicales.

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INTRODUCTION

The cocoa *Theobroma cacao* L. is one of the most important crop systems in tropical areas of South and Central América. The cultivation of *T. cacao*, as an option to traditional crop land in tropical areas is established under an agroforestry system (AFS), which is associated with shady species (Somarriba y Beer, 2011). This system simulates a natural forest system where the nutrients loss is lower compared to a non-AFS (only forestry and/or only crop), since the nutrients recycling in agroforestry systems works as a complex network of flows (Hartemink, 2005; Tscharntke *et al*., 2011). Furthermore, AFS is the link where soil organic matter (SOM) and nutrients are transferred from the tree biomass back to the soil as above ground residues (Smiley y Kroschel, 2010). AFS of *T. cacao* may have different effects on litter production, soil and leaf litter nutrients than non-AFS (Blaser *et al*., 2017).

It is widely known that leaf litter decomposition from AFS, by microbial action, can to contributes soil and leaf litter nutrients (Isaac *et al*., 2007), and depends on climatic factors (time of year, luminosity, precipitation, humidity, evapotranspiration), edaphic factors and mixed species type are the most important factors (Traore *et al*., 2004; Sileshi *et al*., 2014; Sida *et al*., 2017). This can also be affected by nutrient translocation, litter volume, transfer of nutrients that occurs between the plant and the soil and others such as composition leaf litter chemistry, the C/N ratio (Kimaro *et al*., 2007).

Agroforestry systems (AFS) not only help improve the fertility of tropical soils, they also contribute to the soil C sequestration, and mitigate the negative impacts caused by global climate change (Mbow *et al*., 2014), as they also reduce the chemical fertilization that contributes to the high N_2O emissions to the environment (Silva-Parra *et al*., 2018). For a cocoa crop with 48 months older is required 438 kg.N.ha^{-1}; 48 kg.ha^{-1} P; 633 kg.ha^{-1} K; 373 kg.ha^{-1} Ca and 129 kg.ha^{-1} Mg (Leiva, 2012).

The reduction of nutrient and organic matter content in non-AFS of *T. cacao* crop is a serious problem in many tropical zone (Rojas *et al*., 2017). In this sense, AFS of *T. cacao* provides a sustainable opportunity to restablish infertile soils at tropical zones, improve the recycling of nutrients and decrease the dependence on chemical fertilizers, depending of shade trees (Blaser *et al*., 2017).

Litterfall and litter decomposition of agroforestry systems (AFS) and subsequent nutrient release represent major biological pathways for soil nutrients transfer, and play an important role in regulating nutrient cycling, and in maintaining soil fertility in tropical agro-ecosystems (Luedeling *et al*., 2016).

In this study, we focus on the role that AFS of *T. cacao* and non-AFS may have on soil and leaf litter quality under different seasons in tropical zone of Colombia. We hypothesise that higher soil and leaf litter nutrients will be altered closer to AFS that to non-AFS, likely due to an-input of organic matter from litter production to the soil. We also hypothesise that litter production, soil and leaf litter nutrients will be different between seasons, because of the differences in ecological conditions for season in study zone.

MATERIAL AND METHODS

Study sites

The study site is located between the coordinate 4°04'47'' N and 73°35'17''W. The experiment was conducted specifically in Barcelona farm, Unillanos University, Piedemont of Villavicencio city, Meta state, Colombia East (figure 1).

A tropical climate characterizes this region with two distinct seasons, that are, rainy season (april-november), and dry season (december-march). The annually average rainfall is 3856 mm. The highest average rainfall (526 mm) occurs in the month of may and the lowest average rainfall (51 mm) occurs in the month of january, data obtained from the meteorological station of the Llanos University.

The mean annual temperature is 25.5°C with a range of 21–28.5°C (Instituto de Hidrología, Meteorología y Estudios Ambientales, 2019). Villavicencio is low (200 masl), and located on a Piedemonte plain which is predominated by sedimentary rock predominate that is strongly folded and failed from the rise of the Eastern Cordillera, the soil is a leached sandy soil with sand loam texture, and is similar to a Typic Hapludox (Soil Survey Staff, 2006).

Agroforestry system (AFS) of *T. cacao* is located in the experimental farm of Barcelona of the University of the Llanos, Villavicencio, Colombia, which is considered equivalent to three forestry species: Cocoa (*Theobroma cacao)* + yopo (*Anadenanthera peregrina*) + Acacia (*Acacia mangium*), four years old. In this AFS, the following arrangements were identified as followed: Non-AFS of *T. cacao* crop (CC), Yopo forestry *A. peregrina* (YF), Acacia forestry *A. mangium* (AF), AFS of *T. cacao* associated with Yopo *A. peregrina* (CYF) and AFS of *T. cacao* associated with Acacia *A. mangium* (CAF) under rainy (RS) and dry season (DS) (figure 2). The AFS stand was highly dominated by cocoa trees. The standard cocoa clone used was IMC 67 coming from Arauca, established in April 2012 as clonal garden. The current inventory is from 781 of cocoa trees and 395 shade trees (232 yopo and 163 acacia forestry trees). From the data generated in the grid, it was calculated that 13.8 % of the total trees have been lost, represented by 14.1 % of cocoa crop, 9.7 % of Yopo forestry and 17.7% of Acacia forestry (figure 2; table 1).

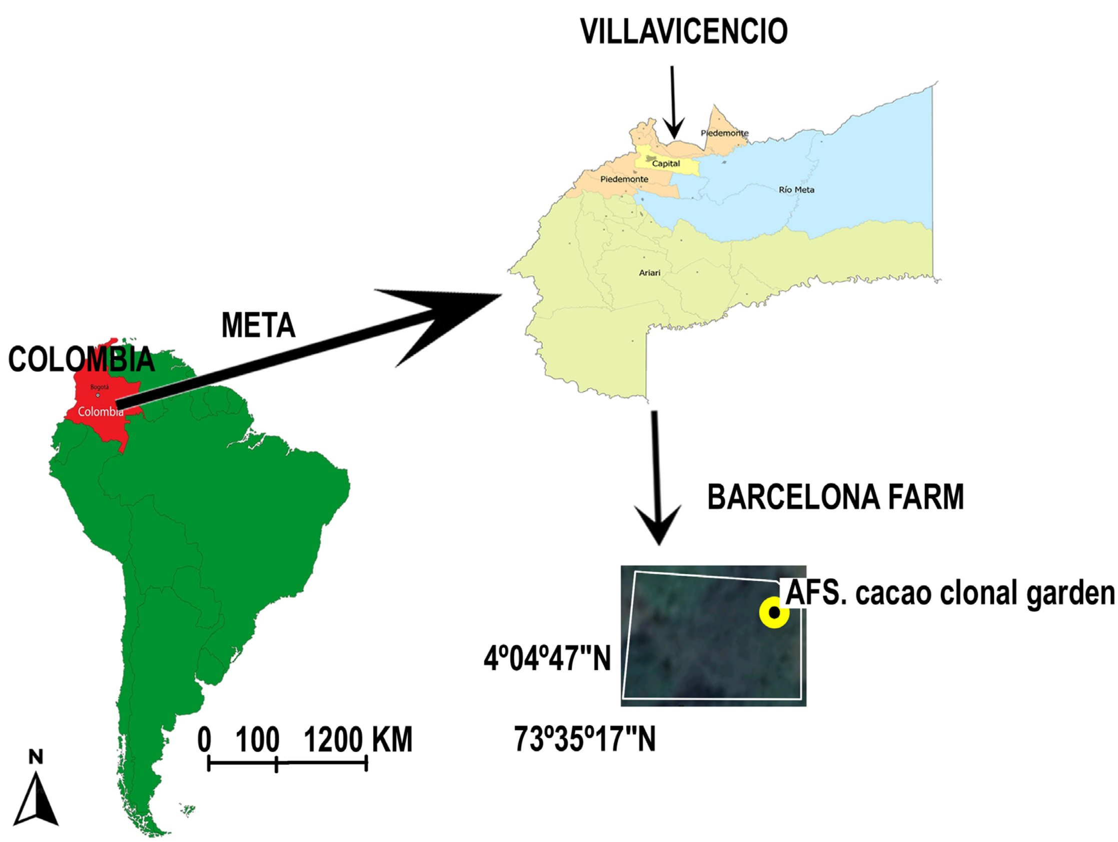

Figure 1. Close photo location of AFS *T. cacao* clonal garden at Barcelona farm, Unillanos University, Villavicencio city, Meta state, Colombia.

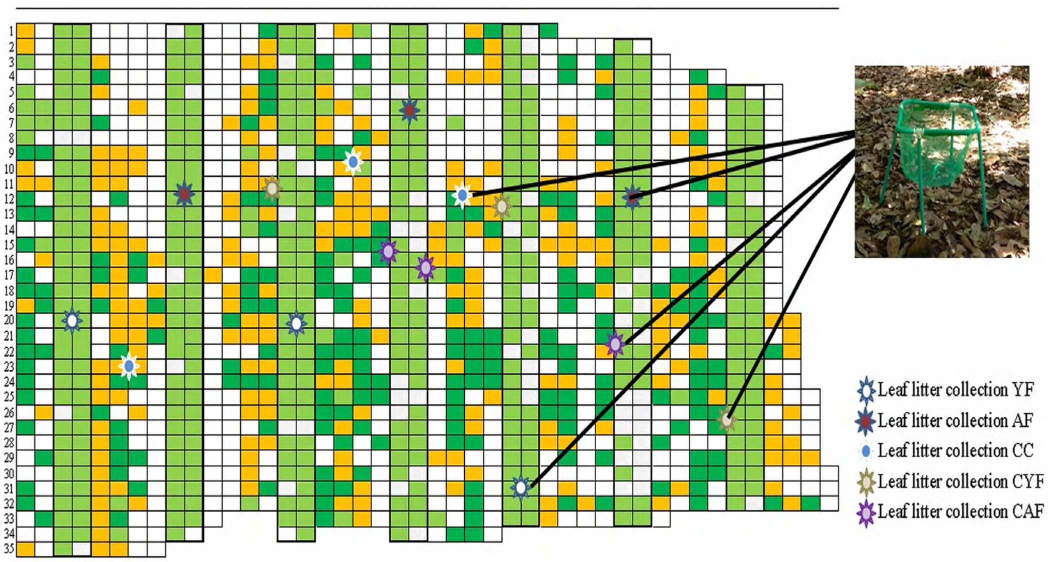

Figure 2. Selected of *T. cacao*, yopo forestry and acacia forestry trees in the clonal garden of the AFS *T. cacao* at Barcelona farm. The distribution of cocoa trees is each 3 x 4 m within the AFS arrangement which is formed by contiguous double rows of yopo *A. peregrina* and acacia *A. mangium* trees each 12 m, between double rows are yopo and *A. mangium* trees at planting distances of 3 m x 6 marranged in north - south orientation.

Table 1. Current number of trees found in the clonal garden of the cocoa agroforestry system in the Experimental Farm of Barcelona, calculated from the grid found in the field at 2017

Tree Species	Initial trees 2012	Current 2018	Trees survival %	Trees lost[1] %
Cocoa trees	909	781	85.9	14.1
Yopo forestry	257	232	90.3	9.7
Acacia forestry	198	163	82.3	17.7
Shade trees total	455	395	86.8	13.2
Total	1364	1176	86.2	13.8

[1] Mainly due to pest and disease problems of forest at tropical zones.

The design was in random design in a factorial arrangement (5 x 2), corresponding to 5 treatments (3 non-AFS and 2 AFS), and 2 evaluation seasons (RS and DS), with three repetitions, for a total of 30 treatments, 15 treatments for each evaluated period. The AFS is located on site number 9 of the Barcelona Farm, with a total area of 9690 m^2. The area of field selected was seven double rows of yopo *A. peregrina* and acacia *A. mangium* including cocoa trees covering by each treatment an area of 12 mlonge x 10 m, 120 m^2, accounting 1800 m^2 of total area.

The treatments sites used in this study with featured ecological conditions were deliberately selected through the AFS all, to serve as replicates three trees by each treatment (site location with respect to rows). The purpose of each random replication was to control the ecological variation that typically occurs in similar forest types. This sampling coverage was achieved mainly by random allocation of treatments in the study AFS, due to that *A. mangium* and *A. peregrina* trees were observed higher development that trees of *T. cacao* crop. However, *A. mangium* opens its cups from the center of the double furrow and inclines its main and secondary branches towards the cocoa system, leaving a small space on the cocoa, because effect of annual wind (Instituto de Hidrología, Meteorología y Estudios Ambientales, 2019).

Data collection

In clonal garden of AFS of *T. cacao* the samples were carried out during rainy season of September to November 2017 and the dry season of december to march 2018, and the prescribed samples were conducted over three consecutive months (under similar weather conditions) at the end of february 2018. In each site at a depth of 20 cm, we chose at 3 disturbed sampling plots each 50 cm, adjacent to AFS and non-AFS on the rows, in each site (treatments), there was a total of 45 sampling plots at RS and 45 sampling plots at DS. Production of leaf litter was measured according to Anderson e Ingram (1989) where litter samples were collected from the surface of the soil using a basket including a square of PVC that was of 1.0 x 1.0 mat each sampling point to form a composite sample (figure 2). The litter samples were cleaned and then dried in an oven at 65 ºC for 48 h. The samples were sieved in a 2 mm mesh. The leaf litter samples were ground and processed using acid digestion (Allen, 1974). The digested sample extracts were processed according to ICA (1989) to determine N by Kjedahl method and P concentrations using a UV-Visible recording spectrophotometer and Ca, Mg, K concentrations in sample extracts were determined by flame photometry (Allen, 1974), in the soil laboratory at Llanos University. Quality control was assured by using duplicates. Reagent blank and several certified reference materials were used to check the accuracy and precision of the analytical data. Analysis of certified reference materials (High-Purity Standards) indicated that the recovery of Cu, Fe, Mn, Zn, and B, for leaf litter determination was 100 ± 20 %. Chemicals were analytical grade (MERCK). For the determination of soil chemical properties, during the same sampling, the soil samples were collected at 10-20 cm depth. Soil organic matter was determined by the Walkley y Black method through chromic acid wet digestion, available soil P for Bray II method with NaF 0.03 N, exchangeable Al with KCl 1N, and soil bases (Ca, Mg, K) were extracted with Ammonium acetate 1N at neutral pH (ICA, 1989).

Data analysis

The data obtained in the field were analyzed statistically with the Infostat software (version 2011; Di Rienzo *et al.*, 2011) and a oneway analysis of variance to evaluate the significant differences among means of all tested parameters at 99 % level of confidence. Further statistical validity of the differences among treatment means were estimated using the Tukey's test at 95 % level of confidence.

RESULTS

Leaf litter production

When comparing AFS and non-AFS, the highest leaf litter production was found in *T. cacao* crop CC (0.79 and 0.73 $ton.ha^{-1}$) and the lowest (0.56 and 0.31 $ton.ha^{-1}$) in *A. mangium* (AF), during RS and DS, respectively ($p \leq 0.05$). The leaf litter from the AFS in CYF and CAF, as YF, accounted higher amounts than in AF and lower than in CC ($p \leq 0.05$), however, there were not different ($p \geq 0.05$; table 2). Leaf litter under RS and DS showed similar amounts ($p \geq 0.05$).

Soil nutrients

The concentrations of soil nutrients showed significant differences between AFS and non-AFS in each season ($p \leq 0.05$). The content of SOM of the AFS of CAF, and non-AFS of CC and YF was higher than in the other treatments in both seasons, similarly, the content of available soil P in AFS of CYF and CAF, available soil P rate ranged from 4.83 to

Table 2. Significant test of leaf litter production during Rainy and Dry seasons (three month each season), in AFS an non-AFS of *T. cacao*, Barcelona farm

Seasons	Non-AFS			AFS		Mean[2]
	CC	YF	AF	CYF	CAF	
	Leaf litter production ton.ha^{-1}					
RS	0.79**	0.67*	0.56ns	0.72*	0.68*	0.68*
DS	0.73**	0.55*	0.31ns	0.60*	0.54*	0.54*
Total	1.52**	1.22*	0.87ns	1.32*	1.22*	
Mean[1]	0.76**	0.61*	0.43ns	0.66*	0.61*	

[2] Values in the rows (seasons) and columns (treatments) with the same significance (** highly significant; * significant; ns non-significance) are not different, Tukey´s test P <0.05. RS = rainy season; DS = dry season.

28.60 mg.kg^{-1} in YF and CYF during DS and RS, respectively, however, these contents are considered as lower levels in tropical soils, according to Igac (2000). The highest levels of soil bases Ca, Mg and K, were observed in the area with AFS of CYF and YF, less K for YF, that was of CC and CAF, in RS and DS, respectively. However, the lowest levels of soil Mg, and K was of AF in RS and DS seasons, respectively, associated with higher exchangeable soil Al. The highest level of exchangeable Al was found in CC during DS (2.47 cmolc.kg^{-1}) associated with a pH of 4.53. Contrary, in CYF during RS and DS were lower (table 3). Taking into account the levels established by Igac (2000), all the AFS and non-AFS evaluated showed a concentration below the critical for soil bases levels. Ca was lower in the dry season and Mg in the rainy season. In general terms, CC had a good behavior of soil macronutrients, less Mg, and soil micronutrients, with little variation between seasons. On the other hand, AF did not respond positively to P, Mg, K and Zn in both seasons.

The lowest levels of soil micronutrients were observed of YF in DS. AFS of CYF and CAF maintained the soil micronutrients with highest levels, less Cu, in both seasons. These results show that the soil from areas subjected to AFS and non-AF indicated similar soil micronutrients between the evaluated seasons, less Fe, B and S that was lower in DS (table 3).

Leaf litter nutrients

The contents of macro and micronutrients in the leaf litter of the AFS and non-AFS showed differences, as between seasons ($p \leq 0.05$), less for Mg, Cu, Fe, Mn, and B ($p \geq 0.05$).

The contents of nutrients were found to decrease gradually at the end of the experiment from RS for DS, for CC less Mn and Zn, YF, and AF less Cu (table 4). AFS of CYF maintained a good level of leaf litter nutrients in both seasons. N was higher in CYF, and differed markedly from CAF, non-AFS showed intermediate N with no difference between them. N varied between 1.49 % in CAF during RS and 6.74 % in CYF during DS. The content of P in the leaf litter of AF was lower and differed significantly from the other treatments that were the same indicating higher values. P varied between 0.05 % in AF during both seasons, and 0.11 % in CYF and YF in RS. The content of Ca and K in the leaf litter of the AFS of CAF were higher than in the other treatments significantly and highly significant, respectively, however, for Mg, were higher in the leaf litter of CC and CYF than CAF and, in turn, higher than in YF and AF, which were lower in RS. There was no difference between seasons for N, P, Ca and K. Hence, CYF and CC were leaf litter nutritionally better than CAF in both seasons (table 4).

Table 3. Significant test of soil nutrients of AFS and non-AFS (Rainy and dry season)

Seasons	Non-AFS			AFS		Mean[3]
	CC	YF	AF	CYF	CAF	
			Soil organic matter (SOM) %			
RS	2.83**	2.90**	2.67ns	2.57ns	3.10**	2.81**
DS	2.93**	2.93**	2.90**	2.73*	3.03**	2.90**
Mean	2.88**	2,91**	2.78*	2.65*	3.06**	
			Available soil P mg.kg^{-1}			
RS	15.17*	8.83ns	9.53ns	28.60**	22.20**	16.86*
DS	12.83*	4.83ns	6.30ns	22.10**	20.87**	13.38*
Mean	14.00*	6.83ns	7.91ns	25.35**	21.53**	
			Exchangeable Al cmolc.kg^{-1}			
RS	2.23*	2.17*	2.40**	1.73ns	2.43**	2.19*
DS	2.47**	2.08*	2.33**	1.82ns	2.03*	2.14*
Mean	2.35**	2.12*	2.36**	1,77ns	2.23*	
			Soil bases cmolc.kg^{-1}			
			Ca			
RS	0.97*	0.98*	1.00**	1.28**	0.86ns	1.01**
DS	0.83ns	1.03**	0.83ns	1.17**	0.95**	0.96*
Mean	0.90*	1.00**	0.91*	1.22**	0.90*	
			Mg			
RS	0.08ns	0.15**	0.01ns	0.15**	0.04ns	0.09ns
DS	0.07ns	0.13**	0.07ns	0.17**	0.17**	0.12*
Mean	0.07ns	0.14**	0.04ns	0.16**	0.10*	
			K			
RS	0.25**	0.16ns	0.15ns	0.22**	0.18*	0.19*
DS	0.22**	0.18*	0.14ns	0.22**	0.26**	0.20*
Mean	0.23**	0.17ns	0.15ns	0.22**	0.22**	
			Soil micronutrients mg.kg^{-1}			
			Cu			
RS	1.25*	1.37*	1.80*	1.40*	1.17ns	1.39*
DS	1.35*	1.18ns	3.65**	1.10ns	1.33*	1.72*
Mean	1.30*	1.27ns	2.72**	1.25ns	1.25ns	
			Fe			
RS	240..83*	239.16*	289.37**	272.50**	288.95**	266.16**
DS	177.29*	123.94ns	183.75*	188.54*	220.83*	178.87*
Mean	209.06*	181.55*	236.56**	230.52**	254.89**	
			Mn			
RS	1.58*	1.47*	1.13*	1.25*	2.07**	1.5*
DS	1.08ns	1.35*	1.30*	1.38*	2.43**	1.5*
Mean	1.33*	1.41*	1.21*	1.31*	2.25**	
			Zn			
RS	2.65**	0.80ns	0.73ns	2.13*	1.75*	1.61*
DS	1.88**	0.98ns	0.93ns	2.07*	2.22*	1.61*
Mean	2.26**	0.89ns	0.83ns	2.10*	1.98*	
			B			
RS	0.82**	0.72*	0.64*	0.62*	0.89**	0,73*
DS	0.47ns	0.36ns	0.54*	0.63*	0.67*	0.53ns
Mean	0.64*	0.54*	0.59*	0.62*	0.78**	
			S			
RS	7.46*	7.46*	11.55**	4.85*	10.08**	8.28**
DS	5.45*	3.92ns	6.35*	3.18ns	6.21*	5.02*
Mean[1]	6.45*	5.69*	8.95*	4.01*	8.14**	

[3] Values in the rows (seasons) and columns (treatments) with the same significance (** highly significant; * significant; ns non-significance) are not different, Tukey´s test P <0.05. RS = rainy season; DS = dry season.

Table 4. Significant test of leaf litter nutrients of AFS and non-AFS (Rainy and dry seasons)

Seasons	Non-AFS			AFS		Mean[1]
	CC	YF	AF	CYF	CAF	
			N %			
RS	1.69*	2.20**	1.56*	2.23**	1.49ns	1.83*
DS	1.53ns	1.90*	1.68ns	6.74**	1.66ns	2.70*
Mean	1.61*	2.05*	1.62*	4.48**	1.57ns	
			P %			
RS	0.08*	0.11**	0.05ns	0.11**	0.06ns	0.082*
DS	0.07*	0,09*	0.05ns	0.09*	0.07*	0.074*
Mean	0.07*	0.10*	0.05ns	0.10*	0.065*	
			Litter leaf bases %			
			Ca			
RS	1.17**	1.00ns	0.95ns	0.96ns	1.11*	1.03ns
DS	1.00ns	0.84ns	0.93ns	1.00ns	1.11*	0.97ns
Mean	1.08ns	0.92ns	0.94ns	0.98ns	1.11*	
			Mg			
RS	0.24**	0.21*	0.18ns	0.25**	0.21*	0.21*
DS	0.36**	0.18ns	0.18ns	0.31**	0.24**	0.25**
Mean	0.30**	0.19ns	0.18ns	0.28**	0.22*	
			K			
RS	0.64ns	0.63ns	0.76*	0.70*	0.82**	0.71*
DS	0.60ns	0.62ns	0.91**	0.76*	0.94**	0.76*
Mean	0.62ns	0.62ns	0.83*	0.73*	0.88**	
			Leaf litter micronutrients $mg.kg^{-1}$			
			Cu			
RS	10.17*	13.33*	8.50ns	13.17*	9.67ns	10.95ns
DS	118.50**	126.33**	118.83**	120.67**	113.33**	119.53**
Mean	64.33*	69.83*	63.66*	66.92*	61.5*	
			Fe			
RS	132.83*	126.17ns	112.83ns	172.67**	117.33ns	132.36**
DS	9.83ns	12.17**	9.17ns	13.33**	8.83ns	10.66ns
Mean	71.33*	69.17*	61ns	93**	63.08*	
			Mn			
RS	198.33ns	200.00ns	236.67*	231.67*	313.33**	236*
DS	231.67*	173.33ns	213.33ns	226.67*	343.33**	237.66*
Mean	215ns	186.66ns	225*	229.17*	328.33**	
			Zn			
RS	59.83*	23.33ns	24.17ns	41.67*	74.17**	44.63*
DS	155.00**	24.00ns	26.33ns	103.33*	135.00*	88.73*
Mean	107.41**	23.66ns	25.21ns	72.5*	104.58**	
			B			
RS	38.09**	17.65ns	39.36**	37.70**	37.40**	34.04**
DS	33.87**	29.12*	28.77*	20.05ns	27.35*	27.83*
Mean	35.98**	23.36*	34.06**	28.87*	32.37**	
			S %			
RS	0.11**	0.11**	0.06ns	0.10**	0.11**	0.098*
DS	0.09ns	0.09Ns	0.13**	0.08ns	0.08ns	0.094*
Mean[1]	0.10**	0.10**	0.09*	0.09*	0.09*	

[1]Values in the rows (seasons) and columns (treatments) with the same significance (** highly significant; * significant; ns non-significance) are not different, Tukey´s test P <0.05. RS = rainy season; DS = dry season.

DISCUSSION

In CC, relatively larger leaf litter production was observed due to higher soil above ground residues that other AFS and non-AFS, as previously reported by Leyva (2012), who indicates that the contribution of leaf litter production from cacao tree between 1 to 4 years old is 0.145 $ton.ha^{-1}$; at 10 years old, 0.5 $ton.ha^{-1}$ and at 15 years old, 1.5 $ton.ha^{-1}$, which the maximum contribution is 2.0 $ton.ha^{-1}$. The amount of leaf litter in CC of 6 years old, was higher than those reported by Leiva. According to Salgado *et al.* (2009) cocoa crop in tropical zone account 3.41 $ton.ha^{-1}.yr^{-1}$ of leaf litter as above ground residues. However, the highest rate of leaf litter production in CC may be attributed primarily on the site productivity (Somarriba y Beer, 2011), but also by climatic factors as reported by Cleveland *et al.* (2011), leaf litter will not be supplied the same rates over the year depending of each season, as leading in AFS and non-AFS of this study, to a probable reductions in litter quantity of RS for DS.

However, the uniform litterfall amounts over the seasons measured in AFS and non-AFS, in both season, may be the result of a mixture of tropical forest types that may sustain 'constant' litterfall rates over the year (Oliveira-Filho *et al.*, 2015). This makes it difficult to assess the degree to which different climatic conditions and agroforestry practices influence leaf fall, and to anticipate their respective consequences on leaf litter production. However, AFS of *T. cacao* (involving forestry and cocoa crop species) also promote a significant leaf litter production, appropriate tree species selection based on soil above ground residues is a vital issue in agroforestry practice (Schalatter *et al.*, 2006). The conversion of non-AFS systems to AFS results in an increase of litter and consequently SOM. In general, the amount of leaf litter production to an ecosystem can vary with the species, edaphic and climatic conditions (Jose, 2009).

The variation in SOM of the studied AFS and non-AFS at both seasons was found highest in non AFS of CC, and YF, as also in AFS of CAF, which it was not closely related to leaf litter production, by if in CC, since although produced a greater number of leaf litter production that CAF. This would indicate the importance that *T. cacao* in tropical zones has in the contribution of SOM, alone and/or as agroforestry system (Andrade *et al.*, 2013). The highest rates of leaf litter production of *T. cacao* alone and/or as agroforestry system could be an indicator of higher soil fertility, due to higher increase of SOM, by photosynthetic carbon fixation from the atmosphere, and by transfering this carbon to the soil, via litter and root decay (Nair *et al.*, 2010), which N release from the leaf litter (Rojas *et al.*, 2017), is required for the growth and development of CC (Leiva, 2012). However, the low SOM and available soil P levels found in non-AFS and AFS, indicates the importance of AFS of *T. cacao* for higher SOM values, as was reported by Silva (2018) at tropical zone of Villavicencio Piedemont, or the need to add these elements (N, P) as a supplement to meet the demands of the cocoa plants (Leiva, 2012).

In this sense, AFS contributes greatly to SOM formation and thus return significant amounts soil-plant nutrients cycling (Rojas *et al.*, 2017), directly affecting soil micronutrients, our result implies that CAF and CYF showed high soil fertility, less Cu and S in CYF under DS, probably AFS are an important strategies for to mantein SOM and high soil fertility in DS. CAF also can be a very good alternative for tropical zones under DS, allowing a better interaction of Acacia tree rhizosphere with soil microorganisms such as N-fixing bacteria's (Nair *et al.*, 2010; Silva-Parra *et al.*, 2018). Organic matter added through leaf litter in AFS, usually improves soil quality as it enhances its soil microorganism activity and nutrients concentration (Hossain *et al.*, 2011). According to Rojas *et al.* (2017), the contribution of the leaf litter produced by the species assessed that constitute the AFS, the fertilization costs can be reduced 10 %. Contrary, the lowest concentration of SOM was added to the soil from AF and CYF during RS, 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 (Hossain *et al.,* 2011). According to Ngoran *et al.* (2006), leaf litter of *A. mangium* under coconut trees has high contents of cellulose and lignin, which make leaf litter descomposition difficult, reducing the rate of decomposition at the beginning and end of the process (Fioretto *et al.,* 2005), which also translates into a lower mineralization of nutrients. For this reason, it is important to know and compare the litter`s nutrient and biomass input from each species that compose the AFS of *T. cacao* (Rojas *et al.,* 2017). This result may indicate that future studies in AFS that combine microbial action, and decomposition rates methods are critically needed.

Several studies in tropical zones have reported that exchangeable soil Al, determines the availability of carbon storage, soil bases and micronutrients (Castro y Gómez, 2010; Silva, 2018). CYF decreased Al interchangeable in both seasons. AFS has been directly linked to the conservation of soil fertility by improved rhizosphere pH (Nair *et al.*, 2010), and is being directly influenced by the nutritional quantity and quality of plant residues that are anually returned to the soil through litter mainly bases and micronutrients release of leaf litter (Rojas *et al.,* 2017). However, considering established levels by Igac (2000), treatments studied all under both seasons showed high exchangeable soil Al, limiting factor in tropical soils (Castro y Gómez, 2010), which may be influencing lower soil fertility.

The variation in leaf litter macro and micronutrients composition of the AFS and non-AFS depend of the selected trees species coming from different forest and crops having variation in leaf litter chemical and biochemical properties (Triadiati *et al.*, 2011). Generally, leaf litter composition of the AFS and non-AFS evaluated showed more N, in both seasons evaluated. The extraction sequence in leaf litter corresponds to N> Ca>K>Mg>S>P. The low amount of P found in the leaf litter is most likely related to the low mobility of the P in the plant (Malavolta *et al.,* 1997), when comparing leaf litter nutrients of all treatments during RS and DS, with the reference values proposed by this author, the N is found to be within the appropriate range, except for CYF, which was higher (6.74 %) in DS. The P showed acceptable level. The K below the proper level. Mg showed lower range of the accepted level. For Ca, most values were below the maximum adequate level of 1.2 %. S contents were below the adequate minimum. The parameters are indicating a lower level of bases content.

According with Rojas *et al.* (2017), the litter produced by the four species that comprise the AFS contributed with 27.44 % of the N and 3.46 % of the P that is usually employed in an AFS with cacao. CYF showed higher concentration of N, P and Mn, as other leaf litter nutrients at both seasons, less Ca in RS, indicated that capabilities of this species to translocate these nutrients were constant during longer period, differently of reported by Hagen-Thorn *et al.* (2006). The effect of microbial activity on N accumulation could also be altered by soil C availability and microclimatic conditions (Aponte *et al.*, 2010). Nitrogen net release to some extent reflecte N soil availability and which is taken up by the shady trees species in AFS (Aponte *et al.*, 2012). However, in leaf litter of CAF also we noted an significant increased of P, Mg, and K, as Cu, Mn, Zn, less Fe, B and S, from RS for DS, the initial rapid decrease of leaf litter nutrients concentration observed in RS, may be due to the loss of the soluble forms of soil nutrients by leaching due to the high rainfall, and a higher release of soil nutrients at the later season during DS, possibly, governed by microbial oxidation of high C:N components as tanines and cell in Acacia leaf litter that late physical and biological fragmentation of these composes (Aponte *et al.*, 2010). On the contrary, leaf litter of *T. cacao* increased N, K, and S concentration during RS, which can probably be attributed to higher microbial mineralization or non-microbial immobilization in the residual leaf litter (Lin *et al.*, 2007), while leaf litter acts as a surface for fungi or heterotrophic organisms providing mobile nutrients in the plant as reported by Malavolta *et al.* (1997).

Leaf litter of non-AFS including AF, showed a significant contribution of N, which consequently can induce higher mineralization. Previous studies have suggested that higher N concentration in leaf litter as reported for *A. mangium*, will induce a greater rate of decomposition and N release soil-plant, leaves from the leguminous trees could be the main source of organic N in the soil (Aponte *et al.,* 2012). The non-agroforestry systems were very similar in the contribution of leaf litter nutrients, except in P, K that was lower and higher in AF, as Mg higher in CC, however, they are a good contribution of leaf litter micronutrients in both seasons. Salgado *et al.* (2009), found that in 3.41 $ton.ha^{-1}.year^{-1}$ of leaf litter cocoa are 481 $kg.ha^{-1}$ of N, 49 $kg.ha^{-1}$ of P, 271 $kg.ha^{-1}$ of K, 492 $kg.ha^{-1}$ of Ca and 472 $kg.ha^{-1}$ of Mg.

However, CAF showed no significance for N in both seasons, normally, this low N release is related with big quantities of structural lignin in the leaf litter of some forest species (Rojas *et al.,* 2017), edafic and climatic conditions, probably also an effect of both species on the arrangement. We found that AFS of *T. cacao* would help to increase the SOM, and therefore the availability of soil nutrients, thus improving the nutritional quality of leaf litter. Regarding K, the highest contents were of CAF and AF in the DS and RS, respectively. According to Rojas *et al.* (2017), 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. K ranged from 0.63 to 0.82 % in YF and CAF during RS respectively, 0.60 to 0.90 % in CC and CAF in DS. Lower values than those reported by Rojas *et al.* (2017), which ranged from 1.85 to 2.43 % in *G. sepium* forestry.

Our results showed that AFS are an effective leaf litter nutrients pool under RS and DS. The quality and quantity of the different leaf litter types of AFS should contribute differently to the composition of organic matter and soil fertility (Salgado *et al.,* 2009). According to Nair *et al.* (2010); Fontes *et al.* (2014); Puentes-Páramo *et al.* (2016), agroforestry systems are important in the recycling of soil-plant-atmosphere nutrients, offering higher resilience to nutrients losses in tropical ecosystems.

CONCLUSIONS

T. cacao crop is considered a higher source of leaf litter production, and SOM, that may sustain 'constantly' litterfall rates over the year**.** AFS of *T. cacao* showed that nutrients cycling is clearly proven, due to that was tentatively observed to be higher soil and leaf litter nutrients compared with non-AFS. AFS of CAF, can be a very good option to maintain soil fertility in tropical zones during DS. The differences between seasons were due to soil and litter nutrients, mainly micronutrients and Ca and Mg, it was not for litter production. AFS of CYF is a very good option that may contribute to the sustainability of *T. cacao* as crop, which is becoming as an important alternative for improve soil and leaf litter quality over RS and DS, in tropical zone of Villavicencio Piedemont.

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CONTRIBUTION BY AUTHOR

J.A. R-M, conducted the investigation in the field; J.A. R-M analyzed the data and A. S-P drafted the manuscript. All authors contributed to the discussion and commented on the drafts.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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