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Cacao agroforestry systems improve soil fertility: Comparison of soil properties between forest, cacao agroforestry systems, and pasture in the Colombian Amazon

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ABSTRACT

The objective of our work was to evaluate soil quality in different cacao agroforestry systems (AFS) in the Colombian Amazon. We compared soil quality of AFS at the study site with soil quality of two control systems: a pasture and a secondary forest.

The study was conducted at the Macagual Amazon Research Center in western Colombian Amazon. We set up eight 600 m^2 plots in each study system. We collected soil samples in each plot, and assessed macrofauna diversity, aggregate morphology, and physical and chemical soil properties. We integrated these variables in a General Indicator of Soil Quality (GISQ).

We found GISQ values of 0.85 for forest, 0.5, 0.65 and 0.59 for AFS and 0.21 for pasture, and the values differed significantly between land uses. The establishment of cacao AFS on degraded pasture was found to significantly improve soil fertility, i.e., by 42%. The intensification level between land uses (Pasture > AFS > Forest) negatively affected macrofauna populations due to soil compaction (physical properties). Forest had the highest physical and biological quality.

Our results show that AFS not only have the capacity to maintain key soil ecological functions, but also to restore soil quality of degraded pastureland. Cacao-based AFS could therefore be a key restoration strategy for degraded pastureland. These results are very important in the context of the Colombian Amazon, where cacao is currently known as the “crop of peace”.

1. Introduction

Agroforestry systems (AFS) are recognized sustainable alternatives in tropical regions, where agricultural production is rapidly expanding at the expense of natural forests. AFS are systems where crops and/or livestock are associated with woody plants (Kay et al., 2017). Several studies have highlighted the ability of AFS to conserve biodiversity and certain ecosystem services without compromising the productivity of the target crop, if established with an appropriate level of shade (Clough et al., 2011; De Beenhouwer et al., 2013; Torralba et al., 2016; Kuyah et al., 2019). More specifically, AFS have been associated with regulating services, including nutrient retention (Pardon et al., 2017), erosion control (Nair, 2007), carbon sequestration (Chatterjee et al., 2018), pollination (Toledo-Hernández et al., 2017), and pest and weed control (Pumariño et al., 2015). In addition, tree products such as timber and fruit provide farmers with additional income (Tscharntke et al., 2011).

The main focus of this work was on cacao-based AFS, which have been associated with different ecosystem services in tropical regions (Tscharntke et al., 2011; Monroe et al., 2016; Blaser et al., 2017;

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Table 1
Characteristics of the different land uses.

Land Use	Acronym	Rotational grazing (years)	Plant succession (years)	Development in plant succession after AFS (years)	Agroforestry Systems	Shade tree species	Shade tree density (ind. ha^{-1})
Forest	Forest	0	50	0			
Old dynamics and most diverse AFS (with 4 remnant tree species and 4 introduced species	*OdMD*	0	15	15	*Genipa americana L* *Osteophloeum platyspermum* *Cariniana pyriformis* *Calycophyllum spruceanum*	*Inga edulis Mart. Capirona decorticans Spruce Vitex klugii Moldenke Schizolobium amazonicum*	95
Old dynamics and diverse AFS (with 3 remnant tree species and 4 introduced species)	*OdD*	0	15	17		*Inga edulis Mart Ocotea longifolia Kunth Jacaranda copaia (Aubl.)*	95
Medium dynamics and simple AFS (4 introduced species)	*MdS*	8	0	7		Without any selection	69
Young dynamics and simple AFS (4 introduced species)	*YdS*	8	7	0		Without any selection	69
Pasture	Pasture	50	0	0			0

Andreotti et al., 2018). At soil level, establishing cacao AFS has been linked to increased macrofauna communities (Duran-Bautista et al., 2020), carbon storage (Gama-Rodrigues et al., 2010), water and nutrient regulation (Niether et al., 2020; Sauvadet et al., 2020).

Cocoa (*Theobroma cacao* L.) is one of the most important commercial export crops in tropical regions (Bai et al., 2017). Cacao AFS are often characterized by a wide range of shade tree species, which improves overall biodiversity (Stenchly et al., 2012; Cassano et al., 2014; Buyer et al., 2017). This animal and plant biodiversity results in ecological functions that are of benefit to society, making cacao-based AFS a key component of agricultural sustainability in tropical regions (Bhagwat et al., 2008; Mortimer et al., 2018).

However, soil fertility in cacao agroforestry systems has rarely been studied to date. Soil fertility is defined as the ability of a soil to provide the conditions required for adequate plant growth (Stockdale et al., 2002). Some authors specifically investigated the effect of shade trees on soil fertility in cacao agroforestry systems (Arévalo-Gardini et al., 2015; Adeniyi et al., 2017; Blaser et al., 2017; Wartenberg et al., 2017; Nijmeijer et al., 2019). However, there is a need to investigate improvement in soil fertility not only considering the effect of shade trees, but also taking agroforestry implementation and management into account. Improvement linked to soil quality also needs to be taken into consideration. Soil quality is a more global variable than soil fertility, as, in addition to fertility, soil quality includes crucial soil characteristics such as physical properties, soil biology and soil aggregation (Velásquez et al., 2007).

The present work focuses on soil quality in agroforestry systems and we define "soil quality" as the interaction between biological, hydrological and physical components, as well as chemical properties. We specifically focused on assessing macrofaunal diversity as soil macrofauna communities are sensitive to aboveground and belowground disturbances. This is particularly true in the case of termites and earthworms, as soil engineers: (Rodríguez Suárez et al., 2018). In the case of cacao AFS, soil macrofaunal communities are also sensitive to cacao agroforestry management, because changes in stand structure affect soil biomass as well as soil quality (Moco et al., 2009). Macrofaunal diversity is an indicator of both biodiversity and fertility (Rousseau et al., 2012; Vasconcellos et al., 2013). In that context, an increase in macrofaunal communities improves soil biodiversity and related ecological functions (Nijmeijer et al., 2019). Improvement also affects soil physical and hydrological properties, thus enabling restoration of degraded soils (Vanhove et al., 2016; Adeniyi et al., 2017; Wartenberg et al., 2017). Using synthetic indicators of soil quality, we also considered soil attributes that incorporate key soil functions including chemical composition, hydrological services, and protection of organic carbon that are directly linked to soil fertility (Greiner et al., 2017; Bünemann et al., 2018; Drobnik et al., 2018).

Knowledge is lacking on how shade trees affect soil fertility in cacao agroforestry systems specifically in the Amazon region of Colombia. This knowledge is crucial, given the social and economic importance of cocoa, currently known as the “crop of peace” (Sierra, 2016). The use of land to produce cocoa is expanding and will expand even more in the future (Salazar et al., 2018). In addition to the social context, there is a need to restore soils in the Colombian Amazon that have been degraded by livestock (Decaens et al., 2018). Establishing cacao-based agroforestry systems is one way to restore degraded soils and recover soil fertility associated with a range of ecological functions (Cornwell, 2014).

The aim of this study was to evaluate the effect of the implementation and management cacao agroforestry systems on soil quality in areas of the Colombian Amazon that have been degraded by livestock grazing. We compared soil quality in cacao AFS to that in pastures or forests to assess variations in soil quality along a gradient from pasture (more intensive) to forest (less intensive). We discuss the ability of cacao agroforestry systems to ensure key soil ecological functions related to soil quality, and the relevance of cacao-based AFS systems as a strategy for restoring degraded soils in the Colombian Amazon.

2. Material and methods

2.1. Study area

The study was conducted in three-year-old agroforestry systems at the Macagual Amazon Research Center in the western Colombian Amazon (1° 30′ 4.87″ N and 75° 39′ 47.16″ W). The center is located in a humid zone with mean annual precipitation of 3793 mm and monomodal rainfall distribution, with maximum precipitation between the months of April and September. It has 1,707 h of sunshine per year, a mean temperature of 25.5 °C, and mean relative humidity of 84.3%.

2.2. Characteristics of each land use

The aim of the study was to assess variations in soil quality under different cacao agroforestry systems. We compared the soil quality of four types of AFS that are representative of the area, both in their stand composition and in their dynamics before establishment. Here we define the term ‘dynamics’ as the implementation (or establishment) of a process conducive to the different types of AFS we studied.

The soil quality of the four types of AFS was also compared to that of two control systems: a pasture (most intensive control plot in terms of management) and a secondary forest (least intensive control plot in terms of management, compared with the dynamics of natural

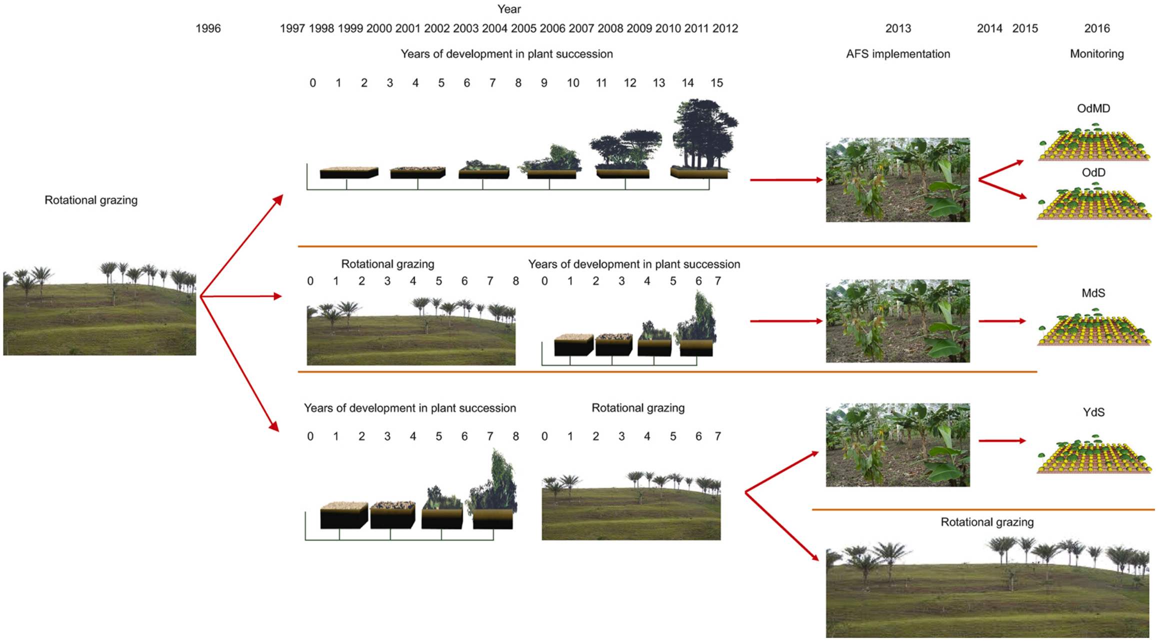

Fig. 1. XXX.

secondary forest).

The study site where the six different land uses were studied covered ca. 48 ha with six pastures each measuring approximately 8 ha in size that were used for rotational grazing from the 1950s on. Since 1996, the use of some of the different parts of the pasturelands has changed. When our study of AFS began, the dynamics were the following: the *Old dynamics and most diverse* AFS (OdMD) plot was delimited in a 15-year-old abandoned pasture left fallow from 1996 to 2012; the plot contained four forest tree species remnant of the secondary forest that were left in place. The *Old dynamics and diverse* AFS (OdD) plot was characterized by the same conditions and was delimited in an abandoned pasture with the same 15 years of fallow; the plot contained three species of remnant forest trees left in place. In both these study plots, the desired percentage of shade was obtained by adding trees belonging to four species *Genipa americana*, *Osteophloeum platyspermum*, *Cariniana pyriformis* and *Calycophyllum spruceanum*. The *Medium dynamics and simple* AFS (MdS) plot was delimited in an area under pasture that had been used as pasture for eight years (1996–2004) and left fallow for seven years (2005–2012). In this plot, in 2012, all the trees were felled and the same four tree species as those used in the two previously-mentioned plots were planted as shade species. The *Young dynamics and simple* AFS (YdS) plot was delimited in a fallow that had been abandoned for eight years and then used for continuous rotational grazing for seven years, and that showed signs of soil degradation. In 2012, the same four tree species were planted to create the AFS. All the cacao AFS were limed (dolomite lime at a rate of 150 g per plant), and also received an organic amendment (Bocashi, at a rate of 200 g per plant) at eight-month intervals after establishment. The cacao AFS were not grazed. The secondary forest used as one of the controls established itself in a pasture abandoned since 1996 and is still not grazed today.

Pastureland with rotational grazing was the most intensive control in terms of management. The pasture was characterized by soil degradation. Soil characteristics under the different land uses are summarized in Table 1. Fig. 1 shows the dynamics that led to the selected land uses to illustrate their similarities and differences.

The cacao trees in the four study agroforestry systems were planted in these fallows and degraded pasture systems in 2012 in a regular pattern: rows aligned in a north-south direction with distances of 3.5 × 3.5 m between trees. The different tree species selected from the secondary forest succession (remnants), and the four shade tree species introduced to form the shade canopy of the cacao agroforestry systems, continue to grow at the same densities today. The shade tree species planted correspond to species prioritized by cocoa producers in the study region because of their architectural and functional traits including a high decomposition rate of the leaves, small leaves to provide light shade, leguminous species for N fertilization.

The quality of the soil under the different agroforestry systems associated with cacao was compared with that of the two control land uses (pasture and forest). The two control land uses were selected as being on an intensification gradient related to soil quality: from pasture under rotational grazing (most disturbed, degraded, least fertile soil) to secondary forests (least disturbed, most fertile soil). The intensification gradient ranged from least to most intensive soil quality, i.e., from secondary forest, *Old and most diverse dynamics* AFS (OdMD) and *Old and diverse dynamics* AFS (OdD) with 15 years of fallow, *Medium and simple dynamics* AFS (MdS) with seven years of fallow, to *Young and simple dynamics* AFS (YdS) with no fallow, and finally to pasture under rotational grazing.

2.3. *Characterization of soil quality*

Samples were collected in November and December 2016 to measure parameters related to soil quality. Systematic sampling was carried out in each study system, i.e., AFS, pasture and secondary forest. In each of the six land uses, two transects were set up following the slope and at least 80 m apart. The slopes were generally slight i.e. less than 10%, in our study site. Along each transect in each study system, four 600 m^2 sub-plots (20 × 30 m) were delimited 30 m apart. Soil was sampled in each of the 8 × 6 × 600 m^2 sub-plots giving a total of eight soil samples for each of the six soil uses (total: 48 samples). The eight sub-plots per land use were discrete replicates of the experimental plan.

The following soil components were evaluated at each sampling point: i. macrofaunal biodiversity, ii. aggregate morphology, iii. physical properties, and iv. soil chemistry. The samples for soil analysis were different monoliths: a 25 × 25 × 10 cm monolith for biological analyses, and a 10 × 10 × 10 cm monolith for aggregation. Samples were taken to analyze the physical variables before samples for the chemical variables, but at the same locations in the plots as described below.

For chemical analyses, soil samples were taken at five locations in the plots (in the center and at the four corners) at depths of between 0 and

10 cm and pooled to make a composite sample

The different soil components were assessed using the methods detailed below.

2.3.1. *Soil macrofaunal communities*

Soil macrofaunal communities was quantified using standard ISO 23611-5 (ISO, 2011). The monolith of soil taken in each plot was used to sample the macrofauna. All macrofauna specimens were extracted from the monolith and stored in 70% alcohol. Back in the University of Amazonia laboratory, the different groups of macrofauna were separated and classified to the level of class or order, then counted to estimate their respective abundance.

2.3.2. *Soil aggregate morphology*

To assess soil aggregate morphology, we used the methodology of Velasquez et al. (2007), i.e. integrated measurement of soil biological activity. To this end, we removed a second 10 × 10 × 10 cm monolith next to the one used to identify the soil macrofauna. The new monolith was carefully removed and stored to avoid compaction before transport to the Amazonia University laboratory, where the monoliths were manually separated into different components: biogenic macroaggregates produced by soil fauna that were characterized by dense, round shapes providing clear evidence of biological activity (galleries, molds, structures); physical macroaggregates, with geometric shapes resulting from physical processes (wetting and drying); root macroaggregates, a product of the interaction between the root system and soil aggregates; and a non-macroaggregated soil (< 5 mm). All the categories identified and separated were dried and weighed. Other soil components including leaves, roots, and pieces of wood classified as organic material were also quantified. Inorganic material was not quantified.

2.3.3. *Soil physical properties*

We measured physical variables related to the hydraulic services of soil. Soil texture was determined using the hydrometer method. Bulk density (BD) was calculated in relation to the total dry mass of the soil and the volume of the cylinder (Blake and Hartge, 1986; IGAC, 2006). Particle density (PD) was determined using the pycnometer method (IGAC, 2006). Total porosity was calculated based on BD and PD [(1-BD/PD) × 100)] (Zamudio et al., 2006; IGAC, 2006). Resistance to penetration was measured in the field using a manual Eijkelkamp penetrometer. Gravimetric soil moisture content was estimated by drying a fresh composite soil sample in the oven at 105 °C for 24 h (Zamudio et al., 2006).

2.3.4. *Soil chemistry*

pH was measured in a 1:1 soil water solution. Organic carbon was measured using the Walkley-Black method (Nelson and Sommers, 1996). Available phosphorus was measured using the P-Bray II method (Bray and Kurtz, 1945). The exchangeable cations Ca, Mg, and K were extracted using 1 N neutral ammonium acetate and measured using atomic absorption spectrophotometry. Exchangeable soil acidity was extracted using 1 N potassium chloride and 0.1 N NaOH. Cation exchange capacity (CEC) was determined using 1 N neutral ammonium acetate (IGAC, 2006). The variables of each component were evaluated in the Amazonia University soil laboratory.

2.4. *Data analysis*

For a comprehensive evaluation of the different land use effects, the variables of each component (i. macrofauna biodiversity, ii. aggregate morphology, iii. physical properties, and iv. soil chemistry) were combined in a single general indicator of soil quality (GISQ) using the methodology of Velásquez et al. (2007) and be adapting the method of Lavelle et al. (2014). First, principal component analysis (PCA) was carried out on the four data sets (i. macrofauna biodiversity, ii. aggregate morphology, iii. physical properties, and iv. soil chemistry) to

Table 2

Abundance of soil macrofauna taxa in different land uses: forests, cacao agroforestry systems and pasture in the Colombian Amazon. Each taxa abundance is expressed as individuals. m^{-2}.

	Forest				*OdMD*				*OdD*				*MdS*				*YdS*				Pasture				
	Mean		SE		Mean		SE		Mean		SE		Mean		SE		Mean		SE		Mean		SE		p-value
Araneae	165.3	±	24	a	30	±	12.6	b	22	±	4.21	b	10	±	4.21	b	16	±	5.24	b	16	±	5.84	b	<0.0001
Blattodea	34.67	±	19.1		8	±	6.05		22	±	11.3		2	±	2		6	±	6		8	±	5.47		ns
Coleoptera	98.67	±	29.9	a	32	±	9.56	b	56	±	19.4	ab	34	±	13.7	b	38	±	10	b	104	±	27	a	0.0225
Collembola	56	±	21.4	a	6	±	4.21	b	2	±	2	b	4	±	2.62	b		–				–			<0.0001
Chilopoda	56	±	5.47	a	12	±	9.91	bc	26	±	11.7	b	6	±	2.93	c		–				–			<0.0001
Diplopodo	144	±	22.3	a	20	±	11.6	b	8	±	3.02	b	6	±	4.21	b	88	±	42.7	a		–			<0.0001
Gastropoda	2.67	±	2.67	b	2	±	2	b	16	±	7.41	a	2	±	2	b	2	±	2	b		–			0.0412
Ants	693.3	±	197	a	128	±	68.8	b	150	±	56.1	b	156	±	80	b	96	±	24.2	b	258.7	±	104	b	0.0001
Hemiptera	18.67	±	4.92	a	2	±	2	b	16	±	6.05	a	2	±	2	b		–			2.67	±	2.67	b	0.0004
Isopoda	93.33	±	21.2	ab	42	±	18.4	b	134	±	40	a	10	±	6	b	72	±	40.9	ab	5.33	±	5.33	b	0.0164
Termites	2237	±	514		2506	±	704		3138	±	790		2476	±	720		1944	±	583			–			ns
Earthworms	85.33	±	17.4	b	234	±	46.3	b	124	±	42.1	b	144	±	27.2	b	454	±	81.6	a	450.7	±	71.4	a	<0.0001
Total abundance*	3685	±	594	a	3022	±	699	a	3714	±	784	a	2852	±	710	a	2716	±	638	ab	845.3	±	74.6	b	
Richness*	10.67	±	0.33	a	6.5	±	0.57	c	8.63	±	0.6	b	5.88	±	0.35	cd	6	±	0.57	c	4.33	±	0.61	d	<0.0001

Mean ± Standard error (n = 8). Means with the same letter in the same row are not significantly different at 5% ($p > 0.05$).

[*] Per monolith.

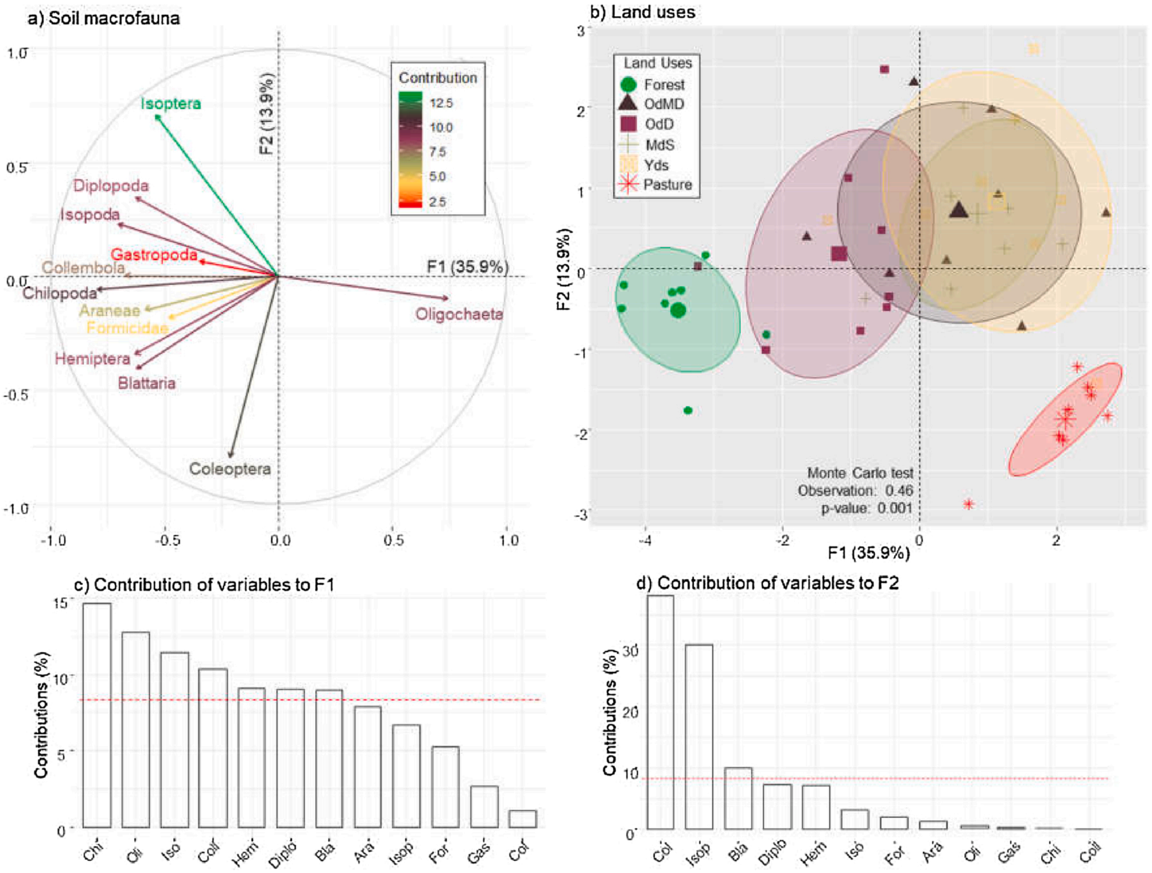

Fig. 2. Projection of soil macrofauna variables and sampling points on the factorial plane F1/F2 of the PCA, grouped according to land use. (a) Correlation circle between the macrofauna groups; (b) Soil samples sorted according to land use; (c) and (d) contribution of macrofauna variables to the formation of the F1/F2 of the PCA. under different cacao agroforestry systems.

identify the variables that caused the most variance in the formation of the first two components, and to assess the effects of land use through Monte Carlo permutation tests (1000 simulations). For the first two axes of the PCA, we selected variables with a significant contribution (variable weights that contributed more than 50% of the maximum value calculated for F_1 and F_2 of the PCA). The values of each variable were multiplied by their corresponding weight factors (variable contribution and variability explained by the component) and summed, giving sub-indicators of i. macrofauna biodiversity, ii. aggregate morphology, iii. physical properties, and iv. soil chemistry with the following formula:

$$Y = F1 * (\beta_1 a + \alpha_1 b + \gamma_1 c) + F2 * (\beta_2 a + \alpha_2 b + \gamma_2 c)$$

where Y is the sub-indicator value to be calculated, F is the percentage of variance explained by the PCA on the corresponding axis, β, α, and γ represent the contribution of the variables to the formation of their respective axes, and a, b, and c are the values of the selected variables on their corresponding axes.

The values of the subindicators were scaled from 0.1 to 1 using a homothetic transformation:

$$Y = 0.1 + ((x - b)/(a - b)) * 0.9$$

where Y is the value of the variable after transformation, x is the variable to be transformed, a is the maximum value of the variable and b is the minimum value of the variable.

The four different sub-indicators (macrofauna biodiversity, aggregate morphology, physical properties, and soil chemistry) and the general indicator of soil quality (GISQ) were compared between the six different land uses, using one-way analysis of variance (one-way ANOVA). Fisher's LSD test was performed when there were significant effects ($p < 0.05$) among the land uses. All analyses were performed using InfoStat statistical software (Di Rienzo et al., 2017).

PCA and the Monte Carlo tests to compare land uses were performed using R 3.6.1 software (R Core Team, 2017), with the *Ade4* statistical package (Dray et al., 2007).

3. Results

3.1. Soil macrofaunal communities

The highest average abundance of soil macrofauna was found in *OdD* and Forest, but did not statistically differ from the other cacao-based AFS (Table 2). The average abundance per m^2 was 2854 individuals. The diversity of soil macrofauna, which we defined as richness in this study, comprised a total of 12 invertebrate taxa (Table 2). Richness (expressed as the number of taxa per monolith) varied widely between land uses, ranging from a minimum of 4.3 ± 0.6 taxa (pasture) to 10.6 ± 0.3 taxa (forest), with an average of seven taxa per monolith. With 8.6 ± 0.6 taxa, *OdD*, tended to be the most similar to forest. Table 2 lists the results for soil macrofauna richness (number of taxa per monolith) and the density of individuals (the number of individuals per m^2). Soil engineers accounted for the highest proportion (abundance), their populations represented 91% of abundance, followed by, ranked in descending order: termites (74.7%), earthworms (8.6%) and ants (7.9%). Although termites dominated in the forest, their abundance was not statistically different from the other cacao-based AFS (Table 2). Ants were more abundant in forest than in the other types of land use, but there were more ants in the pasture than in the cacao-based AFS (Table 2). Earthworms clearly dominated in places with a history of grazing, such as in pasture and *YdS*, while forest had the lowest

Table 3
Size of soil aggregates in the 10 cm × 10 cm × 10 cm monolith of soil samples in the forests, cacao agroforestry systems and pasture in the Colombian Amazon. Soil aggregate size is expressed as the% of the mass of the whole monolith.

	Forest				*OdMD*				*OdD*				*MdS*				*YdS*				Pasture				
	Mean		SE		Mean		SE		Mean		SE		Mean		SE		Mean		SE		Mean		SE		p-value
BM	14.88	±	3.15	b	42.88	±	3.82	a	39.98	±	4.22	a	43.39	±	5.05	a	20.18	±	2.91	b	11.91	±	1.55	b	<0.0001
PM	19.44	±	2.22	b	20.47	±	3.49	b	9.93	±	0.92	c	22.89	±	3.72	b	14.79	±	2.29	bc	42.23	±	4.32	a	<0.0001
RM	12.4	±	2.23	b	2.56	±	0.85	d	6.3	±	1.23	cd	3.17	±	1.23	cd	7.47	±	1.08	c	25.07	±	2.53	a	<0.0001
NM	52.67	±	4.18	ab	33.98	±	4.12	cd	43.43	±	3.11	bc	30.27	±	3.52	de	57.45	±	4.04	a	20.75	±	1.61	e	<0.0001
Org	0.61	±	0.13	a	0.11	±	0.03	cd	0.35	±	0.06	b	0.28	±	0.08	bc	0.12	±	0.04	cd	0.05	±	0.02	d	<0.0001

Mean ± Standard error ($n = 8$). Means with the same letter in the same given row are not significantly different at 5% ($p > 0.05$). BM: biogenic macroaggregates, PM: physical macroaggregates, RM: root macroaggregates, NM: non-macroaggregated soil, and Org: organic material.

earthworm abundance (Table 2).

The first two PCA axes for macrofauna explained 49.8% of the total variability of the data (Fig. 2). Axis 1 (35.9%) clearly split the forest sites with the highest abundance of Araneae, Chilopoda, Coleoptera, Collembola, Diplopoda, Hemiptera, ants and Isopoda, on the left hand side of the axis, from those YdS and pasture sites associated with the highest abundance of earthworms, on the right. The projection of sampling sites on the factorial plane showed a decrease in macrofauna from forest > OdD > *OdMD* > MdS > YdS > pasture. (Fig. 2). Axis 2 (13.3%) mainly contrasted termite and Coleoptera taxa (Fig. 2). A Monte Carlo test showed that the macrofauna significantly differentiated ($p < 0.001$) land uses in our study.

A sub-indicator for biological diversity was created using 10 out of a total of 12 variables (Fig. 2c) and revealed that Forest (0.93 ± 0.03) was of the highest quality, followed by *OdD* (0.67 ± 0.05), *OdMD* (0.52 ± 0.05), *MdS* (0.47 ± 0.04), and *YdS* (0.21 ± 0.03). Pasture (0.21 ± 0.03) scored the lowest quality. These results are in agreement with the results of the PCA, where - with the exception of earthworms - the greater the deforestation and intensification of soil use, the lower the density and diversity of macrofauna. The PCA showed a clear gradient between forest and cacao AFS highlighting the capacity of cocoa agroforestry systems to increase soil macrofaunal communities.

3.2. Aggregate morphology

An average of 39% of the soil classified did not consist of macroaggregates, while respectively, 28% and 23% of the remainder corresponded to biogenic and physical macroaggregates. The largest proportion of biogenic macroaggregates was found in the cacao agroforestry systems, including *MdS*, *OdMD*, and *OdD*, that differed significantly from the Forest and Pasture control systems (Table 3). Pasture, the most intensive land use, had the largest proportion of physical macroaggregates that differed significantly from the cacao-based AFS and Forest (Table 3). However, root macroaggregates predominated in pastureland, which was the most intensive land use (Table 3). *YdS* and forest had the highest proportion of non-macroaggregates (< 5 mm); thereby differentiating them from the other land uses (Table 3).

The PCA for macroaggregates explained 74.9% of total variability with the first two axes separating land uses ($p < 0.001$) (Fig. 3). Axis 1 (40.9%) represented places with the most physical and root macroaggregates, both associated with Pasture (Fig. 3). Axis 2 (34%) associated *OdMD*, *OdD*, and *MdS* with biogenic macroaggregates, while Forest was associated with non-macroaggregated soil and organic material (Fig. 3). Our results show the high capacity of cacao agroforestry systems (especially OdMD) to increase soil macrofaunal communities that directly affect biogenic aggregates.

A sub-indicator for macroaggregates was built using five of the variables measured (Fig. 3c), and the highest quality was recorded in the agroforestry systems *OdMD* (0.73 ± 0.06), *MdS* (0.7 ± 0.08), *OdD* (0.69 ± 0.06), and *YdS* (0.45 ± 0.04). This was attributed to the capacity of these systems to generate biogenic macroaggregates. The scores for Forest (0.27 ± 0.04) and Pasture (0.18 ± 0.03) were negatively affected, because they contained the largest amounts of non-macroaggregated soil and physical macroaggregates, respectively.

3.3. Hydrological properties of the soil

Significant differences between intrinsic soil variables were found for the different land uses. For example, the sand content was significantly higher in *YdS*, *MdS*, and *OdD*, while the clay content was highest in *OdMD* and *OdD* (Table 4). Forest soil was the least disturbed and included the factors that most improved the soil hydrological cycle, including low bulk density and penetration resistance, as well as high values for soil porosity and soil moisture (Table 4). For this soil component, the cacao-based AFS were closest to Pasture, and their physical attributes did not facilitate soil hydrology (Table 4).

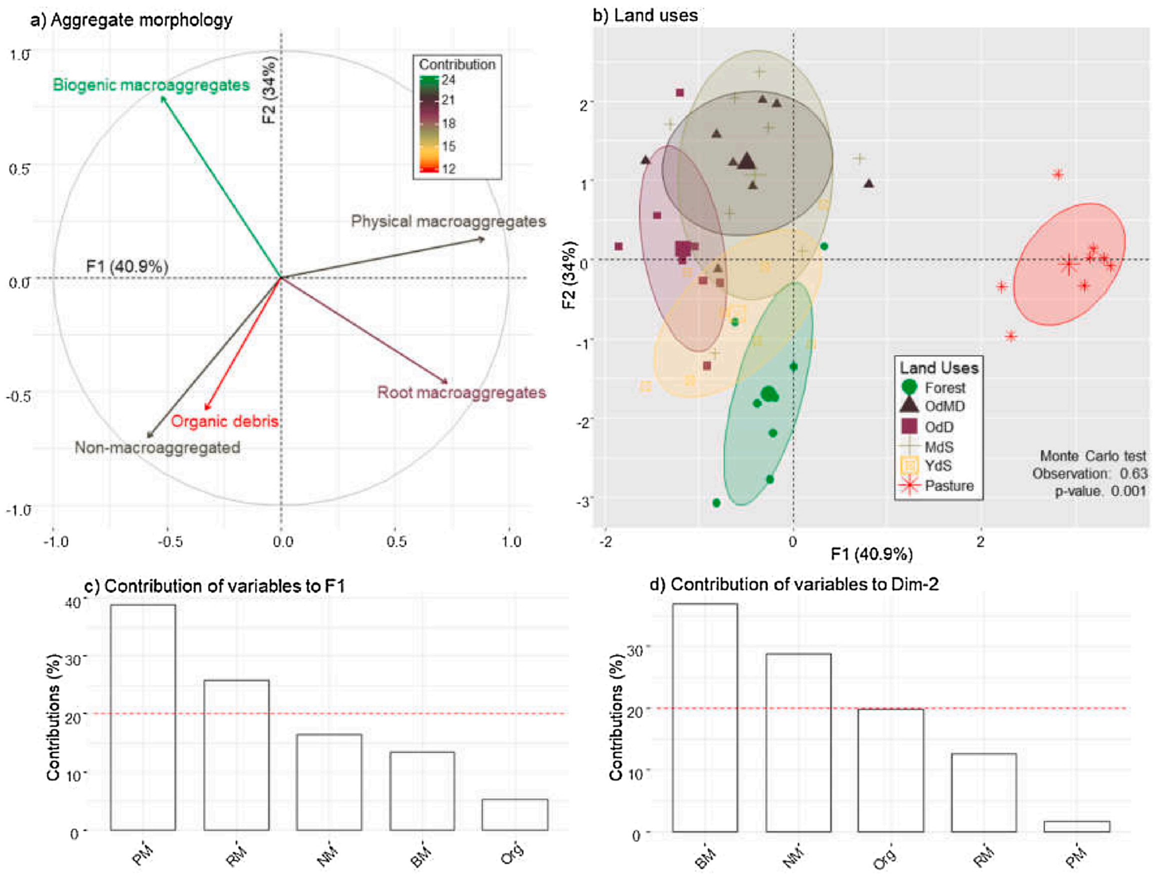

Fig. 3. Projection of aggregate morphology variables and sampling points on the factorial plane F1/F2 of the PCA, grouped according to land use. (a) Correlation circle between the aggregate morphology variables BM: biogenic macroaggregate, PM: physical macroaggregate, RM: root macroaggregate, NM: non- macroaggregated, and Org: organic debris; (b) Soil samples sorted according to land use; (c) and (d) contribution of aggregate morphology variables to the formation of the F1/F2 of the PCA under different cacao agroforestry systems.

The PCA of the physical soil variables explained 70.1% of total variability along the first two axes, separating the different land uses ($p < 0.001$) (Fig. 4). Axis 1 (45.6%) contrasted the most compacted soils (pasture and *OdMD*) from soils with the highest soil moisture content and porosity (forest) (Fig. 4). Axis 2 (24.5%) stood out for its high percentage of silt that was associated with forest, and its percentage of sand associated with *YdS* (Fig. 4).

A physical sub-indicator was created using six of the eight variables measured (Fig. 4c). Forest (0.9 ± 0.03) differed significantly from the other land uses ($p < 0.001$). The values for agroforestry systems and pasture were well below the center of the indicator scale (< 0.5). Ranked in decreasing order *MdS* (0.4 ± 0.04), *OdD* (0.37 ± 0.04) *YdS* (0.31 ± 0.04), *OdMD* (0.26 ± 0.03), and pasture (0.21 ± 0.03). The sub-indicator was mainly sensitive to soil compaction, which varied with the intensity of the land use.

3.4. Chemical fertility

The land use plots studied here had acidic soils, with an average pH ranging from 3.86 in Forest to 4.75 in *MdS* (Table 5). Soil organic carbon content was significantly higher in the cacao-based AFS than in the forest and pasture plots (Table 5); calcium levels, which prevailed in the cacao AFS, followed the same pattern (Table 5). The highest magnesium content was recorded in *MdS*, in contrast to cacao-based AFS, forest, and pasture (Table 5). The CEC in the cacao AFS was double that in forest and pasture while forest had the highest soil phosphorus and potassium contents (Table 5).

The PCA of the chemical soil variables explained 60.3% of total variability along the first two axes, and separated the different land uses ($p < 0.001$) (Fig. 5). Axis 1 (39.2% of total variability) showed that systems *OdMD, MdS*, and *YdS* had the highest magnesium and calcium contents, as well as high pH and CEC values (Fig. 5). Axis 2 (21.1%) associated forest with phosphorus and potassium contents (Fig. 5).

A sub-indicator was created for chemical fertility using six of the eight variables measured (Fig. 5c) and significantly distinguished land uses ($p < 0.0001$). The sub-indicator varied from high values for *MdS* (0.74 ± 0.04), *OdMD* (0.66 ± 0.04), and *YdS* (0.62 ± 0.06) to intermediate values in *OdD* (0.5 ± 0.04) and forest (0.39 ± 0.06), and low values in pasture (0.26 ± 0.03). These results are in agreement with those found by the PCA, showing that AFS are influenced by practices such as stand modification or fertilization, and forest, as a sink for phosphorus and potassium.

3.5. Covariations between data sets

Coinertia analysis between data matrices produced significant covariances with relatively high matrix coefficients (Table 6). The set of physical variables had higher coefficients than macrofauna (0.50), chemical (0.45), and morphological (0.40) characteristics, suggesting that changes in the soil physical variables in the land uses studied were

Table 4
Physical soil properties, comparison between forest, cacao agroforestry systems and pasture in the Colombian Amazon.

	Units	Forest				OdMD				OdD				MdS				YdS				Pasture				p-value
		Mean		SE		Mean		SE		Mean		SE		Mean		SE		Mean		SE		Mean		SE		
BD	gr cm^{-3}	0.87	±	0.02	c	1.21	±	0.03	a	1.06	±	0.03	b	1.07	±	0.04	b	1.07	±	0.03	b	1.28	±	0.02	a	<0.0001
PD	gr cm^{-3}	2.41	±	0.03		2.37	±	0.02		2.38	±	0.03		2.44	±	0.02		2.3	±	0.03		2.41	±	0.04		ns
TP	%	63.68	±	0.98	a	49	±	1.19	c	55.09	±	1.35	b	56.16	±	1.59	b	53.56	±	1.42	b	46.81	±	0.79	c	<0.0001
PR	kPa	0.38	±	0.06	d	1.53	±	0.09	ab	1.4	±	0.05	b	1	±	0.03	c	1.66	±	0.04	a	1.66	±	0.08	a	<0.0001
SM	%	55.61	±	2.06	a	34.03	±	1.3	c	45.76	±	1.34	b	35.73	±	1.61	c	48.33	±	2.54	b	26.04	±	0.71	d	<0.0001
Sand	%	37.85	±	1.52	b	40.65	±	3.38	b	55.19	±	2.29	a	55.86	±	1.39	a	60.2	±	2.93	a	44.63	±	2.56	b	<0.0001
Silt	%	47.33	±	1.38	a	20.52	±	2.3	c	10.47	±	1.58	d	17.03	±	1.27	c	10.31	±	1.83	d	37.17	±	2.29	b	<0.0001
Clay	%	14.83	±	0.61	d	38.84	±	2.98	a	34.34	±	2.5	ab	27.1	±	1.2	c	29.5	±	1.76	bc	18.2	±	0.79	d	<0.0001

Mean ± Standard error (n = 8). Means with the same letter in the same row are not significantly different at 5% ($p > 0.05$). BD: bulk density, PD: particle density, TP: total porosity, PR: penetration resistance, SM: soil moisture.

the main drivers of changes in soil processes and characteristics.

3.6. Synthetic indicator of soil quality

The GISQ significantly differentiated the land uses studied here (Table 7, Figs. 6 and 7). Forest had the best soil quality, with a GISQ of 0.84, which was associated with its high physical and biological quality. The PCA of the General Indicator of Soil Quality (GISQ) explained 86.1% of total variability with the first two axes separating land uses ($p < 0.001$) (Fig. 6). Axis 1 (51.6%) clearly revealed the gradient from pasture (most intensive management) to secondary forest (least intensive management) with lower and higher values of the sub-indicators of physical properties and soil macrofauna (Fig. 6). Axis 2 (34.4%) associated the different agroforestry systems (OdMD, OdD, MdS and YDS) with the chemical fertility and aggregate morphology sub-indicators (Fig. 6).

Comparing the establishment history of the four AFS with their soil quality index showed that the GISC of the AFS implemented after 15 years of fallow (OdMD and OdD) increased by approximately 10% compared with AFS implemented after seven years of fallow (mean GISC of 62 for OdMD and OdD, compared to the mean GISC of 56.5 for MDS and YDS).

In the AFS implemented after 15 years of fallow, the GISC of OdD represents an increase of 10% compared to the GISC of OdMD (0.59 and 0.65 respectively).

In the AFS implemented after seven years of fallow, the implementation of AFS just after the fallow (GISC of MdS) increased the GISC by 26% compared to the GISC of YDS, in which the fallow was followed by grazing, and the YdS AFS were implemented just before grazing (0.63 for MdS, 0.50 for YdS).

4. Discussion

In this study, we evaluated the biological, hydrological, physical, and chemical properties of soils under different cacao agroforestry systems. In order to evaluate variations in soil quality along a defined gradient from pasture (most intensive form of management) to forest (least intensive management), we also compared the soil in agroforestry systems with that in pastures and secondary forests. This enabled us to quantify the range of soil properties under the main land uses in the Colombian Amazon. We focused on the soil components macrofauna and physical properties, both keys to evaluating soil ecosystem services.

Setting up a cacao agroforestry system on pasture with degraded soil was found to significantly improve soil data. Indeed, in the study plots, cacao agroforestry improved soil fertility in three years. This result was found when we compared soil fertility between pasture and the *Young Dynamics and Simple* AFS (*YdS*). *YdS* was established on a pasture resembling the current study pasture. The establishment of a cacao AFS had doubled the GISQ, from 0.21 to 0.5, just three years after establishment. This improvement in GISQ supports the conclusion that cacao agroforestry improves the soil properties of degraded pastureland.

Our study also accounted for the impact of the different land use histories in the improvement in soil fertility found in AFS. Indeed, the different cacao land use histories further improved soil fertility compared to YdS. Comparing *YdS* with the three different older cacao agroforestry systems (the *Old dynamics and most diverse* AFS (*OdMD*), *Old dynamics and diverse* AFS (*OdD*) and *Medium dynamics and simple* AFS (*MdS*), revealed how different rotations (land use histories) before AFS implementation further improved the GISQ. *OdMD, OdD* and *MdS* were linked to a significant improvement in the GISQ compared to the *YdS* GISQ (no significant difference between the three). The improvement obtained by establishing AFS (from pasture to *Young dynamics and simple* AFS (*YdS*); from 0.21 to 0.5) was greater than the improvement revealed by comparing *YdS* and diverse rotations including seven or 15 years of fallow (from 0.5 to 0.65 or 0.59).

These comparisons underline the potential of AFS systems to restore

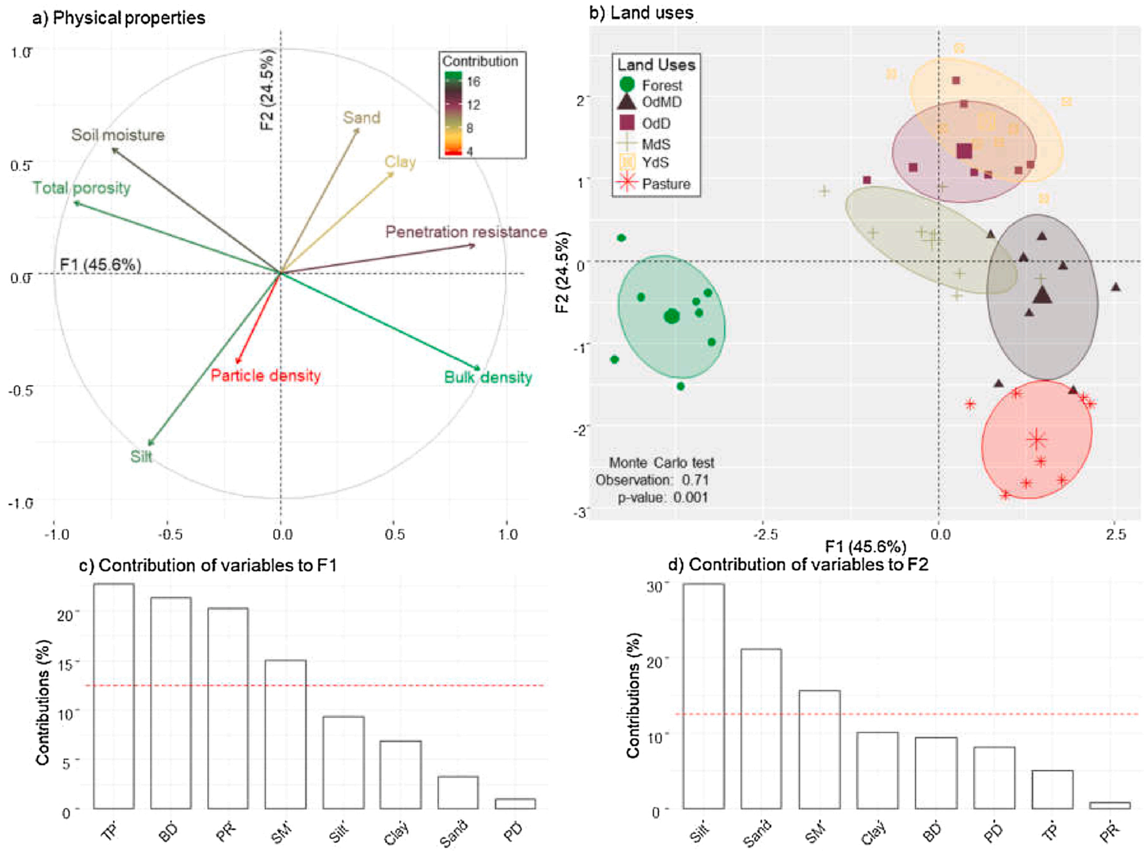

Fig. 4. Projection of physical variables and sampling points on the factorial plane F1/F2 of the PCA, grouped according to land use. (a) Correlation circle between the physical variables BD: bulk density, PD: particle density, PR: penetration resistance, TP: total porosity, and SM: soil moisture; (b) soil samples sorted according to land use; (c) and (d) contribution of physical variables to the formation of the F1/F2 of the PCA under different cacao agroforestry systems.

soil quality. Our results and the conclusions we draw from the comparison between *Young dynamics and simple* AFS (*YdS*) and pasture demonstrate the ability of cacao agroforests to improve soil quality compared with that of the other AFS systems.

4.1. *Soil macrofaunal communities*

Concerning differences in land use, macrofauna diversity was the most sensitive sub-indicator, up to the point of a reduction or the disappearance of their populations in plots under the most intensive land use. Establishing cacao agroforestry systems in degraded pastures demonstrated the capacity of this system to increase macrofauna biodiversity in the soil, as found in *YdS*. *OdD* was close to forest, mainly due to the moderate level of disturbance. Thanks to the fact that vegetation with a tendency to regenerate naturally conserved this ability when the cacao trees were planted, the resources required to restore biological activity were still available. Our results prove that the conversion of forest to agriculture affects soil diversity. The same trend has been demonstrated in other studies in tropical zones (Rousseau et al., 2013; Marichal et al., 2014).

Macrofaunal groups associated with fallen leaves, such as decomposers (Collembola and Diplopoda) and predators (Araneae and Chilopoda), were mainly affected by the intensification of land use. Collembola are individuals that depend on soil moisture (Turnbull and Lindo, 2015). Specifically, in our results, we found a strong relationship between Collembola density and soil moisture. This relationship was supported by the results of co-inertia between the matrix of soil macrofauna communities and the physical soil variables. We therefore suggest that changes in their density occurred due to variations in the microclimate of the land uses studied, as previously demonstrated by Heiniger et al. (2015). For example, Turnbull and Lindo (2015) found a density of 20 individuals per gram in dry soil samples, a density that was reduced to only five individuals in water saturated soil. We also found variations, with higher densities (56 ± 21.4 individuals) than those mentioned in the study of Turnbull and Lindo (2015). This taxon is therefore very sensitive to the moisture conditions created by different land uses. When Turnbull and Lindo (2015) compared a community of springtails in closed vegetation (forest) with open vegetation (pasture), they found the highest density in forest, which they attributed to a better microclimate. According to Vasconcellos et al. (2013), Diplopoda are indicators of soil quality, due to their association with more stable environments, or with places that contain more organic matter. Chilopods are associated with an abundance of fallen leaves in forest areas, and their abundance decreases with deforestation (Marichal et al., 2014). Spiders are indicative of conservation or greater structural complexity of the vegetation, due to a high abundance of prey, and suggest an improved trophic chain (Rousseau et al., 2012; Amazonas et al., 2017).

Earthworms were the only organism whose population size appeared to increase with agricultural intensification. They were the most abundant taxa in pastures and *YdS* where cattle were present. We therefore believe that the abundance of earthworms can be attributed to the species *Pontoscolex corethrurus*, which is invasive and associated with deforested landscapes in the Amazon (Lavelle et al., 1987; Marichal et al., 2012). However, in the present work, earthworms were not identified to the species level.

4.2. *Aggregate morphology*

Land use intensification, particularly that associated with forestry practices, increased the formation of biogenic macroaggregates in

Table 5
Chemical soil properties of forest, cacao agroforestry systems and pasture in the Colombian Amazon.

	Units	Forest				*OdMD*				*OdD*				*MdS*				*YdS*				Pasture				p-value
		Mean		SE		Mean		SE		Mean		SE		Mean		SE		Mean		SE		Mean		SE		
OC	gr kg^{-1}	2.50	±	0.14	c	3.56	±	0.26	ab	3.64	±	0.18	ab	3.85	±	0.24	ab	4.19	±	0.17	a	3.23	±	0.37	b	0.0003
pH		3.85	±	0.06	c	4.58	±	0.04	ab	4.43	±	0.07	b	4.75	±	0.17	a	4.48	±	0.13	ab	4.31	±	0.09	b	<0.0001
P	mg kg^{-1}	19.27	±	3.86	a	7.65	±	0.68	b	7.01	±	0.59	b	7.44	±	1.32	b	10.68	±	0.36	b	1.58	±	0.63	c	<0.0001
Ca	meq 100 g^{-1}	0.21	±	0.03	c	1.25	±	0.25	ab	1.28	±	0.51	ab	1.48	±	0.27	a	0.99	±	0.17	ab	0.54	±	0.05	bc	0.0114
Mg	meq 100 g^{-1}	0.19	±	0.03	d	0.79	±	0.08	b	0.53	±	0.03	c	0.94	±	0.03	a	0.67	±	0.07	b	0.21	±	0.03	d	<0.0001
K	meq 100 g^{-1}	0.25	±	0.03	a	0.19	±	0.02	ab	0.12	±	0.01	c	0.17	±	0.03	bc	0.18	±	0.02	bc	0.16	±	0.02	bc	0.0109
CEC	meq 100 g^{-1}	12.76	±	0.88	b	24.09	±	2.2	a	22.86	±	1.98	a	26	±	1.71	a	24.4	±	2.64	a	11.38	±	0.59	b	<0.0001
EA	meq 100 g^{-1}	3.02	±	0.14	c	4.89	±	0.11	a	3	±	0.36	c	4.01	±	0.37	b	2.53	±	0.14	c	2.49	±	0.12	c	<0.0001

Mean ± Standard error (n = 8). Means with the same letter in common in the same row are not significantly different at 5% ($p > 0.05$). OC: organic carbon, P: phosphorus, Ca: calcium, Mg: magnesium, K: potassium, CEC: cation exchange capacity, and EA: exchangeable acidity.

OdMD, *MdS*, and *OdD*. We mainly attribute this to the abundance of termites in these systems (Table 2), and termites were the most abundant group in the present study. However this could also be attributed to the presence of earthworms (Lavelle et al., 1987). Some authors hypothesize that the cultivation of cacao and shade trees provides the best resources for earthworms, including a favorable microclimate, food and shelter (Bottinelli et al., 2015), which allows them influence the soil through bioturbation, during which they mix the mineral layer of the soil with organic matter (Lavelle et al., 2016). In this respect, Chen et al. (2017) mentioned that agroforestry systems generally improve the accumulation of organic material thanks to the constant supply of plant residues that enable improvements in the aggregation and stability of the aggregate. However, some authors reported no increase in the stability of soil aggregates (i.e., MWD), or any significant differences in the proportions of macroaggregates, or in the storage of C with increased diversity of shade trees in cacao plots (Wartenberg et al., 2017). One possible explanation is that at the time our study was conducted, the plots were too young to show significant effects. Other studies, such as those by Wartenberg et al. (2019) at the level of tree species, reported effects on soil aggregation, therefore suggesting better long-term storage of OM and increased availability of N and P under shade trees. Future work on AFS should therefore investigate the specific effect of the species of shade tree selected, specifically their capacity to increase soil organic matter content.

Consequently, the absence of tree cover in the land uses appeared to be reflected in the increase in macroaggregates. This was particularly driven by abiotic factors (the wetting and drying cycle), which was the case in pasture, the most intensive management system. Even so, the existence of pastures with a dense root system also increased the formation of root macroaggregates. According to Erktan et al. (2016), fine roots lead to the formation of macroaggregates by compressing roots during their growth stage, and through the presence of organic material produced by dead roots. Velásquez et al. (2012) reported similar results, and a higher proportion of aggregates derived from roots when *Brachiaria brizantha* was present, which these authors attributed to its dense root system. We also recall that in our study, pasture hosted the highest abundance of earthworms, which can also lead to the formation of macroaggregates (Velásquez et al., 2012).

4.3. *Hydrological properties of the soil*

The intensification of land use resulted in degradation of the hydraulic properties of the soil (forest > AFS > pasture). The term 'hydrological properties' covers all the physical variables that allow the movement of water through the soil profile. Our results are consistent with those of Owuor et al. (2018), who reported that the conversion of native forests to other types of land use increases bulk density, and consequently reduces water infiltration capacity. These changes in the soil physics, can also affect root penetration, especially when related to bulk density (Arevalo-Hernandez et al., 2019). Pasture has higher bulk density and reduced soil moisture content, mainly due to the intensity of grazing (Abdalla et al., 2018). Additionally, it has been reported that some pastures require a lot of water. However, soil compaction reduces water availability in the soil under intense grazing (Lathuillière et al., 2019). Compaction not only affects the soil under pastures, but also the soil under other agroforestry systems, such as *OdMD* and *YdS*, by increasing resistance to penetration, possibly due to either the preparation of the site, or to intensive agricultural practices (Owuor et al., 2018). However, in our study, none of the three land uses exhibited the average values critical for root development (PR: 2 Mpa and BD: 1.65 g. cm^{-3}) (Cherubin et al., 2016). A significant effect on the hydrological properties of the soil has been reported in cacao-based agroforestry systems, for example, that found by Arévalo-Gardini et al. (2015) in the Peruvian Amazon, where the authors linked the positive incidence of the water available to the plant to the porosity and bulk density of the soil.

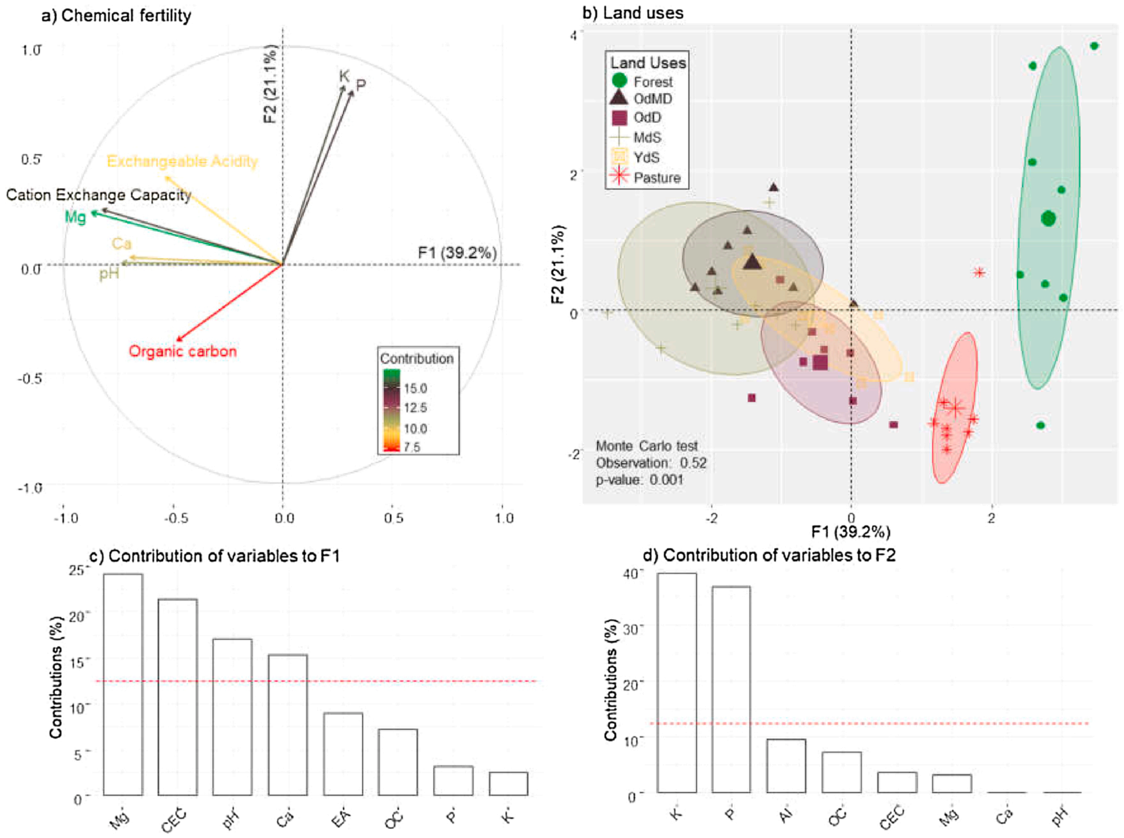

Fig. 5. Projection of chemical variables and sampling points on the factorial plane F1/F2 of the PCA, grouped according to land use. (a) Correlation circle between the chemical variables OC: organic carbon, P: phosphorus, K: potassium, Ca: calcium, Mg: magnesium, CEC: cation exchange capacity, and EA: exchangeable acidity; (b) sorting of soil samples according to land use; (c) and (d) contribution of chemical variables to the formation of the F1/F2 of the PCA under different cacao agroforestry systems.

Table 6
Matrix coefficient between the four data sets (i. chemical fertility, ii. physical properties, iii. aggregate morphology, and iv. soil macrofauna).

Coinertia analysis	RV	p-value
Soil macrofauna-Chemical fertility	0.35	0.001
Soil macrofauna-Physical properties	0.50	0.001
Soil macrofauna-Aggregate morphology	0.41	0.001
Chemical fertility-Physical properties	0.45	0.001
Chemical fertility-Aggregate morphology	0.39	0.001
Physical properties-Aggregate morphology	0.40	0.001

RV: coefficient between the two matrices.

4.4. *Chemical fertility*

We also found an improvement in soil chemistry in the cacao AFS. The use of Dolomite lime or organic amendment (Bocashi) doubtless positively affected soil chemistry. It resulted in a higher CEC in the agroforestry systems, along with increased Ca and Mg content, and high pH. However, P and K were found to be more sensitive to changes in land use, which is in agreement with the results of Arévalo-Gardini et al. (2015), who reported a decrease in P and K at a soil depth of 0−20 cm under cacao agroforestry systems over time. Likewise, when Maranguit et al. (2017) evaluated the conversion of forests to farmland, they found that P fractions in the top soil layer (0−10 cm) decreased, and mentioned that practices like synthetic fertilization (N-P-K) only maintained P in the short term. In particular, Blaser et al. (2017) evaluated the benefits of shade trees for soil fertility in cacao agroforestry systems, and found that the trees were incapable of maintaining sufficient levels of P and K to produce cocoa. In that respect, it has been reported that soil P and K contents decrease due to diverse factors, including a decrease in the return of fallen leaves to the soil (Kotowska et al., 2016), but also to leaching caused by heavy rainfall in the study Amazonian region (793 mm year^{-1}). Extraction of nutrients by the crop (Maranguit et al., 2017), and increased erosion (Guillaume et al., 2015), probably limit cacao productivity. Likewise, when the influence of past land use on soil quality was analyzed in central Cameroon after 15–30 years, a difference was found between cacao agroforestry systems established on land that was formerly forest or savanna, with differences in soil pH, cation exchange capacity (CEC), as well as in the concentrations of C, total N, interchangeable Ca and Cu (Nijmeijer et al., 2019). In the present study, we analyzed young AFS systems (< four years old), that are not yet productive. Future works will include the impact of soil quality on cacao productivity in the different AFS systems studied here.

4.5. *Indicators of soil quality*

Forest had the best soil quality indicator (0.84 ± 0.03), which was expected based on the premise that a top quality soil is at equilibrium with all the other components of the environment, a climax soil developed under climax vegetation (Gil-Sotres et al., 2005). We demonstrated the potential of cacao agroforestry systems to sustain acceptable soil quality, with GISQ values > 0.5, which were highest in *OdD*

Table 7
Soil quality indicators of the forest, cacao agroforestry systems and pasture in the Colombian Amazon.

	Forest				*OdMD*				*OdD*				*MdS*				*YdS*				Pasture			
	Mean		SE		Mean		SE		Mean		SE		Mean		SE		Mean		SE		Mean		SE	
Macrofauna	0.93	±	0.03	a	0.52	±	0.05	c	0.67	±	0.05	b	0.47	±	0.04	c	0.43	±	0.05	c	0.21	±	0.03	d
Aggregate	0.27	±	0.04	c	0.73	±	0.06	a	0.69	±	0.06	a	0.70	±	0.08	a	0.45	±	0.04	b	0.18	±	0.03	c
Physical	0.9	±	0.03	a	0.26	±	0.03	cd	0.37	±	0.04	b	0.40	±	0.04	b	0.31	±	0.04	bc	0.21	±	0.03	d
Chemical	0.39	±	0.06	c	0.66	±	0.04	a	0.5	±	0.04	bc	0.74	±	0.04	a	0.62	±	0.06	ab	0.26	±	0.03	d
GISQ	0.84	±	0.03	a	0.59	±	0.03	b	0.65	±	0.03	b	0.63	±	0.02	b	0.50	±	0.03	c	0.21	±	0.02	d

Mean ± Standard error (n = 8). Means with the same letter in the same row are not significantly different at 5% ($p > 0.05$).

(0.65 ± 0.03), followed by *MdS* (0.63 ± 0.02), *OdMD* (0.59 ± 0.03), and *YdS* (0.5 ± 0.03). These results are similar to those reported by Rousseau et al. (2012) in cacao agroforestry systems in Talamanca, Costa Rica. These authors found that cacao agroforestry systems are capable of conserving soil and providing a high level of ecological services. Likewise, Arévalo-Gardini et al. (2015) reported that the physical and chemical properties of the soil in cacao agroforestry systems in the Peruvian Amazon tended to be near equilibrium after six years of management.

Evidence shows that using *YdS* allowed recovery of degraded areas in the Colombian Amazon because the system was established on degraded pasture and, within a short time after establishment (< 4 years), was capable of increasing the GISQ by 42%.

Generally, the impact depends to a large extent on the practices applied under each type of land use (Menta et al., 2018). Using GISQ to reflect soil quality enabled us to acquire a deeper understanding of particular land uses, because using indicators allowed us to identify inhibitors within particular issues. For example, conventional pasture-land use negatively impacted the biological and physical quality of the soil, probably associated with the presence of cattle (Marichal et al., 2014), whereas conservation practices, such as including shade trees or organic fertilization, boosted chemical fertility and macroaggregation, thereby maintaining macrofaunal diversity at average values (Rousseau et al., 2012).

Our GISQ has a high predictive capacity because our experimental plan was designed appropriately, i.e., with discrete replicates. This allowed us to identify soil Ca and Mg as binding agents that stabilize the aggregates, in particular biogenic aggregates. This result was supported by the results of the co-inertia analysis that explained 32% of total variability. Thus, the differences observed between land uses are actually due to the land use and are not the result of the original soil conditions. Indeed, all the plots in our study were originally part of the same large pasture. This eliminates a possible effect of different land use histories on macroinvertebrate communities, soil macroaggregation, and soil chemical composition.

5. Conclusion

In this paper, we provide a precise evaluation of the biological, hydrological, physical and chemical properties of soils under different cacao agroforestry systems. In addition, we compare these properties to soils under pasture and forest, to evaluate variations in the quality of soil along a gradient from pasture (most intensive form of management) to secondary forest (least intensive form of management). We thus consider different ways of measuring the role played by cacao agroforestry systems in restoring soil biodiversity and ecological functions of degraded soil.

Our study led us to conclude that:

1 Cacao-based AFS stimulate the biological formation of macroaggregates in the soil, which results from the activity of soil engineers, and can, over time, become organic carbon sinks by protecting organic matter from degradation.
2 Cacao-based AFS can mitigate soil compaction better than other intensive land uses, such as pasture. Nevertheless, the different levels of disturbance found in each type of cacao AFS studied here resulted in values that were far from those recorded in forest.
3 Agroforestry practices and organic fertilization notably improve the chemical fertility of the soil, compared to other referenced land uses.

Cacao-based AFS have the capacity to maintain the key ecological functions of soil. These systems have the capacity to recover soil quality in degraded areas, thereby improving ecosystem services. Cacao-based AFS can thus be a key restoration strategy for lands degraded by livestock grazing in the Colombian Amazon.

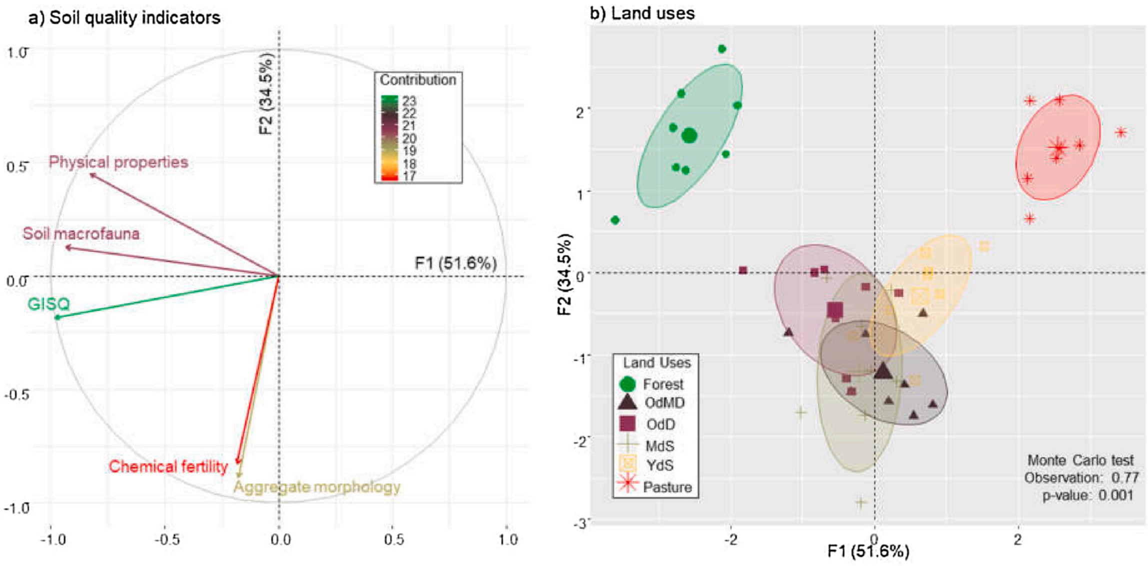

Fig. 6. Projection of synthetic indicators of soil quality and different sampling points on the factorial plane F1/F2 of the PCA grouped according to land use. (a) Correlation circle between GISQ (General Indicator of Soil Quality) and different soil components; (b) soil samples sorted according to land use.

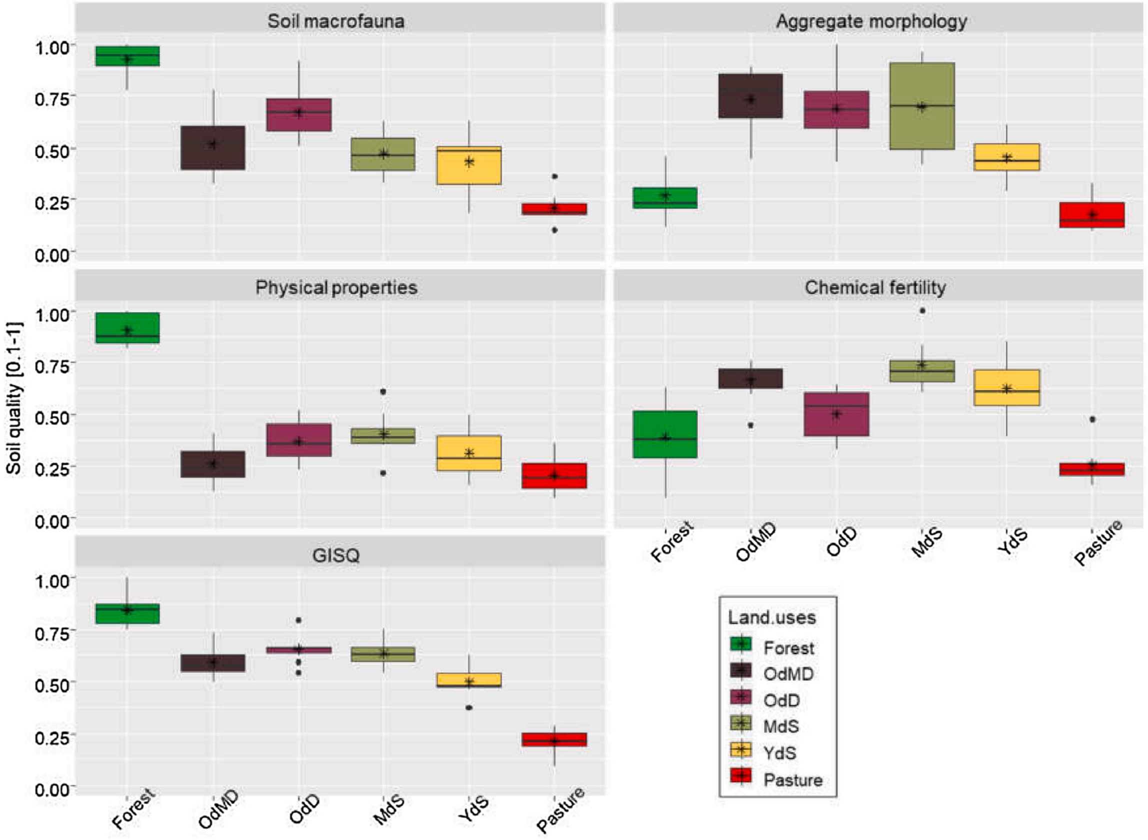

Fig. 7. Box plot of soil quality sub-indicator and GISQ under different land uses. GISQ (General Indicator of Soil Quality), OdMD: Old dynamics and most diverse AFS; OdD: Old dynamics and diverse AFS; MdS: Medium dynamics and simple AFS; YdS: Young dynamics and simple AFS.

Declaration of Competing Interest

The authors report no declarations of interest.

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