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Original Article

Silviculture

Soil Macrofauna and Edaphic Properties in Coffee Production Systems in Southern Colombia

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ABSTRACT

The objective of this study was to evaluate the occurrence of the soil macrofauna in coffee production systems, as well as their relationship with edaphic properties. Therefore, two coffee production systems were selected: coffee plantations at full-sun with conventional management (Intensive) and shaded coffee plantations with organic management (Traditional). In each crop system, three soil samples were collected randomly, in the form of blocks (25 × 25 cm), to a soil depth of 10 cm. In total, 17,109 individuals were recorded in this study being the Oligochaeta group the most representative, regardless of the coffee production system. The average density of soil macrofauna was higher in traditional coffee plantations ($p < 0.05$) due to the higher density of Oligochaeta, Diplopoda and Blattodea. The traditional coffee plantations provided a better soil chemical fertility reflected in the principal component analysis. Furthermore, these chemical attributes probably could affect the occurrence of the soil macrofauna groups.

Keywords: co-inertia analysis, organic management, shade trees, edaphic fauna.

1. INTRODUCTION

In Colombia coffee is grown at full-sun, but it is common to observe coffee plantations associated with different types of shade trees (Arcila et al., 2007). Indeed, from 920,200 hectares cultivated with coffee, about 50% is grown under a canopy of shade trees (Farfán, 2014). Farmers' preference for no-shade system in the coffee plantations is thought to be mainly driven by the economic advantages and short-term profit (Guimarães et al., 2016), although no-shade coffee plantations generally require higher fertilizers, pesticides and labor (Sauvadet et al., 2019). This management practices often have a negative effect on soil quality, with a higher tendency to soil compaction, loss of mineral nutrients, and reduction of soil biota (Vasconcellos et al., 2013).

In recent years, the environmental challenges encountered in no-shade coffee plantations is prompting a reversal to the use of shade trees and a reduction of agrochemical use (Tscharntke et al., 2011). The use of tree species within the coffee plantation reduces the entry of sun-light, increases soil organic matter, soil nutrients and soil moisture, which allows the conservation of soil quality and soil biota (Guimarães et al., 2015). Furthermore, the organic coffee production system has emerged as an alternative to increase economic profitability, environmental conservation and human health (Lammel et al., 2015). This set of practices increases the sustainability of coffee plantations and positively influences in the reestablishment of soil invertebrate community (Guimarães et al., 2017).

Soil macrofauna constitutes an important component of soil biota given the significant impact of their activities in ecosystem functions (Kamau et al., 2017), besides being part of different trophic levels, presents interactions with the edaphic properties (Lavelle et al., 2006). There are physical and chemical soil properties that interact with soil macrofauna groups by influencing their metabolism, while at the same time responding to the behavior of soil macrofauna (Santos et al., 2018; Oliveira et al., 2018). The most cited physical properties are soil texture, soil density and porosity, which are associated with soil structure (Rousseau et al., 2012), while the chemical properties are associated to organic matter content, soil fertility and nutrient availability (Lima et al., 2010). As reported by Santos et al. (2018), chemical attributes may have a great impact on soil macrofauna, and some chemical properties clearly correlated much better with soil macrofauna than with other soil attributes under coffee plantations.

In this context, the objective of this study was to evaluate the occurrence of the soil macrofauna in two systems of coffee production and its relationship with edaphic properties. For this, the following hypotheses were formulated: i) shaded coffee production systems benefit the density and diversity of soil macrofauna due to tree cover that modifies the conditions under its canopy; and ii) the macrofauna are correlated with edaphic properties due to their role in the regulation of key soil functions, such as decomposition of soil organic matter, nutrient cycling and maintenance of soil structure.

2. MATERIAL AND METHODS

The study was conducted in 2016 in the Pitalito-Huila municipality (1°51'14" N, 76°03'05" O). A total of 30 coffee (*Coffea arabica* L.) lots were studied. Two coffee production systems were evaluated as follows:

Intensive coffee plantations: Coffee production system presents densities greater than 7,000 trees ha^{-1} of the variety Castilla at full-sun exposure. The crop system receives at least three applications of urea (600 kg ha^{-1} per year), diammonium phosphate (DAP; 110 kg ha^{-1} per year) and potassium chloride (KCl; 315 kg ha^{-1} per year) per year, and the intensive use of fertilizers and pesticides.

Traditional coffee plantations: Coffee production system presents densities smaller than 5,500 trees ha^{-1} of the variety Castilla and is traditionally grown under a canopy of shade trees (*Inga* sp. and *Erythrina* sp.). In parallel, the system is linked to an organic certification program, for which it refrains of the agrochemical use. The crop system receives regularly applications of compost and coffee husks.

To collect the soil macrofauna, the ISO 23611-5 standard was followed. Three monoliths were made per lot (25 × 25 cm blocks up to 10 cm of soil depth). The soil was manually checked *in situ*. The soil macrofauna was preserved in 70% alcohol and separated into large taxonomic units (class or order). At the sampling points of the soil macrofauna, soil samples were also taken for the characterization of edaphic properties such as pH (potentiometer method in water), organic carbon (Walkley-Black method), total nitrogen (Kjeldahl), phosphorus (modified Bray II method), total bases (K, Ca, Mg, Na) (extraction with 1N and neutral ammonium acetate), exchangeable acidity (volumetry), cation exchange capacity (extraction with 1N and neutral ammonium acetate), texture (Bouyoucos method) and bulk density (cylinder method of known volume). All techniques for the physical and chemical properties were based on the methods of soil analysis described by Zamudio et al. (2006).

We estimated the abundance of soil macrofauna by transforming the number of individuals found in each sample into the number of individuals per square meter (individuals.m^{-2}). The data was analyzed with analysis of variance and Fisher's LSD test ($p < 0.05$) if it fitted a normal distribution; otherwise, a nonparametric Kruskal-Wallis analysis ($p < 0.05$) in the InfoStat (Di Rienzo et al., 2018) software was performed.

In order to analyze the overall effect of coffee production systems on the soil macrofauna and edaphic properties, principal component analysis (PCA) were performed. Prior to PCA, the soil macrofauna relative abundance were log transformed to decreasing the effect of dominant groups. To test for a significant effect of coffee plantations on soil macrofauna and edaphic properties, permutation Monte-Carlo tests were performed. Finally, the association between soil macrofauna relative abundance and edaphic properties was analyzed using co-inertia analysis (Dray et al., 2003) and Pearson's correlation coefficients were calculated. To display the correlations, the heatmap were constructed. All the multivariate statistical analyses were performed using R v.3.4.4 (R Core Team, 2018), and the packages "ade4", "ggplot2", "factoextra" and "corrplot".

3. RESULTS AND DISCUSSION

In total, 17,109 individuals were obtained in this study, being Oligochaeta the most representative group in both coffee production systems (Table 1). The average density of soil macrofauna was significantly ($p < 0.05$) higher in traditional coffee plantations than in the intensive (Table 1). There were found 15 large taxonomic units, presenting significant differences ($p < 0.05$) for Blattodea, Diplopoda and Oligochaeta (Table 1).

According to Pompeo et al. (2016), the primary decomposers (Blattodea) are related to sites with greater diversity and quantity of deposited plant material, which explains the relationship of this group with traditional coffee plantations due to the diverse contribution of leaf litter by shadow trees. Likewise, this trend was found for Diplopoda, for which they have been described as important due to their ecological function in terms of the initial fragmentation of all types of soil organic waste (Teixeira et al., 2014).

A lower density of Oligochaeta group in systems with intensive management can be explained by the use of herbicides (García-Pérez et al., 2014) and pesticides (Bartz et al., 2009). In fact, there would be expected a greater occurrence of Oligochaeta in more sustainable management systems, such as the organic management (Lammel et al., 2015). Particularly Aquino et al. (2008), when evaluating soil worms in coffee systems, also found lower density of earthworms in coffee crops at full-sun with conventional management compared to shaded coffee plantations and organic management.

According to the principal component analysis (p-value: 0.28 Monte Carlo test, Figure 1), in general

Table 1. Density (individuals.m^{-2} ± Standard error) of soil macrofauna groups of the coffee production systems in southern Colombia.

	Intensive coffee plantations	Traditional coffee plantations
Araneae	6.40 ± 1.64 a	3.00 ± 1.23 a
Blattodea	0.36 ± 0.36 b	2.67 ± 1.10 a
Chilopoda	12.44 ± 2.92 a	10.00 ± 2.11 a
Collembola	1.78 ± 1.16 a	4.67 ± 1.34 a
Coleoptera	41.24 ± 8.32 a	43.33 ± 6.70 a
Dermaptera	8.53 ± 3.51 a	5.67 ± 1.61 a
Diplopoda	6.04 ± 2.11 b	17.67 ± 4.13 a
Diptera larvae	2.13 ± 0.82 a	4.00 ± 1.21 a
Hemiptera	2.84 ± 1.37 a	5.33 ± 2.25 a
Hymenoptera	28.44 ± 5.31 a	27.00 ± 5.11 a
Isopoda	5.33 ± 1.69 a	6.33 ± 2.77 a
Isoptera	18.84 ± 7.41 a	14.33 ± 7.77 a
Lepidoptera larvae	0.71 ± 0.50 a	2.33 ± 1.17 a
Oligochaeta	341.70 ± 37.1 b	468.70 ± 46.60a
Symphyla	4.98 ± 1.59 a	2.67 ± 1.10 a
Density total	481.80 ± 36.7 b	617.7 ± 48.30a
Richness	4.84 ± 0.26 a	5.00 ± 0.27 a

Mean: 15 replicate ± Standard error. Averages followed by equal letters in the row do not differ from each other at 5% probability.

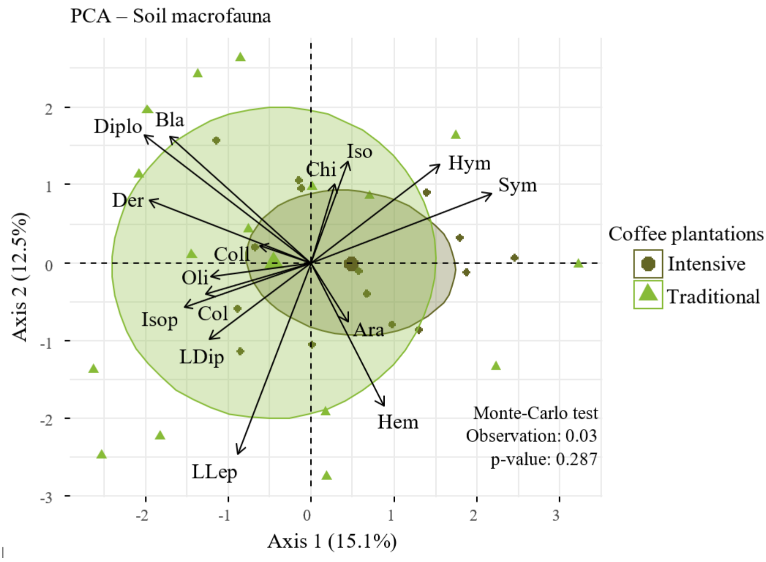

Figure 1. Projection in the F1/F2 factorial plane from a principal component analysis of the soil macrofauna and from sampling points grouped according to the coffee production system. Ara: Araneae; Bla: Blattodea; Chi: Chilopoda; Coll: Collembola; Col: Coleoptera; Der: Dermaptera; Diplo: Diplopoda; Oli: Oligochaeta; Hem: Hemiptera; Hym: Hymenoptera; Iso: Isopoda; Isop: Isoptera; LDip: Diptera larvae; LLep: Lepidoptera larvae; Sym: Symphyla.

the effect of coffee production systems on the soil macrofauna was not significant. The axis 1 indicated that Symphyla and Hymenoptera abundance were associated with intensive coffee plantations, while Diplopoda, Dermaptera, Blattodea and Isoptera abundance were associated with traditional coffee plantations (Figure 1). On the other hand, the axis 2 showed that Lepidoptera and Hemiptera abundance was related with traditional coffee plantations (Figure 1). However, the separation of the centroids that represent the coffee production systems in the factorial plane of the PCA was not evident (Figure 1).

In total, 14 edaphic properties were evaluated, from which eight presented significant differences ($p < 0.05$) between coffee production systems (Table 2). The traditional coffee plantations were characterized by a clay-loam texture, while the intensive coffee plantations showed a loam texture. In this sense, there were significant differences in clay content (Table 2). Soil acidity (pH) in coffee production systems corresponded to acid soils with significantly higher values in traditional coffee plantations (Table 2). These results coincide with Santos et al. (2018), who report an increase of soil pH up to 6.0 in coffee plantations under organic management.

The soil organic carbon presented relatively high percentages, although it was higher in traditional coffee plantations (Table 2). This is similar to what

Table 2. Edaphic properties evaluated in coffee production systems in southern Colombia.

	Intensive coffee plantations	Traditional coffee plantations
pH	4.89 ± 0.14 b	5.71 ± 0.15 a
OC (%)	2.28 ± 0.20 b	2.82 ± 0.19 a
N (%)	1.06 ± 0.02 b	1.15 ± 0.03 a
P (ppm)	1.53 ± 0.02 a	1.56 ± 0.02 a
K (meq $100g^{-1}$)	0.56 ± 0.05 b	0.89 ± 0.15 a
Ca (meq $100g^{-1}$)	6.74 ± 1.83 b	13.04 ± 2.13 a
Mg (meq $100g^{-1}$)	1.49 ± 0.19 b	2.41 ± 0.29 a
Na (meq $100g^{-1}$)	0.88 ± 0.06 a	0.83 ± 0.04 a
EA (meq $100g^{-1}$)	2.10 ± 0.50 a	0.32 ± 0.06 b
CEC (meq $100g^{-1}$)	14.91 ± 1.27 a	17.60 ± 1.53 a
Sand (%)	38.96 ± 2.80 a	46.91 ± 3.58 a
Clay (%)	35.19 ± 1.98 a	24.97 ± 1.92 b
Silt (%)	25.84 ± 1.94 a	28.12 ± 2.63 a
BD (g cm^{-3})	1.05 ± 0.06 a	1.02 ± 0.03 a

Mean: 15 replicate ± Standard error; pH: potential of hydrogen; OC: organic carbon; N: nitrogen; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; Na: sodium; EA: exchangeable acidity; CEC: cation exchange capacity; BD: bulk density. Averages followed by equal letters in the row do not differ from each other at 5% probability.

Lammel et al. (2015) suggested: the high concentration of OC in coffee plantations under organic management is a consequence of the greater addition of organic materials, especially coffee husks. Nitrogen content was slightly higher in traditional coffee plantations (Table 2), possibly to the presence of leguminous species biologically fix atmospheric nitrogen (Munroe & Isaac, 2014).

The concentrations of K, Ca and Mg were significantly higher in traditional coffee plantations (Table 2), possibly attributed to the contribution of organic fertilizer. It was demonstrated by Fernandes et al. (2013), who affirm that depending on the dose of the organic fertilizer, it is produced increases in CEC and in the levels of Ca, P, B and K in coffee plantations. The exchangeable acidity was higher in intensive coffee plantations (Table 2), attributed to the loss of exchangeable bases (K, Ca, Mg), which occurs through erosion and leaching processes, as well as soil acidification (Effegen et al., 2008).

The principal component analysis explained a 57.8% variability of edaphic properties data with the first two axes (Figure 2). The axis 1 evidenced that the highest contents of Mg, sand, OC, pH, CEC and K were linked to the plots of traditional coffee plantations (Figure 2). On the other hand, the axis 2 indicated that the content of silt and the bulk density were associated with traditional coffee plantations, while the exchangeable acidity was related with intensive coffee plantations (Figure 2).

The separation of the coffee production systems according to soil properties was significant (p-value: 0.002) according to the Monte Carlo test (Figure 2). In this sense, we considered that soil conditions were optimal for macrofauna under traditional coffee plantations due mainly to organic management and the inclusion of shade trees, which produced a more heterogeneous environment with greater soil chemical fertility and a greater food supply for soil macrofauna groups (Kamau et al., 2017; Santos et al., 2018). However, this was only verified for some soil macrofauna groups (Blattodea, Diplopoda and Oligochaeta) (Table 1). Therefore, the distribution of the other groups of soil macrofauna can be attributed to environmental variables such as temperature and soil moisture, which has been widely discussed by various authors as Lavelle et al. (2006) and Santos et al. (2008), or even to soil texture, considered an inherent soil property (Grimaldi et al., 2014).

The co-inertia analysis showed significant covariance (RV: 0.33, p-value: 0.002, Monte Carlo test) between soil macrofauna and edaphic properties (Figure 3). These results coincide with previous studies describing the different relationships between soil macrofauna groups and soil properties (Lima et al., 2010; Vasconcellos et al., 2013; Oliveira et al., 2018).

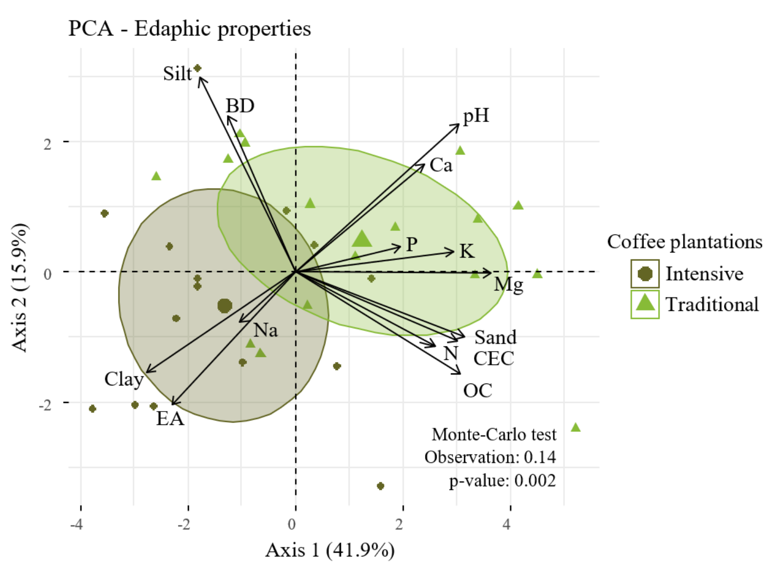

Figure 2. Projection in the F1/F2 factorial plane from a principal component analysis of the edaphic properties and from sampling points grouped according to the coffee production system. pH: potential of hydrogen; OC: organic carbon; N: nitrogen; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; Na: sodium; EA: exchangeable acidity; CEC: cation exchange capacity; BD: bulk density.

In parallel, the heatmap identified some significant relationships (Figure 4) that help explain the distribution of soil macrofauna abundance under coffee plantations. For example, the Blattodea, Collembola, Diplopoda, Hemiptera and Isopoda groups showed significant correlations with some parameters such as pH, CO, N, Ca, Mg and CEC. Like soil macrofauna, soil chemical properties mentioned above were also characteristic of traditional coffee plantations, and to a lesser extent of intensive coffee plantations (Tables 1, 2). These findings provide good evidence that changes in soil chemistry could potentially affect the occurrence of soil macrofauna and foster favourable environments for their increased ecological functions (Kamau et al., 2017; Karungi et al., 2018; Santos et al., 2018).

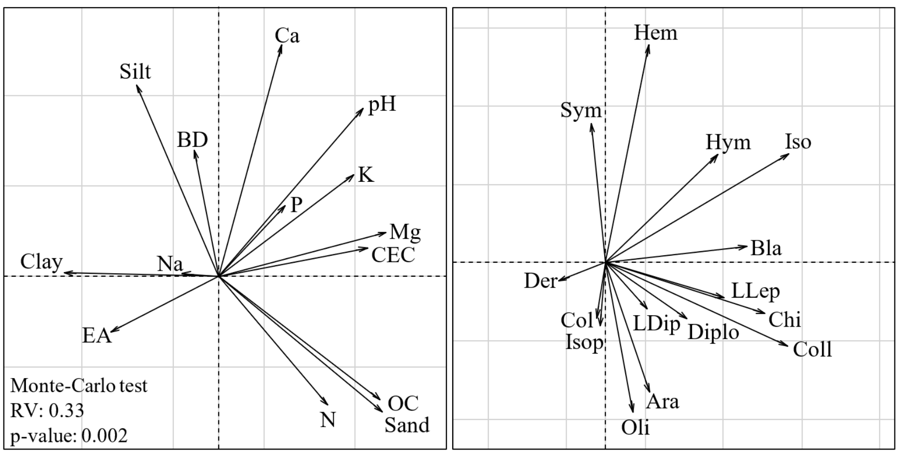

Figure 3. Projection in the F1/F2 factorial plane from a co-inertia analysis of edaphic properties (left) and soil macrofauna (right) in coffee production systems in southern Colombia. pH: potential of hydrogen; OC: organic carbon; N: nitrogen; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; Na: sodium; EA: exchangeable acidity; CEC: cation exchange capacity; BD: bulk density. Ara: Araneae; Bla: Blattodea: Chi: Chilopoda; Coll: Collembola; Col: Coleoptera; Der: Dermaptera; Diplo: Diplopoda; Oli: Oligochaeta; Hem: Hemiptera; Hym: Hymenoptera; Iso: Isopoda; Isop: Isoptera; LDip: Diptera larvae; LLep: Lepidoptera larvae; Sym: Symphyla

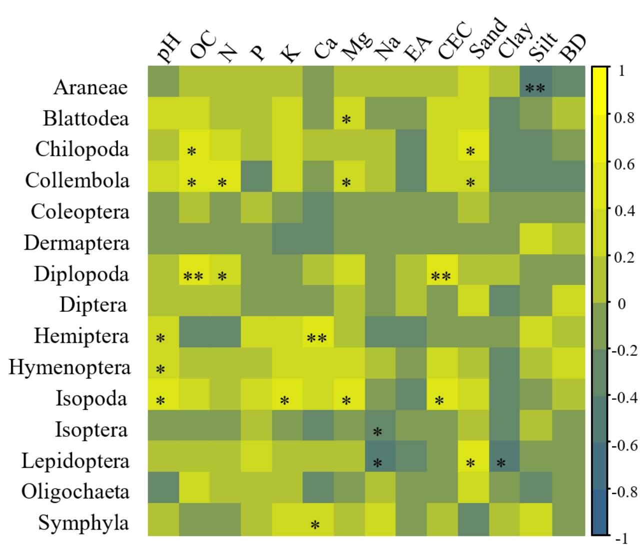

Figure 4. Heatmap of Pearson correlation coefficients between soil macrofauna and edaphic properties. Colors represent the direction and strength of the correlation, * and ** significant correlations at 5 and 1% probability, respectively. pH: potential of hydrogen; OC: organic carbon; N: nitrogen; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; Na: sodium; EA: exchangeable acidity; CEC: cation exchange capacity; BD: bulk density.

4. CONCLUSIONS

The use of shade trees and the organic management in coffee plantations provided higher soil chemical fertility, resulting in a higher average abundance of soil macrofauna and a highest proportion Blattodea, Diplopoda and Oligochaeta.

Soil macrofauna was correlated with edaphic properties, which indicates that changes in soil chemistry under coffee plantations probably could affect the occurrence of soil macrofauna.

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